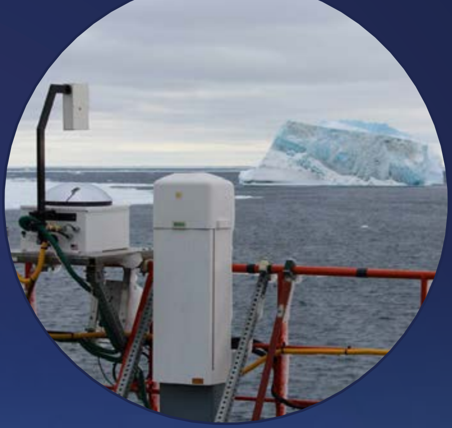
Atmospheric Radiation Measurement (ARM) User Facility

ARM MOBILE FACILITY WORKSHOP REPORT



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Atmospheric Radiation Measurement (ARM) User Facility

ARM Mobile Facility Workshop Report

Convened by

U.S. Department of Energy
Office of Science
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Organizers

Sally McFarlane, Atmospheric Radiation Measurement User Facility
Shaima Nasiri, Atmospheric System Research
Rick Petty, Atmospheric Radiation Measurement User Facility

Co-Chairs

Nicki Hickmon, Argonne National Laboratory
Rob Wood, University of Washington
Guang Zhang, University of California, San Diego

Writing Team

Mike Jensen, Brookhaven National Laboratory
Steve Klein, Lawrence Livermore National Laboratory
Ruby Leung, Pacific Northwest National Laboratory
David Mechem, University of Kansas
Paquita Zuidema, University of Miami

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Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
AMF	ARM Mobile Facility
AOS	aerosol observing system
ARM	Atmospheric Radiation Measurement
ARMBE	ARM Best Estimate
ARSCL	Active Remotely Sensed Cloud Layers
ASR	Atmospheric System Research
AWARE	ARM West Antarctic Radiation Experiment
BAECC	Biogenic Aerosols–Effects on Clouds and Climate
BBOP	Biomass Burning Observation Project
BER	Office of Biological and Environmental Research
CAPE	convective available potential energy
CAP-MBL	Clouds, Aerosol, and Precipitation in the Marine Boundary Layer
CAPT	Cloud-Associated Parameterizations Testbed
CCN	cloud condensation nuclei
CESD	Climate and Environmental Sciences Division
CHEESEHEAD	Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-Density Extensive Array of Detectors
CLAMPS	Collaborative Lower Atmospheric Mobile Profiling System
CLIVAR	Climate Variability and Predictability
CMDV	Climate Model Development and Validation
COMBLE	Cold-Air Outbreaks in the Marine Boundary Layer Experiment
CSAPR	C-Band Scanning ARM Precipitation Radar
DHS	Department of Homeland Security
DIMOP	Diurnal Cycle Interactions with Madden-Julian Oscillation Propagation
DOE	U.S. Department of Energy
DYNAMO	Dynamics of the Madden-Julian Oscillation
E3SM	Energy Exascale Earth System Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EDGAR	Emissions Database for Global Atmospheric Research
EERE	Office of Energy Efficiency & Renewable Energy
ENA	Eastern North Atlantic

ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency
ESM	earth system model
FASMEE	Fire and Smoke Model Evaluation Experiment
FIREX	Fire Influence on Regional and Global Environments Experiment
GCM	global climate model
GCSS	GEWEX Cloud System Study
GEWEX	Global Energy and Water Exchanges
GoAmazon	Observations and Modeling of the Green Ocean Amazon 2014/15
GPCI	GCSS Pacific Cross-Section Intercomparison
GPM	Global Precipitation Measurement
GPS	Global Positioning System
HALO	High Altitude and Long Range Research Aircraft
IMPROVE	Inter-agency Monitoring of Protected Visual Environments
IN	ice nuclei
INP	ice nucleating particle
ISDAC	Indirect and Semi-Direct Aerosol Campaign
KORUS-AQ	Korea-United States Air Quality
ITCZ	intertropical convergence zone
LASSO	LES ARM Symbiotic Simulation and Observation
LES	large-eddy simulation
LTER	Long-Term Ecological Research
MAGIC	Marine ARM GPCI Investigations of Clouds
MARCUS	Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean
MCS	mesoscale convective system
MICRE	Macquarie Island Cloud and Radiation Experiment
MJO	Madden-Julian Oscillation
ModEx	model-observation-experiment
MODIS	Moderate Resolution Imaging Spectroradiometer
MOSAIC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
MPACE	Mixed-Phase Arctic Clouds Experiment
NASA	National Aeronautics and Space Administration
NEON	National Ecological Observatory Networks

NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
NSF	National Science Foundation
NWS	National Weather Service
PBL	planetary boundary layer
PDF	probability density function
PI	principal investigator
RADAGAST	Radiative Divergence using AMF, GERB and AMMA Stations
RHUBC	Radiative Heating in Underexplored Bands Campaign
RRM	regionally refined mesh
R/V	research vessel
SBR	Subsurface Biogeochemical Research
Sc-Cu	stratocumulus-to-cumulus
SGP	Southern Great Plains
SHEBA	Surface Heat Budget of the Arctic Ocean
TES	Terrestrial Ecosystem Science
TOGA-CORE	Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment
TWP	Tropical Western Pacific
UAS	unmanned aerial system
USGS	U.S. Geological Survey
VAP	value-added product
VARANAL	Large-Scale Forcing Data from Constrained Variational Analysis
WCRP	World Climate Research Programme
WE-CAN	Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting (model)
XSAPR	X-Band Scanning ARM Precipitation Radar

Executive Summary

The U.S. Department of Energy (DOE) held a workshop for the Atmospheric Radiation Measurement (ARM) user facility ARM Mobile Facility (AMF) in August 2018 to bring together representatives of the scientific community to discuss critical climate challenges where ARM observations could impact and improve earth system models (ESM). White papers were requested from attendees and the broader scientific community and the workshop discussions were organized around the primary regions or regimes identified in the white papers. The discussions for each region or regime focused on which scientific challenges could be addressed in each region, how these would impact models, and what deployment duration, spatial coverage, combination of ARM assets, and collaborations would be critical to addressing these challenges. The workshop also included sessions on how to increase the scientific impact of the AMFs and how to make better connections between ARM observations and the ESM community.

Common scientific challenges were represented across many sessions of the workshop discussion. Accurate representation of clouds, processes affecting transitions of cloud type, interactions with aerosols and/or the land surface, and precipitation were themes of scientific interest across most regimes.

The following regions and processes were identified by the workshop co-chairs as the highest priority for discussion and key elements of the discussion were highlighted in each session:

- The **southeast United States** is a warm and humid region with abundant locally forced, atmospheric convection inland and enhanced convection along coasts. The strong coupling with the surface supports the study of the impacts of variations in land surface on cloud climatology and transition between cloud regimes as well as their associated precipitation. Large amounts of secondary organic aerosols and scattered urban populations allow for observations to support studies of aerosols' radiative impacts and the interaction between naturally produced and urban aerosols.
- **High-latitude regions** are important due to the changing cryosphere. Observations in the high latitudes are often sparse due to logistical difficulties, and model improvements based on arctic observations might not necessarily apply to the Antarctic. Southern Greenland, boreal forests in high latitudes, Alaska, and inland Antarctica are critical regions with quite different feedbacks between the surface energy budget, clouds and aerosols, and atmospheric moisture transport.
- **Mountainous and complex terrain regions** have orographically forced convection, varied surface conditions (i.e., vegetation, glacier, snowpack), and aerosols, with a large influence on clouds and precipitation. Mountainous regions contribute disproportionately to precipitation over land worldwide, greatly affecting the hydrologic cycle and fresh water supply. Observations could support studies to improve the significant understanding gaps in the areas of convection, extreme precipitation and weather, and interactions between atmospheric circulation, radiation, and land-surface conditions.
- Clouds that develop in **marine regions** generate 80% of the Earth's precipitation. However, this regime is undersampled due to its large size and the logistical difficulties of marine deployments. ARM observations could improve the understanding of aerosol impact on cloud and precipitation and their long-range transport and removal. Observations in various marine regions could target specific types of cloud model representation biases, such as subtropical regions, tropics, and high latitudes.
- Poor representation of processes **associated with organized convection** is linked to biases in the amount, type, spatial distribution, and diurnal timing of precipitation in ESMs. Precipitation produced by organized convection is important in both continental and marine regions; however, organized convection has different characteristics in each region. Due to the large spatial scales and long lifetimes, observations of organized convection will likely require extended facilities or multiple sites along the propagation path. Several regions where observations could capture organized convection and its evolution are the central United States between the Rockies and the Great Plains, southeast United States, Tropical Pacific, Maritime Continent, and the Amazon.

The regions mentioned above were identified for discussion because of their mention in multiple white papers. An additional session was held for discussion of topics or regions that attendees felt were important but that did not receive as much emphasis in the white papers. These included the Great Lakes region of the United States, Asian monsoon, Asian pollution, urban areas, wildfire-prone regions, and convection in semi-arid regions.

Increasing the impacts of observations on ESMs can be done by improving parameterizations, testing and evaluating model representation of the processes observed, providing large-scale forcing data sets, or as direct input in process-model simulations and model data assimilations. Ideas for how ARM could improve the impact of AMF campaigns revolved around the earlier engagement of modelers with the observationally focused scientific community. Available, high-quality data are of the utmost importance for process studies and model advancement; therefore, emphasis should be placed on robust calibrations, maintaining inventory of critical spare parts and instrumentation, and preparing observational data for model use, as funding allows. Past successful campaigns, with strong collaborations involving experimentalists and modelers, should provide useful future deployment design elements to balance the time needed for these needs and urgency to provide appropriate value-added-products (VAPs) and model input to the community. Dedicated site-focused modeling activities, like Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO), should be used to bridge observations with efforts to improve larger-scale ESMs. New technologies should continue to be explored, allowing the potential for increased flexibility, spatial coverage, and in situ and remotely sensed measurements.

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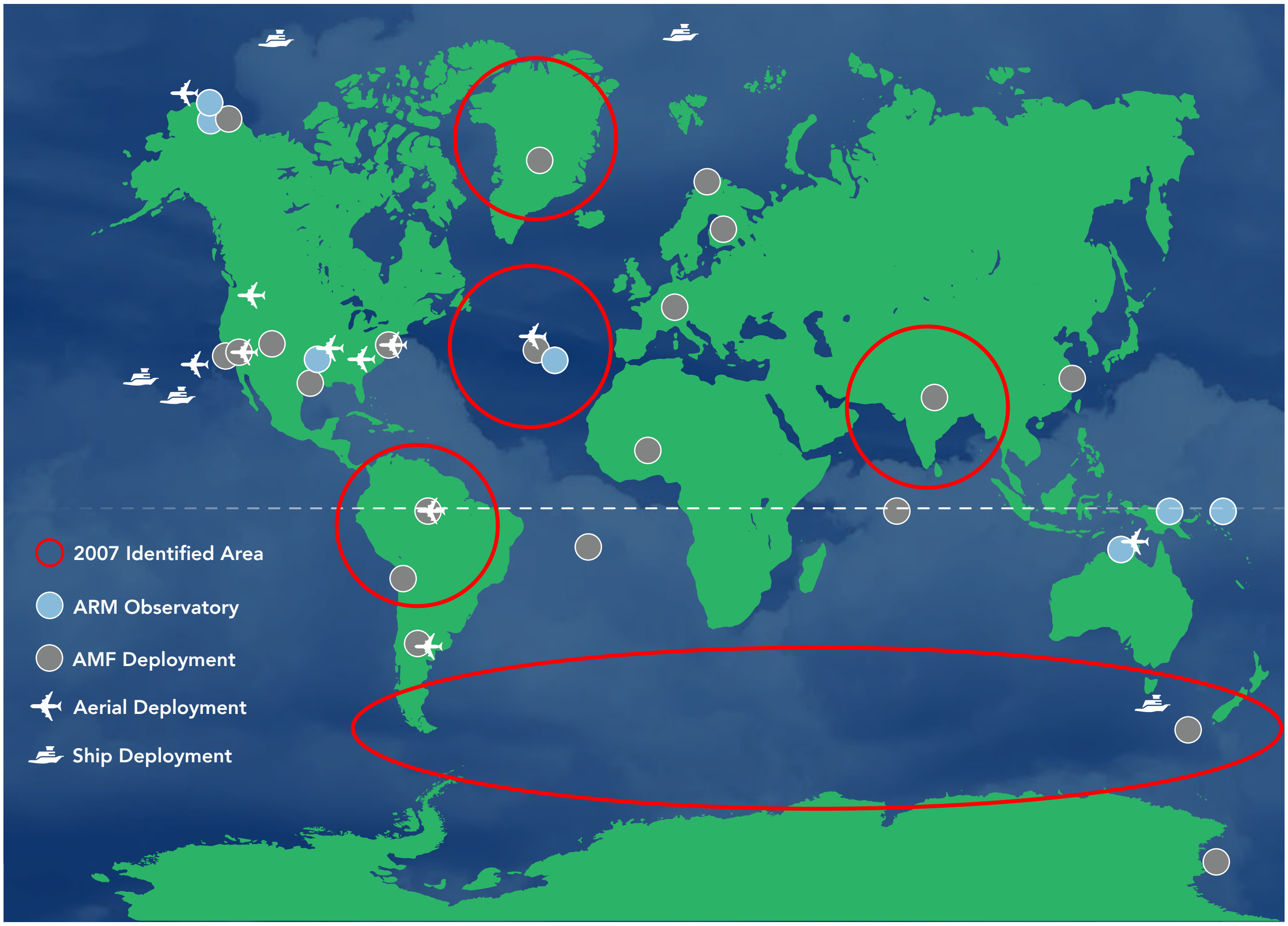
Introduction

The mission of the U.S. Department of Energy (DOE) Office of Biological and Environmental Research (BER) Atmospheric Radiation Measurement (ARM) user facility, as a DOE Office of Science user facility, is to provide the climate research community with strategically located in situ and remote-sensing observatories designed to improve the understanding and representation, in climate and earth system models (ESMs), of clouds and aerosols as well as their interactions and coupling with the Earth's surface. To fulfill this mission, ARM began collecting observations in 1992 at the Southern Great Plains (SGP) site in Oklahoma. Additional observatories were added in strategic climate locations of the North Slope of Alaska (NSA) in 1996, the Azores islands in the Eastern North Atlantic (ENA) in 2013, and the Tropical Western Pacific (TWP) sites from 1996 to 2013. The ARM Aerial Facility (AAF) has provided observations in various locations since 2007, with the capability of manned and unmanned aircraft providing in situ measurement capabilities that complement the ground-based remote-sensing observations.

Included in the earliest ARM program planning, the ARM Mobile Facility (AMF) concept was developed to address particular areas of interest for shorter periods of time than envisioned for the fixed sites. Deployments on the timescale of three months to two years were clearly an expectation when initial locale recommendations were made in a 1991 report. Revived discussion and design occurred from 2001 to 2003 during the ARM Science Team Meetings and a workshop, which resulted in deployment in 2004 of the first AMF. With this new AMF capability, ARM targeted observing shorter-duration phenomena with a more flexible approach and design. An example for the design and deployment of the AMF was the earlier Surface Heat Budget



The 2007 expansion workshop identified areas for future deployments, indicated in red. Since then, ARM has collected measurements in many of the high-priority locations identified from that workshop, as highlighted on ARM's deployment map.

of the Arctic Ocean (SHEBA) collaboration between ARM and National Oceanic and Atmospheric Administration (NOAA), which demonstrated the scientific potential and value of shorter-duration, interdisciplinary, collaborative efforts. Much of the 2018 AMF workshop discussion supported the original methodology of deployment, with three phases: examination of existing data and models; deployment; and in-depth analysis of processes and their interactions from data.

In 2005, ARM began operating the first ARM Mobile Facility (AMF1). The second ARM Mobile Facility (AMF2) was deployed in 2010 and the third (AMF3) in 2013. Each mobile facility added unique capabilities to ARM, as the AMF2 brought deployment capability aboard marine vessels, and the AMF3 brought extended-duration arctic support. Over the past 25 years, ARM has proven its capability to successfully observe on every continent.

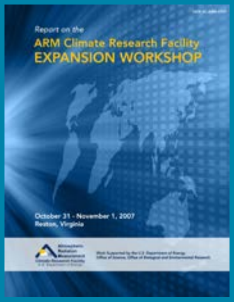
From the beginning, ARM sought community feedback to support continuous improvement and to identify high-priority science locations and questions for ARM observations. Feedback has been gathered through formal workshops, Atmospheric System Research (ASR) working groups, field campaign investigators, the ARM User Executive Committee, the ARM Science Board, and DOE reviews. The last formal workshop that specifically focused discussion on high-priority scientific locations was the 2007 ARM Expansion Report. The top five high-priority locales from this report were: Azores, Greenland, South Asia, Amazon Rainforest, and Middle- Latitude Storm Tracks in the Southern Ocean. This document also provided the rationale for improvements to the AMF design.

Over the past 10 years, ARM has conducted measurements in many of the high-priority locations identified in the 2007 workshop. In addition, BER has developed and released a new ESM, the Energy Exascale Earth System Model (E3SM), that demands targeted field observations in order to improve, test, and validate modeling capabilities. Therefore, it is timely to obtain new input from the community on current scientific priorities for AMF deployments. In 2018, BER hosted a workshop to facilitate input and discussion from the scientific community on the highest-priority scientific objectives, research challenges, and opportunities for the AMF capabilities to best address the BER goal of improving the predictability of ESMs.

The workshop organizers sought input from the community and participants prior to the workshop. Co-chairs developed a set of guiding questions, included in Appendix B, and encouraged attendees and the broader scientific community to submit white papers addressing the questions. Contributors are listed in Appendix F. Co-chairs organized the workshop agenda, included in Appendix C, around the major themes of the white paper submissions. Session leads facilitated discussion among the participants and rapporteurs took notes during the discussions. This report summarizes the feedback provided and discussion held during the workshop.

Additional Resources

Learn more about the history of the ARM mobile facilities in these historical ARM documents and American Meteorological Society Monograph:


Report on the
ARM Climate Research Facility
EXPANSION WORKSHOP
October 31 - November 1, 2007
Reston, Virginia

ARM Climate
Research Facility
Expansion Workshop
December 2007

Identification,
Recommendation,
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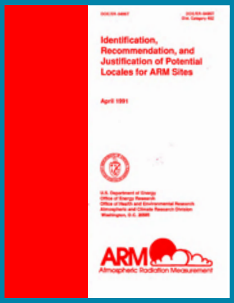
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Office of Energy Research
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ARM
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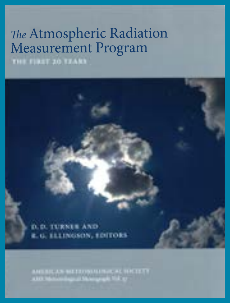

The Atmospheric Radiation Measurement Program
THE FIRST 20 YEARS
D. D. TURNER AND
R. G. ELLINGSON, EDITORS
AMERICAN METEOROLOGICAL SOCIETY

The Atmospheric
Radiation Measurement
(ARM) Program:
The First 20 Years
April 2016

For access to these documents and more, visit the ARM Facility Documents web page at https://www.arm.gov/about/facility-documents.

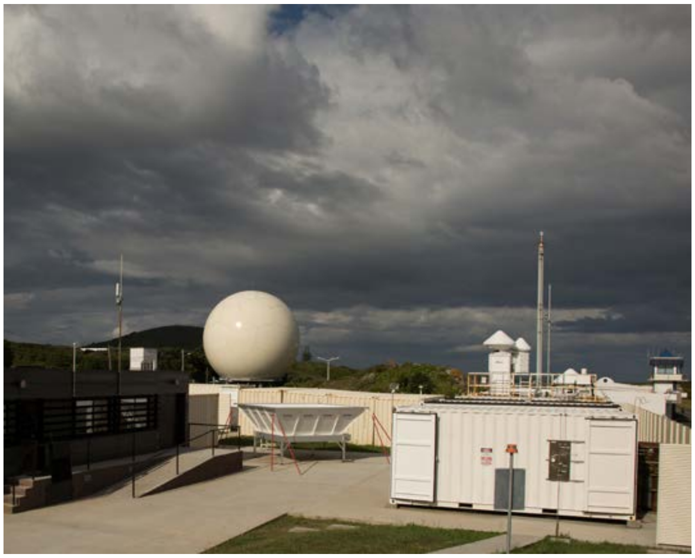
Regime/Region Areas of Interest

Predicting earth system variability and change requires understanding and modeling of multi-scale and interdependent processes that govern the radiative energy balance, water cycle, and biogeochemistry in terrestrial and ocean systems. Solar radiation provides the primary source of energy for Earth, but the net input of energy to Earth and its temporal and spatial distribution are determined by the complex and regionally varying interactions between radiation, water vapor, clouds, aerosols, atmospheric composition, atmosphere and ocean circulation, and the surface. In particular, through storage of energy and water, and exchange of energy, water, and biogeochemical fluxes with the atmosphere, the ocean, land, and ice that cover the Earth's surface have a dominant influence on radiation, clouds, aerosols, and precipitation. The latter processes are the primary focus of the ARM user facility for delivering improved understanding and modeling of Earth's system through in situ and remote-sensing observations of the atmosphere and its interactions with the surface. Hence, the AMF workshop was organized by discussion groups focusing on radiation, clouds, aerosols, and precipitation in regions or regimes of the ocean, land, and cryosphere systems that interact with the atmosphere.

The ocean covers 70% of the Earth's surface and provides more storage for energy and water compared to any other of the earth system components. The flux of water from the ocean to the atmosphere also contributes up to 80% of the global precipitation. On average, over two-thirds of the ocean is covered by clouds of various types, making the marine atmospheric environment and marine clouds and precipitation key elements for understanding and modeling the Earth's energy and water cycles. Through its role in the global energy and water cycles, the ocean also exerts significant remote influence over land and the cryosphere systems through its impacts on the large-scale atmospheric circulation.

Over land, radiation, clouds, aerosols, and precipitation are modulated by complex topography, land cover/land use characteristics, and coastlines that provide unique environments interacting with the atmosphere to support clouds with different diurnal and subseasonal-to-seasonal variability. Mountains, for example, exert a major influence on convection and cloud formation through orographic forcing of the atmosphere and seasonal snow cover and vegetation that changes the surface albedo. Land-sea contrast plays an important role in cloud formation in coastal regions such as the southeastern United States and the Maritime Continent. At larger scales, contrast in energy inputs such as that associated with land and ocean drives monsoon circulations that interact with clouds, aerosols, and convection. In arid and semi-arid environments, land-atmosphere interactions influence convection differently, as compared to moist environments with larger convective available potential energy (CAPE) and longer land-surface memory associated with plentiful surface and subsurface moisture. At smaller scales, large surface water bodies such as the Great Lakes, the urban built environment, and wildfires have important effects on radiation, clouds, aerosols, and precipitation through perturbations of the surface fluxes and mesoscale circulation.

Over both ocean and land, organized convection is a major driver of large-scale atmospheric circulation as the large stratiform precipitation regions produce a top-heavy diabatic heating profile that perturbs the upper-tropospheric circulation. Organized convection is also a major contributor to mean and extreme precipitation. Failure of global ESMs in simulating organized convection has significant implications for the ability to model the global and regional circulation and water cycle.



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Lastly, cryosphere processes over ocean and land play a key role in radiation, clouds, aerosols, and precipitation, as the atmosphere, ocean, land, and ice components of the Earth system interact through complex processes modulated by large surface heterogeneity. High-latitude processes are both influenced by transport of energy, moisture, and aerosols from the lower latitudes, and in turn influence the lower latitudes through their impacts on mid-latitude storm tracks and jet streams.

The following sections summarize the science questions, deployment strategies, modeling impacts, and potential collaborations from breakout group discussions organized by regions or meteorological regimes beginning with the marine region, the southeast United States, mountainous regions, organized convection over both ocean and land, and high-latitude (cryosphere) regions with complex surface cover (ocean, land, and ice). Those regions received the most input from the community in the white paper contributions before the workshop, and so separate discussion sessions were organized for each. These are then followed by shorter discussions of regions that were also mentioned in the white papers, but by fewer participants. These include the Great Lakes of the United States, the south and southeast Asian monsoon regions, Asian pollution, urban regions, wildfires, and convection in arid and semi-arid environments. Along with the science questions and modeling impacts that can be addressed, the report discusses considerations for deployment strategies and opportunities for collaboration for each region. Altogether, the region/regime discussions present high-priority scientific opportunities for advancing understanding and the ability to accurately simulate radiation, clouds, aerosols, and precipitation in diverse environments.

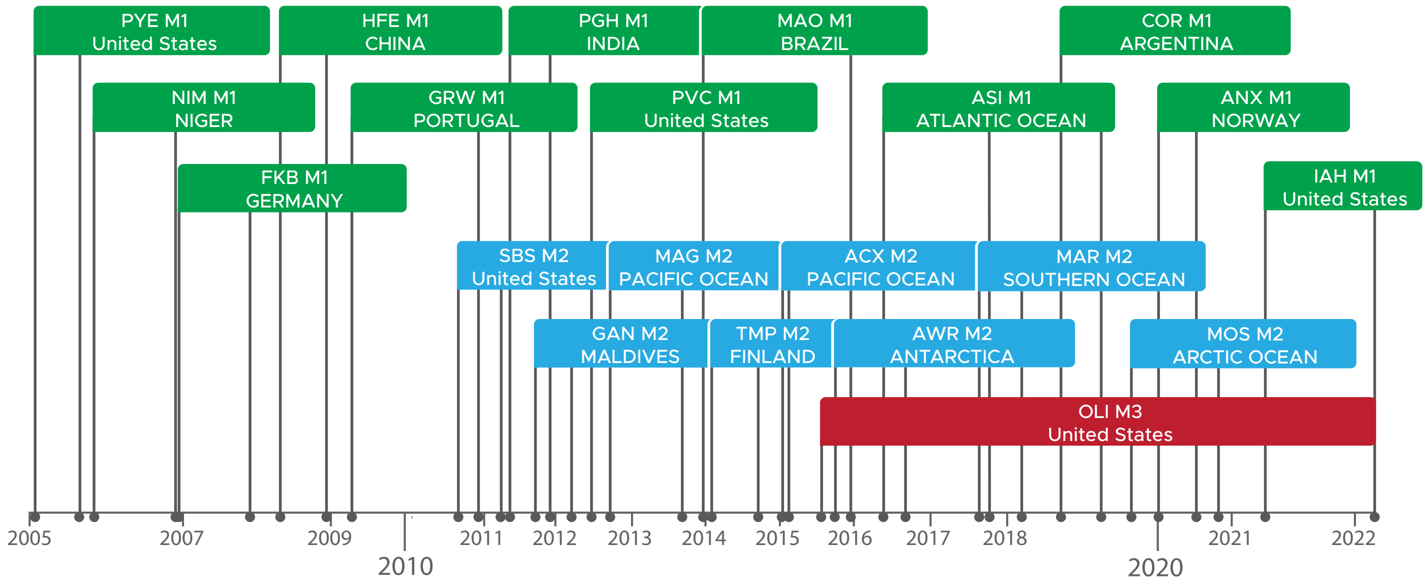
Marine Regions

Approximately 80% of all low clouds on Earth occur over the oceans, and uncertainty in how marine low clouds are expected to change with increasing greenhouse gases remains the largest source of uncertainty in cloud feedback and climate sensitivity. In addition, although most anthropogenic aerosols originate from emissions over land, models show that a disproportionately large fraction of the global aerosol indirect forcing is associated with aerosol-cloud interactions over remote marine regions. Earth system models suffer from major biases in their representation of clouds, precipitation, and aerosols in marine regions.

AMF Deployments Timeline

Since 2005, ARM's mobile facilities have traveled to every continent in their 22 deployments. Consisting of several portable shelters, a baseline suite of instruments, communications, and data systems, these facilities explore research questions beyond those addressed by ARM's fixed atmospheric observatories.

For more information, visit the AMF observatory web page at https://www.arm.gov/capabilities/observatories/amf.



During approximately 25 round trips between Los Angeles, California, and Honolulu, Hawaii, AMF2 obtained continuous on-board measurements of cloud and precipitation, aerosols, and atmospheric radiation; surface meteorological and oceanographic variables; and atmospheric profiles from weather balloons launched every six hours.

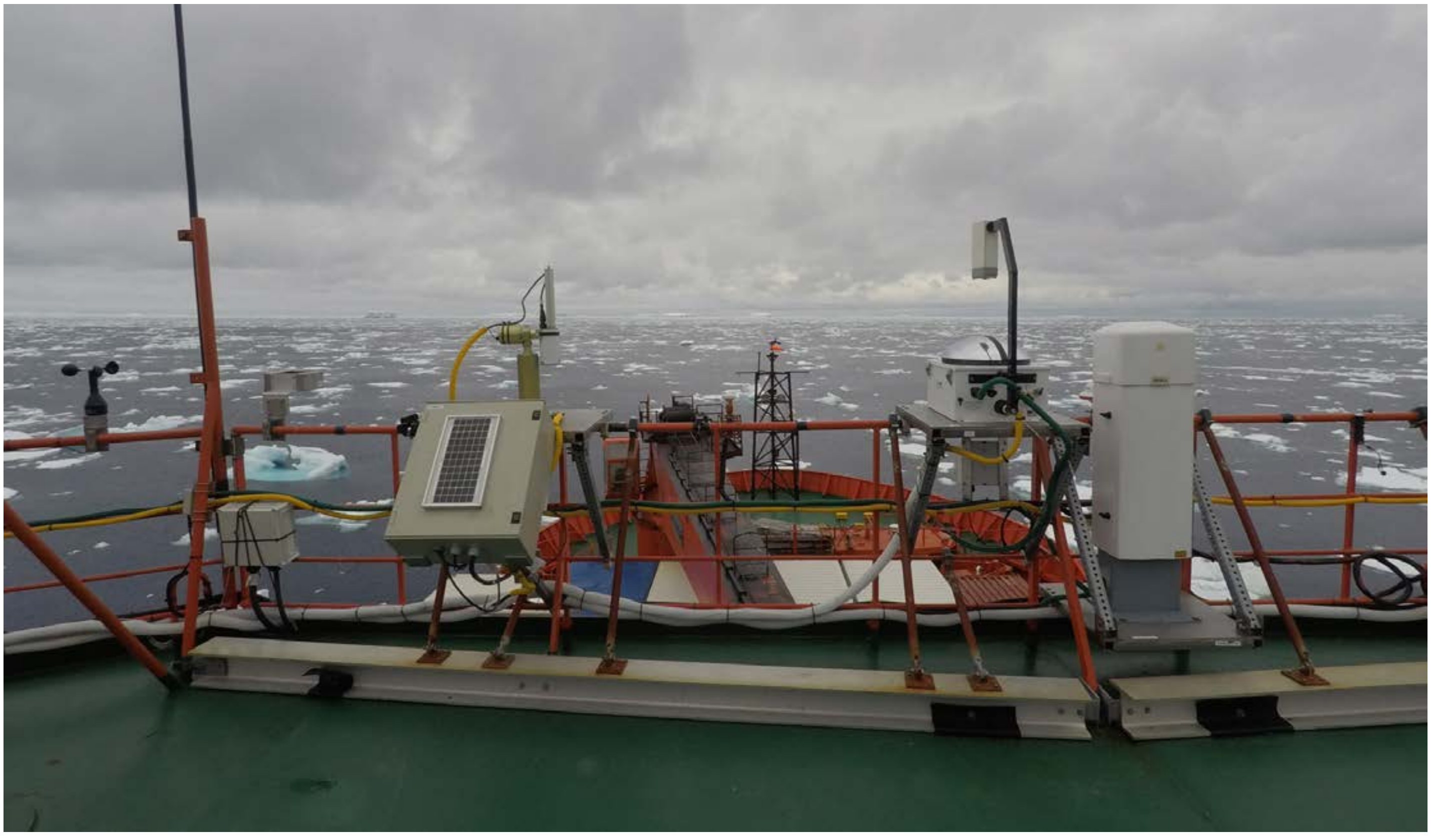
In subtropical regions, climate models tend to produce marine low clouds that are insufficient in coverage but are too optically thick (the "too few, too bright" problem). In the tropics, climate models tend to produce too much precipitation, do not adequately capture existing east-west precipitation gradients, and distribute tropical precipitation too evenly about the equator (the double ITCZ problem). In high latitudes, models struggle to faithfully represent shallow cloud transitions. Model representation of the ice versus liquid phase is also an issue in the high latitudes; this section only focuses on liquid-only clouds.

There is a great need for surface and in situ observations of clouds, aerosols, and precipitation in marine regions, but logistical and measurement challenges mean that such observations are mostly restricted to relatively short campaigns with research vessels and/or aircraft. In the past decade, ARM has made important investments to provide surface-based AMF observations in marine settings. In addition, the fixed Eastern North Atlantic (ENA) site on Graciosa Island in the Azores archipelago has, since 2015, provided a continuous, comprehensive suite of cloud, aerosol, and precipitation measurements in a remote marine environment. These investments are providing key data sets to improve large-scale weather and climate models, but a number of marine regimes remain under-sampled. This is unsurprising; despite compelling scientific motivations for studying marine regions, the logistical hurdles are typically larger than for land-based deployments.

Science Questions

Remaining scientific foci appropriate for marine regions/regimes include the following:

- Processes that drive spatial and temporal transitions in marine boundary-layer clouds are both poorly understood and poorly represented in large-scale models. Numerous questions remain regarding factors controlling the stratocumulus-to-cumulus (Sc-Cu) transition in the subtropics/tropics. How important is precipitation in driving the Sc-Cu transition? Can the transition be modulated by differences in aerosol loading? The Sc-Cu transition over the northeast Pacific was sampled with the Marine ARM GPCI Investigations of Clouds (MAGIC) AMF deployment on a cargo ship, but this transition differs somewhat from the other subtropical ocean regions. Similar transitions also occur at higher latitudes as part of synoptic disturbances or moisture intrusions (e.g., transitions from shallow, overcast conditions to deeper open cell convection in cold air outbreaks).
- The tropical trade wind cumulus regime has been poorly sampled and remains a persistent source of disagreement across global climate models (GCMs). How does the large-scale environment (profiles of temperature, moisture, and vertical motion) determine cloud cover and thickness? What is the role of precipitation?
- Factors controlling aerosol budgets in remote marine regions are not well understood, and observations show that the strength of aerosol-cloud interactions varies with marine region. What are the relative roles of long-range transport of aerosol, local production from ocean surface emissions, and cloud (coalescence) processing in determining the local aerosol budget in marine environments?



The Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) field campaign, which took place from October 2017 to April 2018, used AMF2 instruments to capture the variability in aerosol and cloud properties across the Southern Ocean between Tasmania and Antarctica from spring to autumn.

- Most ESMs still do not represent realistic magnitudes and locations of tropical oceanic precipitation. The inflow region into the intertropical convergence zones (ITCZs) has not been systematically observed over the full seasonal cycle, nor has the ITCZ itself.
- How do the thermodynamic, radiative, and cloud and precipitation properties vary across the ITCZ as it moves seasonally?
- Models continue to struggle with representing transitions from shallow to deep convection at multiple scales (from diurnal up to the deepening of clouds as part of the 45- to 60-day Madden-Julian Oscillation [MJO]), as well as credible populations of low, congestus, and deep clouds. Too few systematic observations exist documenting transitions from shallow to deep convection. What is the relative importance of large-scale external meteorology versus internal cloud-controlled processes (e.g., cold pools, self-aggregation) in driving or suppressing transitions?
- Stratocumulus clouds are still a source of substantial radiation biases in large-scale models and uncertainties in the climate sensitivity associated with these clouds remain. While ARM has a long-time record from the ENA site, the other large stratocumulus decks (northeast Pacific, southeast Pacific and Atlantic, southeast Indian Ocean), along with their unique aerosol environments, remain vastly under sampled. What are the fundamental differences in cloud properties and aerosol-cloud-precipitation interactions across the different marine stratocumulus regions?

Deployment Strategies

Marine environments are particularly difficult to sample. A perennial question is whether AMFs deployed to island and coastal sites accurately sample the remote marine environment or whether there are data severely influenced by land artifacts? The answer to this question likely depends upon the particular observation. While it is known that surface fluxes from island sites are not representative of the surrounding open ocean, it is possible that clouds and precipitation may be less affected.

Measurements from ships or buoys upwind of island sites can help provide surface fluxes that are representative of the open ocean.

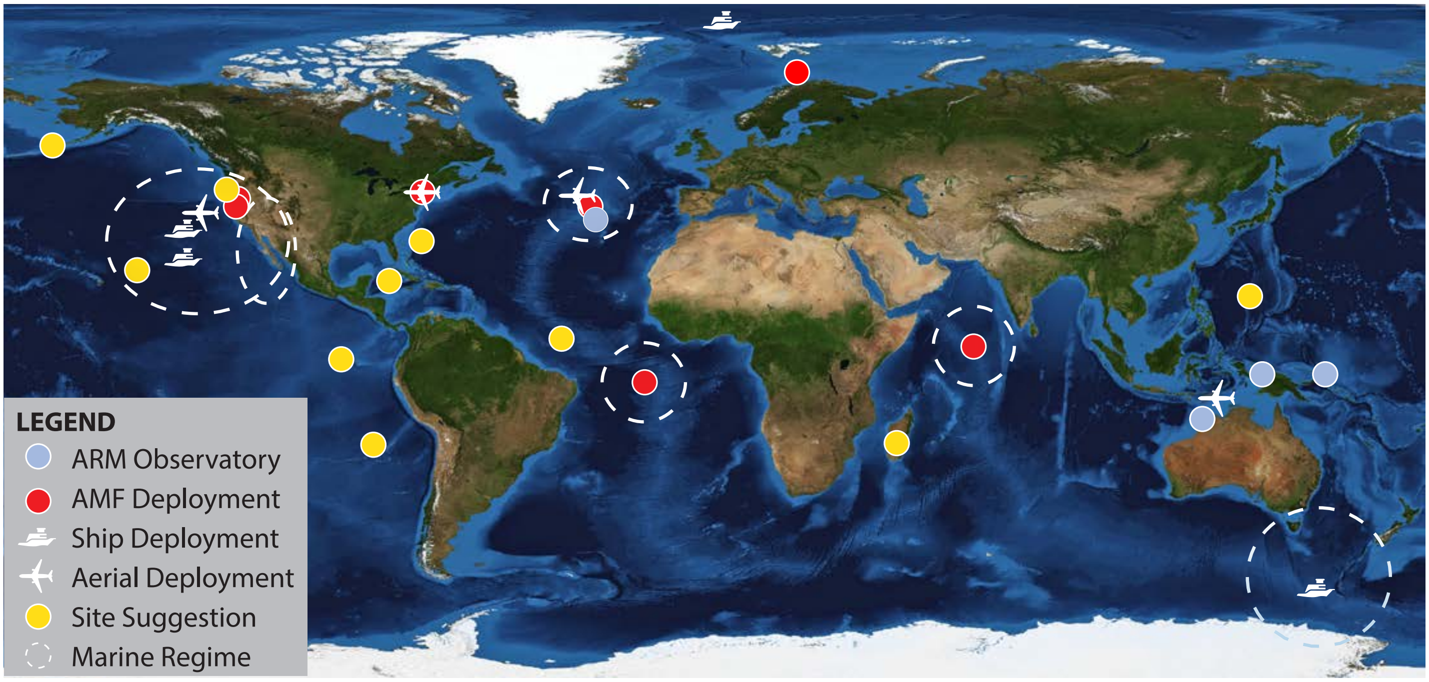
An additional question is whether information from an AMF deployment at a single location is sufficient. Again, the answer is likely observation-dependent. The characterization of precipitation over a larger range than is available to DOE scanning precipitation radars is helpful for understanding the corresponding cloud mesoscale organization. ARM's scanning X- and C-band precipitation radars (XSAPR/CSAPR) can be used in conjunction with existing non-DOE precipitation radar networks to provide additional range for studying large mesoscale convective systems. Constraining the large-scale vertical motion field is crucial for most modeling studies but remains a stubborn problem. A widely used approach is to employ sounding networks, but this requires three to five sites. Another approach is to construct a circle of dropsondes around a particular ground-based site. Coordination with interagency and international partners can increase the effectiveness of an AMF deployment by supporting multi-site deployments, other research aircraft, unmanned aerial systems (UAS), tethered balloons, and research vessels. As atmospheric reanalyses improve, perhaps new data assimilation approaches can be applied to improve subsidence estimates. Closer coordination with National Aeronautics and Space Administration (NASA) satellite programs may also be useful.

Deployment Duration Considerations

Regions/regimes with more homogeneous clouds (e.g., shallow near-coastal subtropical marine stratus/stratocumulus) can be sampled over shorter durations, but deployments targeting regimes with greater underlying synoptic variability, or sampling phenomena characterized by a relatively small number of episodic "extreme" events (e.g., deep convection), will require longer time frames. Regimes with strong inter-annual variability (e.g., high latitudes; regions affected by the El Niño-Southern Oscillation [ENSO]) will require longer-term deployments to provide adequate statistical sampling.

Potential Deployment Locations

Marine regions include a wide range of meteorological, cloud, and aerosol conditions, and there are numerous suggestions for locations where new AMF deployments can provide important data in previously under-sampled marine environments. These include:



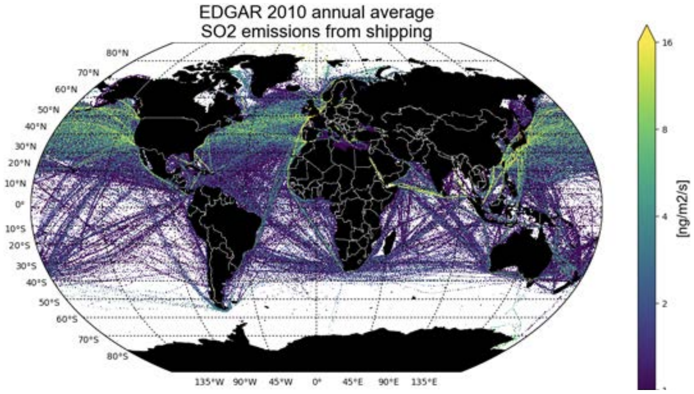
ARM observatories and mobile facilities have sampled, or will sample, many marine regimes, such as subtropical stratocumulus, trade cumulus/shallow convection, summertime midlatitude low clouds, shallow-to-deep convection transition, and polar-north Atlantic connectivity (referenced in the dashed circles). Workshop participants provided suggested locations for future deployments or observatories indicated by the yellow dots.

- Trade wind cumulus regime – The trade wind cumulus regime could be effectively sampled at **Barbados, southern Florida, Kwajalein Atoll,** or **Reunion/Madagascar.** Hawaii is situated in a good location, but the high terrain of the islands likely represents a significant challenge.
- Shallow-to-deep convection transition – **Kwajalein Atoll** is a good location to sample the shallow-to-deep convection transition. Existing infrastructure includes a National Weather Service (NWS) S-band precipitation radar. Other potential sites to sample deep convection and/or the transition between shallow and deep convection include **Guam,** and perhaps the **Galapagos**.
- Mid-latitude oceans – Summertime mid-latitude oceans have the highest coverage of marine low clouds anywhere. This regime could be sampled at the **Aleutian Islands** (52 to 55°N), with the opportunity to sample downwind of major east Asian aerosol sources. In the Atlantic, open ocean extends further poleward, offering the potential for sampling marine regimes straddling the mid-latitudes and Arctic. The high-latitude Atlantic is particularly relevant given the secular trend toward less sea-ice coverage. Cold air outbreaks, warm advection stratus, and poorly sampled mixed-phase cloud regimes would complement/extend existing AMF deployments such as Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) and Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE).
- Marine shipping effects – Shipping lanes present another deployment opportunity because marine shipping currently uses sulfur-rich fuel whose combustion emits high quantities of sulfur dioxide (SO_2), an aerosol precursor gas. Although individual ship tracks are readily detected under conditions of very shallow, stratocumulus-topped planetary boundary layers (PBLs), evidence for time-aggregated signals of shipping lanes on marine low cloud fields has not yet been clearly observed. Regular ship traverses of a major shipping lane could be conducted if a suitable cargo ship can be identified. The International Maritime Organization low-sulfur regulation requires shipping companies to reduce their sulfur emissions by 85% by the year 2020, making the next few years one of significant shipping emissions changes with potential implications for aerosol-cloud interactions.
- Western continental coasts – The shallow subtropical stratocumulus regime off the western continental coasts could be sampled using measurements from an island site (e.g., **San Felix** west of Chile, **San Nicholas** in the U.S. Channel Islands, **St. Helena** in the southeast Atlantic, or from a dedicated barge/ship).

Modeling Impacts

Marine regimes continue to challenge ESMs. Shallow stratocumulus-topped PBLs just off the west coasts of continents remain a major source of bias in the simulation of the radiative budget in ESMs. Additional observations in these regions would be highly valuable. ESM biases stem both from uncertainties in individual parameterizations (e.g., microphysics, turbulent mixing), and from the interplay between the different parameterizations that must work together to produce a realistic representation of clouds (e.g., cloud overlap assumptions used by the radiation parameterizations).

A good representation of mixing between clouds and clear air (both at cloud top for stratocumulus and laterally for cumulus) is critical for accurately representing the cloud climatology and transitions between regimes. Turbulent entrainment is not explicitly represented in large-scale models, and boundary-layer parameterizations need to be tuned using estimates of entrainment from a combination of robust observations and high-resolution large-eddy simulation (LES) model output. New remote-sensing measurements of turbulent processes (e.g., Doppler lidar and radar) will help constrain entrainment parameterizations and mass-flux closure assumptions necessary in parameterizations of shallow and deep convection. LES model domains can be nested within regional models, allowing for explicit representation of turbulent mixing processes and resulting cloud structure that can be compared directly with observations. This modeling hierarchy can then be used to develop improved physical parameterizations for use in large-scale models. There is an opportunity to adapt systematic modeling approaches (e.g., LASSO) to marine regions, although large domains may be necessary to capture known scales of mesoscale variability and to better understand island effects. Different modeling constructs can also be considered (e.g., doubly periodic versus constructs that allow for inhomogeneous surface forcings and spatially asymmetric large-scale forcings).



Annual mean emissions are shown here of sulfur dioxide, a key aerosol precursor gas, from commercial shipping. Commercial shipping is a key, but highly spatially heterogeneous and uncertain, contributor to the marine boundary-layer aerosol budget. Ship emissions lead to more numerous cloud droplet concentrations, smaller droplet sizes, and brighter clouds. *Image credit: Michael Diamond (U. Washington) based on data from the Emissions Database for Global Atmospheric Research (EDGAR).*

Aerosol-cloud interactions remain poorly represented in large-scale models (e.g., a consensus is emerging that the modeled aerosol indirect effect is too strong). Model experiments suggest that accurately representing the susceptibility of precipitation to increasing aerosol may be a key target. AMF deployments are uniquely positioned to provide both the detailed and statistically robust observations needed to quantify this sensitivity in marine environments. Even in highly resolved models with bin microphysics, there is major disagreement regarding precipitation formation, sedimentation, and evaporation, and AMF observations can help provide constraints on these processes. Aerosol long-range transport and removal processes must now be represented accurately in global aerosol ESMs, but model experiments show major sensitivity of aerosol loadings to model resolution in long-range aerosol transport, and to precipitation formation processes.

Challenges for using observations to constrain models in marine regions include how to develop a forcing data set for shallow marine convection—in particular, how to constrain the large-scale advective tendencies and large-scale vertical motion. It is possible that UAS or tethered balloon systems could be used to provide thermodynamic profiles around ship and island sites. Further emphasis on improved data assimilation of AMF observations, together with Cloud-Associated Parameterizations Testbed (CAPT) experiments (climate models run in forecast mode), will be useful to identify the model processes contributing to model biases such as, e.g., tropical precipitation that is too symmetric about the equator (the double ITCZ problem). In addition to constraining model forcings, extensive ARM observations are obviously important for model-observational comparisons. One important consideration is to involve the modeling community as early as is feasible, perhaps through advertising a dedicated webinar as soon as a deployment is approved, and/or through developing preliminary VAPs that can be readily compared to model quantities.

Potential Collaborations

Synergies with other agencies that focus upon making both intensive and longer-term atmospheric measurements in the marine environment (e.g., NOAA, National Science Foundation [NSF], and NASA within the United States) could be leveraged to augment the observational capabilities of the mobile facilities. NASA satellite observations provide regional context for AMF deployments, but also benefit from validation opportunities that can be provided by the AMF observations. NOAA conducts many observations focused on air-sea interactions using research ships and buoys and is testing new autonomous marine research platforms that could be leveraged to design new marine measurement configurations. Because most of the potential marine sites would involve basing the AMF in a foreign country, it will be important to engage the scientific organizations within the host countries to ensure the most fruitful collaborations.

Southeastern United States

The southeast United States is a warm and humid region with abundant atmospheric convection nearly year-round, but most prominently in the summer season. Two regimes of convection are dominant, namely, a continental inland regime and a coastal sea breeze regime. For both regimes, the convection is strongly influenced by the surface and is paced by the diurnal cycle of solar heating. Atmospheric convection over the southeast United States contrasts with that over the ARM SGP atmospheric observatory in Oklahoma: the warm season in the southeast has significantly more moisture and more frequent surface-forced shallow and deep convection. Although much of the deep convection is unorganized, organized deep convection (e.g., mesoscale convective systems) occurs year-round under different forcings. Because of the strong coupling of convection with the surface, the southeast United States is also a good location to study atmospheric convection and the effects of variations in land-surface properties or emissions of aerosols and their precursors.

Atmospheric convection over the southeast United States contrasts with that over the ARM Southern Great Plains atmospheric observatory in Oklahoma. As such, there is a need to study this region with potential comparisons to ARM's largest fixed site.

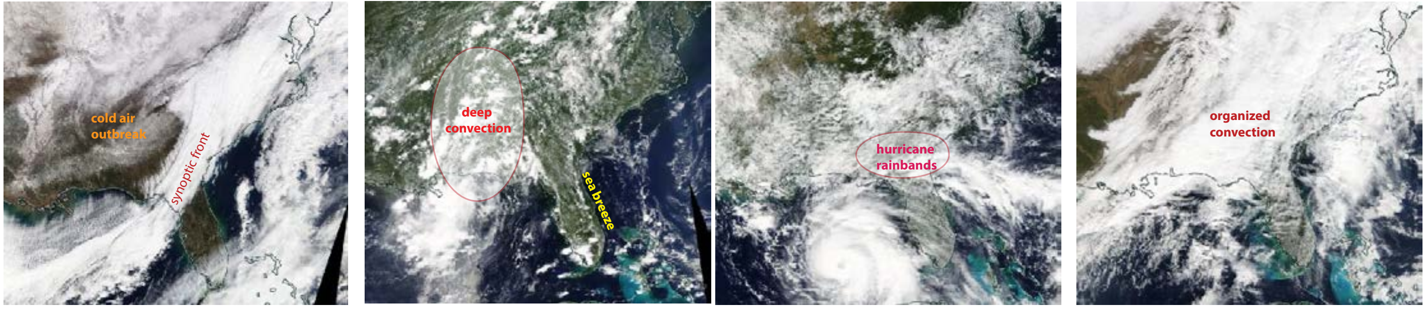
Science Questions

- For the continental inland regime, the typical cloud life cycle features morning shallow convection transitioning to afternoon deep convection that produces precipitation and cold pools with subsequent dissipation after sunset. How do the properties of shallow and deep convection, including vertical extent, amount, vertical velocities, and water content, vary with ambient conditions? How does deep convection form from shallow convection? How do the properties of downdrafts and cold pools relate to those of the deep convection?
- For the coastal sea breeze regime, convection follows a similar diurnal cycle but with the intensity of deep convection enhanced by the sea breeze circulation. How do the properties of deep convection vary with aspects of the sea breeze circulation such as the circulation strength, and moisture content of the imported oceanic air, and sensible heat flux over land?
- Land surface over the southeast United States differs markedly from the SGP with a greater amount of woodland/forests and reduced amount of grasslands. How are the properties of the shallow and deep convection affected by variations in the sensible and latent heat flux with different land-surface types (e.g., woodland/forests versus agricultural land) or seasonally as the vegetation grows and dies? Does deep convection preferentially develop over the agricultural regions with its enhanced sensible heat flux relative to the surrounding woodland/forests?
- Southeast United States has a large amount of biogenic emissions of organic compounds that form secondary organic aerosols as well as the emissions from scattered cities. How large are the radiative impacts of these natural occurring aerosols in comparison to those produced by the cities and what role might they have played in the relative coolness of the southeast United States in recent decades? How do the naturally produced aerosols interact with the urban emissions? How do the properties of shallow or deep convection and its precipitation vary with changes in the aerosol population over the seasonal cycle or between urban and rural regions?

Deployment Strategies

The measurement of atmospheric convection and its properties would be central to any deployment in the southeast United States. This requires vertical profiling measurements such as those given by sensitive cloud radars for cloud vertical extent and microphysics, and wind profilers and Doppler lidars for vertical velocities within and beneath convective clouds. For the important vertical profiles of temperature and especially water vapor, continuous high-quality remote-sensing measurements are needed to fill in the time intervals between radiosonde launches. Characterization of aerosols at the surface and aloft should be done. An important goal would be the measurement of the three-dimensional structure of deep convection through its life cycle, and such measurements may be possible from scanning cm-wavelength radars or Doppler lidars. AMF scanning radars could provide extra detail to the precipitation field beyond that available from the operational radar networks.

Spatially distributed measurements are required for several purposes including measuring the mesoscale circulation forming and produced by deep convection (e.g., initial circulations and cold pools) and measuring variations in the characteristics of land surface and aerosols. Surface state and flux measurements could be made over both the agricultural land and woodland/forests and it would be worthwhile to characterize variations in aerosols between urban and rural regions. Occasional in situ measurements by aircraft or tethered balloons in the boundary layer and in shallow convection could also provide valuable information about horizontal variations of clouds, aerosols, and atmospheric state, particularly in environments surrounding deep convection.



17 Jan 2018: synoptic front, cold air outbreak

2 July 2018: deep unorganized convection, sea breeze

10 Oct 2018: hurricane rainbands

28 Dec 2018: organized convection

Examples of cloud and precipitation processes in the southeast United States from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images. *Cloud map images courtesy of National Aeronautics and Space Administration.*

Site selection would need to be carefully tailored to the science goals. A campaign in the coastal environment would require careful consideration of the spatio-temporal evolution of the sea breeze and its associated convection to decide where to place an AMF site(s). A campaign interested in detecting the effect of the land-surface type on convection may want to identify locales where the patch sizes of agricultural or forests are large enough to significantly impact atmospheric convection. Unless it were part of a project's science goals, locales within significant orography (e.g., the Appalachian Mountains) should be avoided. Satellite studies may assist in identifying preferred locations for observing convection in both the continental inland regime and coastal sea breeze regime. If the science goal is to determine the impact of aerosols on clouds and convection, a site should be selected downwind of a moderate size city (i.e., not as large as Atlanta or Houston) in order to have a well-identified aerosol source that is distinct from the surrounding region. A deployment in the coastal sea breeze regime must have flexibility for rapid evacuation in the case of a hurricane.

The frequent occurrence of shallow-to-deep convection transitions during the warm season means developing good statistics may be achievable with observations over a single extended warm season. This is particularly true for the coastal sea breeze regime, where the locations of deep convection are more fixed. For the continental inland regime, while shallow convection would be amply observed from any site, a longer period of observations (say two warm seasons) would help in collecting a set of cases with deep convection, due to the more scattered occurrence of deep convection in this regime. A longer period of observations would help to tease out more secondary effects such as the influence of aerosols on convective cloud properties. A multi-year campaign would lower the risk of observing inter-annual variability from El Niño teleconnections, which are strong in this region in the cold season but would also be expected to have impacts on the condition of summertime vegetation.

Modeling Impacts

Observations collected in the southeast United States could be very helpful in addressing problems ESMs have modeling the evolution of convection over land, including the competition between shallow and deep convection. ESMs typically produce precipitation near noon instead of nearer sunset as observed. This reflects that ESMs activate their deep convection too easily and do not simulate a long enough period of shallow convection. Observations of the life cycle of convective cloud populations over land could identify the necessary roles for mesoscale circulations in forming deep convection and the resulting cold pools in forming new convection or reducing shallow convection and provide insights necessary for their parameterization. The insights for modeling gathered from the continental inland regime are expected to have wide applicability to the simulation of convective processes over warm-season land areas globally for the regimes where convection processes are only parameterized. However, as the resolution of ESMs increases, the sea breeze circulations will begin to be resolved and observations of convection in this regime may also provide important insights relevant to the modeling of coastal sea breeze regimes globally. Observations collected in the southeast United States would also aid in the improved modeling of land-atmosphere interactions, biogenic aerosols, and aerosol-convective cloud interactions. In particular, the treatment of secondary organic aerosols and aerosol life cycle in general is highly suspect in ESMs. With its large amounts of biogenic emissions, the southeast United States would be a great area for testing and developing new parameterizations of secondary organic aerosols.

The Biogenic Aerosols – Effects on Clouds and Climate (BAECC) field campaign placed the AMF2 in a Scots pine forest in southern Finland from February through September 2014 to obtain surface-based measurements of biogenic aerosols and gases.

Collecting observations in the southeastern United States would also have a large benefit for large-eddy simulation and regional modeling. The observations can be used to test whether the models correctly simulated the mix of deep convection, which is explicitly simulated, and shallow convection, which may or may not be explicitly simulated depending on the resolution of the model. Scanning radars and lidars could make strides in constraining mesoscale precipitation structure, microphysics, and kinematics of shallow and deep convection, allowing one to address whether large-eddy simulation and regional models correctly simulate the life cycle of deep convection. The observations may help one to understand whether a previously identified problem of cloud-resolving models simulating too strong vertical velocities in deep convection applies to convection in these regimes and what factors contribute to it. For the continental inland regime, it will be easy to perform model simulations either with homogeneous forcing from a variational analysis or boundary conditions from the operational models. If a mesoscale network of profiling sites were set up similar to that over the SGP, these observations could be assimilated in a regional modeling framework. Cloud-resolving modeling of convection in the coastal sea breeze regime would be somewhat more challenging as one would need a very large domain to resolve the sea breeze circulation and its dependence on land-ocean thermal contrast and modification by the background flow. Such large-domain simulations would be computationally expensive and might prohibit one from having enough resolution to explicitly simulate any convection except that of the largest deep convective updrafts.

Potential Collaborations

Synergies with the DOE Terrestrial Ecosystem Science (TES) program with measurements of biogenic aerosol emissions and land-surface characteristics (e.g., AmeriFlux) could be explored for collaboration, with the expectation there would be strong interest within DOE. Collaborations with DOE's Earth and Environmental System Modeling program could be explored for the modeling of atmospheric convection, aerosols, and land surface within the DOE E3SM.

Outside DOE, collaborations could be explored to augment the observations collected with the measurement capabilities of other organizations. A C-band research radar and lightning mapping array are maintained by the University of Alabama at Huntsville and NASA's Marshall Space Flight Center in Huntsville, Alabama. The NWS polarimetric operational weather radars can provide important auxiliary radar measurements to complement those from the AMF. NOAA has conducted field operations focused on tornado genesis through the VORTEX-SE campaign. The NOAA Office of Marine and Aviation Operations maintains aircraft for environmental observations such as hurricanes among other phenomena from a base in Florida. Collaborative observations of the land-surface ecosystem are also made as part of the NSF-organized efforts called the Long-Term Ecological Research (LTER) and National Ecological Observatory Networks (NEON).

Mountainous and Complex Terrain Regions

Through topographic forcing on atmospheric circulation and cloud formation, regions of mountains and complex terrain contribute disproportionately to precipitation over land worldwide. Mountain precipitation can accumulate as snowpack that, in turn, acts as a water reservoir in the cold season, releasing snowmelt water in spring and summer for water supply year-round. During the warm season, convective clouds develop frequently in the mountains, with diurnal timing strongly tied to the solar heating at the surface. Convective clouds initiated in the mountains can propagate and develop into mesoscale convective systems, which account for a large fraction of extreme precipitation and severe weather events in regions such as the U.S. Great Plains downwind of the Rocky Mountains and Argentina downwind of the Andes Mountains. During the cold season, orographic forcing enhances precipitation in mountains along the extratropical storm tracks. By influencing the interactions between atmospheric circulation, radiation, and land-surface conditions, complex terrain can induce large differences in the seasonal and diurnal cycle of precipitation and the spatial distribution of surface winds within relatively small areas. This challenges numerical modeling, with important implications to high-resolution modeling of the energy and water balance in mountains. Diagnosing model biases has been difficult due to the sparse networks of observations available to constrain models.

Despite the relatively pristine environment in mountains, orographic cloud properties are susceptible to aerosols from nearby and remote urban areas, deserts, and oceans through long-range transport. Acting as cloud condensation nuclei and ice nuclei, aerosols can exert large influences on orographic mixed-phase clouds to affect both the phase and amount of orographic precipitation. The hydrologic cycle in mountains is sensitive to elevated warming and snow-albedo feedback under radiative forcing. Understanding the interactions between atmospheric (clouds, precipitation, and radiation) and land-surface processes (snowpack, soil moisture, and runoff) in mountain regions is critical to understanding variability and changes in water availability on weather-to-climate timescales.

Science Questions

- Turbulence has a unique signature in complex terrain. How does turbulence vary with airflow, radiation, and surface fluxes in mountains and valleys, and what are the implications for clouds and winds? How do cloud microphysics influence precipitation in different cloud regimes such as convective clouds, pre- and post-frontal clouds, mountain fog, and stable orographic clouds frequently observed in mountains? How may interactions between cloud microphysics and atmospheric dynamics such as mountain gravity waves influence predictions of precipitation? What controls the initiation of convection over complex terrain and the subsequent influence on downwind convection? How does the complex terrain of the Maritime Continent influence the Madden-Julian Oscillation, with global impacts on extreme events?

The AMF2 obtained data about liquid and mixed-phase clouds during the Storm Peak Laboratory Cloud Property Validation Experiment (STORMVEX) field campaign around Steamboat Springs, Colorado. AMF2 instruments were used in conjunction with Storm Peak Laboratory, a cloud and aerosol research facility operated by the Desert Research Institute.

- Aerosols can have a large influence on orographic clouds and precipitation. What controls the long-range transport of aerosols to mountainous regions around the world? What is the trace gas chemistry that influences aerosol formation in mountainous areas? What are the impacts of absorbing aerosols on clouds, precipitation, and snowpack? How do aerosols and convection interact in complex terrain and affect precipitation? What are the impacts of elevated heating due to aerosols on South Asian and North American monsoon circulation and precipitation?
- Land-atmosphere interactions play important roles in the energy and water cycles in mountainous regions. How do interactions among airflow, radiation, and surface fluxes influence the seasonal and diurnal cycle of precipitation in regions of complex terrain? What are the impacts of mountain glaciers and snowpack on surface fluxes and subsequent influence on turbulence and cloud formation? How does topographic influence on radiation affect the surface fluxes and cloud and precipitation? What controls the surface energy and water balance in complex terrain? How are vegetation dynamics influenced by the atmospheric environments in mountains and how does vegetation provide feedbacks on the atmosphere through surface fluxes, aerosols, and extreme events such as wildfires and insect infestation in mountains?

Deployment Strategies

Strong interactions between atmospheric and surface processes in mountains dictate the need for distributed measurements of both atmospheric and surface parameters and general conditions. In addition, a combination of AMF and AAF is important to characterize the spatial distribution of meteorological conditions, radiation, cloud, and precipitation. Deployment of scanning radars in mountains is challenging, but distributed measurements could be made around the AMF to better characterize the meteorological environment along radar and topographic transects. Precipitation and cloud radars as well as Global Positioning System (GPS) water vapor profiles all provide important information for modeling cloud and precipitation. Unmanned aerial systems (UAS) could be used for in-cloud versus out-of-cloud sampling to evaluate the effects of topography on cloud microphysical and macrophysical properties. Measurements of the dynamic and thermodynamic profiles through the boundary layer are useful for characterizing boundary-layer turbulence. Measurements of cloud phase and cloud condensation nuclei/ice nuclei (CCN/IN) concentrations and size distributions can be used to understand aerosol-cloud interactions. Selecting locations that are frequently in clouds will enable more frequent in situ sampling of cloud-aerosol interactions.

Mountain environments are often highly variable, so repeated sampling for more than a year is important to account for inter-annual variability of meteorological conditions and aerosol distribution and composition (e.g., variability of aerosols due to biomass burning). Long-term deployment is also important to quantify atmospheric and surface processes through the snow accumulation and melt seasons when changing surface conditions may have large impacts on atmospheric processes. Deployment should also be planned to sample both cold-season and warm-season orographic processes, as clouds, convection, radiation, and land-atmosphere interactions are expected to differ significantly between the seasons. Intensive observational periods within a longer period for aircraft aerosol and cloud measurements can provide more detailed information for process study and model evaluation. Ultimately the deployment strategies should be designed based on the science questions and informed by the climatology of measurement sites. Combining in situ measurements with satellite data will be useful to provide the broader dynamic and thermodynamic context for modeling and interpretation of the data. Arguably, forcing data in mountains may have larger uncertainties due to surface heterogeneity, so the development of integrated products is particularly important to support modeling efforts.

Deploying the AMF in mountains can be challenging because of the frequent difficulty in obtaining permission to deploy in remote regions and shipping/transporting instruments to high-altitude locations. Site logistics such as power and communication as well as hazardous snow storm conditions and forest fires can also present challenges. Selecting a representative site can also be difficult because of the inherent heterogeneity associated with complex terrain. However, deployments in mountain environments present important opportunities to provide unique data sets in data-sparse regions to greatly improve understanding of the Earth's water cycle, for which mountains are key regions. High-altitude sites provide an environment to study clouds without aircraft, making it possible to obtain in situ measurements on a more routine basis. Improving modeling over complex terrain for both atmospheric and terrestrial processes has high societal impact as mountains play a key role in freshwater supply around the world.

Modeling Impacts

Mountain processes, driven by large topographic gradients, are often not well represented in ESMs. Orographic precipitation, in particular, is poorly resolved in ESMs with typical atmospheric model grid spacings of 50 to 200 km. This has important implications for a host of land-surface processes such as snowpack, soil moisture, runoff, and groundwater that are intimately connected to precipitation. However, even in higher-resolution models, biases in the magnitude and spatial distribution of precipitation can still be large because of uncertainties in model representation of turbulence, cloud microphysics, convection, radiation, aerosols, and their interactions. Ice and snow processes are important in orographic clouds, but their representations vary significantly among different cloud microphysics parameterizations. Mixed-phase clouds are particularly sensitive to aerosol-cloud interactions, which are not well constrained in models. Light-absorbing aerosols and their impacts on snow are poorly represented in ESMs. Neglecting the effects of complex terrain and subgrid variability of land cover such as snow on radiation can have important effects on simulation of surface fluxes and land-atmosphere interactions. Errors in modeling physical processes can induce large errors in atmospheric dynamics through the impacts of diabatic heating on atmospheric phenomena such as mountain gravity waves. Similarly, errors in modeling land-surface processes may amplify errors in clouds and precipitation through land-atmosphere interactions.

Observations are needed in mountainous areas where in situ measurements are invariably very limited. Unique data sets collected in under-sampled mountainous areas can provide

In a nine-month campaign, AMF1 was deployed and operated in the Black Forest area during the Convective and Orographically-induced Precipitation Study (COPS) in summer 2007 for its third deployment. Deploying the AMF in mountainous regions can be challenging because of the difficulty in obtaining permission to operate in remote regions and shipping/transporting instruments to high-altitude locations.

important insights critical to understanding processes unique to mountainous areas. Observations are also needed to improve and evaluate model parameterizations. Collocated measurements of atmosphere and surface processes are particularly useful for model development and evaluation. A hierarchy of models can be used to facilitate model-data integration for improving understanding and modeling. Examples include the CAPT framework using initialized hindcasts for model evaluation, regionally refined meshes in variable resolution models to test and evaluate parameterizations for high-resolution modeling, convection-resolving modeling to more explicitly simulate orographic processes, and offline land-surface models and coupled atmosphere-land models to isolate model errors associated with model representations of land processes and land-atmosphere interactions. LES modeling can be particularly useful for studying turbulence over complex terrain, but this is quite challenging because most LES models use periodic boundary conditions and vertical coordinate systems, which are not conducive to complex topography.

Potential Collaborations

Mountains provide an organizing theme for studying atmospheric and terrestrial processes, so the deployment of the AMF in mountains may foster collaborations between ARM/ASR and TES and Subsurface Biogeochemical Research (SBR) programs to improve understanding and modeling of earth system processes. Mountains provide many resources including water for hydropower generation and winds for renewable energy, so DOE BER could also develop collaborations with DOE's Office of Energy Efficiency & Renewable Energy (EERE; e.g., wind energy program), the U.S. Geological Survey (USGS; e.g., on snowpack and streamflow measurements and hydrologic forecasting), local and state government with water management and water use responsibilities, and the skiing industries and utility companies interested in snowpack and streamflow forecast. Many existing networks of measurements can be used to provide more complete data sets. Examples include measurements from AmeriFlux (surface fluxes), NEON and LTER (ecosystems and terrestrial processes), NOAA HMT-WEST (hydrometeorological measurements), Inter-agency Monitoring of Protected Visual Environments (IMPROVE; air quality, aerosols), Mt. Bachelor observatory (long-range transport, aqueous chemistry, and biomass burning aerosols), proposed NSF White Face Mountain (aqueous chemistry), and the Third Pole project in the Tibetan Plateau.

A number of opportunities exist for synergy between research and operational modeling centers to advance the use of observations to improve modeling over regions of complex topography. One example is the NOAA Hydrometeorological Testbed (HMT) in the western United States (HMT-WEST) that is aimed at accelerating the infusion of new observing technologies, models, and scientific results from the research community into daily forecasting operations. Collaborations could also be initiated with the Global Energy and Water Exchanges (GEWEX) North America hydrometeorological modeling activities such as convection-permitting modeling of the water cycle as part of the World Climate Research Programme (WCRP) food basket for the world grand challenge.

Organized convection produces over half of the rainfall in the tropics and mid-latitudes. The Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign took AMF1 in October 2018 to the Sierras de Córdoba mountain range of north-central Argentina for a seven-month deployment. This region experiences some of the world's largest and most destructive thunderstorms.

Organized Deep Convection

Organized deep convection occurs in both the tropics and mid-latitudes and is ubiquitous over both ocean and land. It includes mesoscale convective systems (MCSs), tropical and extratropical cyclones, or aggregates of these such as convectively coupled equatorial waves, MJO events, and the monsoon. However, tropical and extratropical cyclones were not discussed in detail at the workshop, and thus are excluded in this section.

Organized convection produces over half of the rainfall in the tropics and mid-latitudes. As such, biases in precipitation amount, type, rain rate probability density function (PDF), spatial distribution, and diurnal timing in ESMs are often linked to poor representation of processes associated with organized convection (e.g., the model deficit in warm-season precipitation over SGP). Organized convection has characteristics distinctly different from those of locally forced, isolated convection. For instance, warm-season MCSs over SGP are initiated over the Rockies in the late afternoon and propagate downstream ahead of an upper-tropospheric trough to the SGP to produce maximum precipitation at night over SGP instead of the early afternoon, which is more typical of isolated convection. The representation of organized deep convection in global climate models is almost nonexistent.

Organized deep convection can occur under different meteorological conditions, and in different regions and seasons. It can occur during active or break periods of the monsoon, during the convectively active phase of the MJO, and over land or ocean. Organized convection also interacts strongly with the large-scale circulation. For example, the monsoon circulation helps organize convection, and the organized convection in turn helps to drive the monsoon circulation. Bias in convection over the ocean is known to be responsible for South Asian monsoon circulation biases. While isolated convection typically lasts for under an hour, organized convection can last for hours or even days. Its propagation and longevity can be affected by many factors, including synoptic flow, low-level jets, topography, free-tropospheric humidity, radiative feedbacks, and land-atmosphere interactions. A number of science questions critical to understanding organized deep convection and its representation in ESMs remain to be addressed.

Science Questions

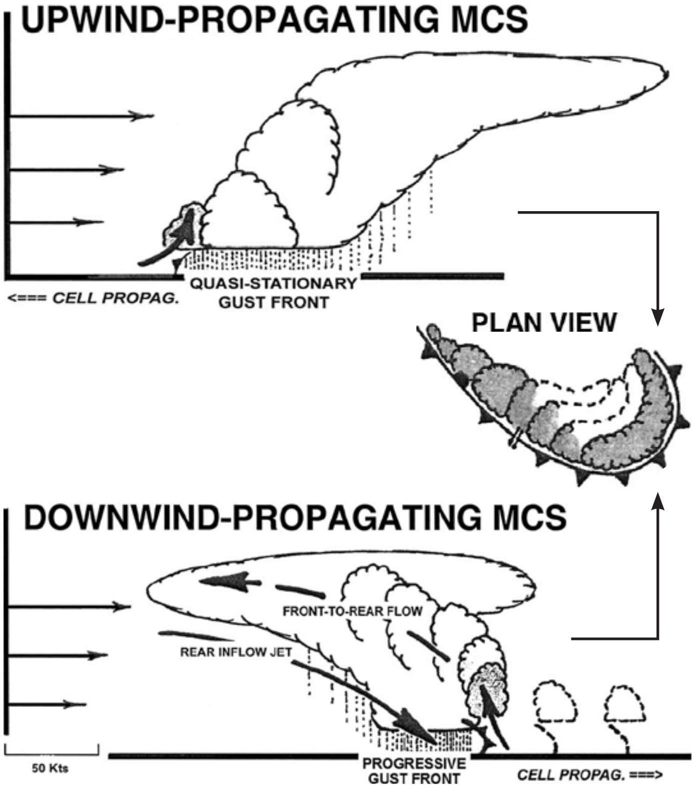
- What are the most important large-scale environmental factors that affect deep convective initiation and organization? How do these vary by season, location (e.g., SGP versus Amazon), and meteorological regime? How well can scientists predict organized convection based on the large-scale environment in different regions and regimes?
- What local factors affect the propagation and longevity of organized convection, and how does this affect the diurnal cycle of rainfall in a particular region?
- What are the interactions between dynamical and microphysical processes in organized convection? What are the causes of excessive riming and overly intense updrafts in high-resolution process models that lead to inaccurate organized convection characteristics?
- What are the interactions between organized convection and the large-scale circulation (e.g., monsoon, Hadley Cells, etc.)?
- How does organized convection interact with aerosols and trace gases and how does it impact vertical transport and wet deposition?
- How do climate change and other physical factors such as urbanization impact convective organization and its associated precipitation, including extreme events?

All these questions are essential to understanding and representing organized convection in ESMs for application to energy.

Deployment Strategies

Organized deep convection has large spatial scales and long lifetimes. Therefore, its holistic measurement requires extended facilities and multiple sites along its propagation path. Vertical profiling by active sensors would be highly useful for cloud macro- and microphysical properties. Vertical profiles of background dynamic and thermodynamic meteorological conditions are also essential. Both operational sounding sites and mobile profiling systems such as the Collaborative Lower Atmospheric Mobile Profiling System (CLAMPS) should be used to measure local and pre-convective environments. These measurements would provide data needed to determine the organization and propagation of organized deep convection. Adaptive scanning of a cluster of cells at high frequency (~2 min), with another radar for surveillance, could be used to provide collocated microphysical and dynamical measurements of initiation

More than 100 instruments, including instrumentation from AMF1, were used to collect atmospheric data at the Manacapuru site downwind of Manaus during the international collaboration known as Green Ocean Amazon, or GoAmazon, field campaign.



Shown here are organized convection formations: (right) Plan view of an elongating cold pool with cross-sections perpendicular to the gust front along (top) a quasi-stationary segment, and (bottom) a progressive segment, showing direction of cell propagation. Image taken from Corfidi, S.F., 2003. "Cold Pools and MCS Propagation: Forecasting the Motion of Downwind-Developing MCSs." *Weather Forecasting*, **18**, 997–1017, https://doi.org/10.1175/1520-0434(2003)018<0997:CPAMPF>2.0.CO;2. © Copyright December 1, 2003, AMS.

and evolution of convective cells. Lagrangian cell tracking using either a single radar or multiple radars (e.g., C and XSAPR) would provide multiple horizontal and vertical cross-sections of storm cores as they propagate across the radar domain.

A convection-penetrating aircraft collaboration would provide important in situ measurements of vertical velocity and microphysics in intensive operational period mode to test remote-sensing techniques and cloud-resolving model dynamical and microphysical links, which are useful for understanding interactions between dynamical and microphysical processes in organized convection. Unmanned aerial systems could be used to supplement conventional instruments for boundary-layer observations of thermodynamics, winds, and aerosols ahead of storm. These observations would provide data to determine factors affecting deep convective initiation. Extra sampling would be helpful during Global Precipitation Measurement (GPM) satellite overpasses for validation and comparison. Large-scale forcing products should be updated with new instruments and observations. AMF observations should be coordinated with other relevant sites and/or networks, including flux towers (for latent and sensible heat fluxes and soil moisture), radar networks, mesonets, and lightning sensors.

Organized convection is typically large in size and can propagate over long distances. It is also relatively rare compared to isolated convection. This poses a special challenge for observing its initiation and evolution from a single site. Multiple sites would be desirable. However, ARM's scanning radars and integration of ARM measurements with other measurement networks and/or deployments by other agencies makes observing this regime tractable. If a remote region (e.g., the tropical western Pacific) is chosen, logistical difficulties in getting instruments there could also be a practical challenge. ARM should use knowledge from past deployments (both standalone and with multiple agencies) to overcome known difficulties and leverage supplemental sites when possible. Instrument simulators could be exploited on select model cases beforehand to determine the representativeness of the field design and its ability to answer science questions, and pre-campaign deployments could be considered to help refine design.

Deployment lengths of multiple seasons should be considered for AMF deployments because of the intermittency or rarity of organized convection and inter-annual variability. Months-long campaigns have the merit of linking to larger, multi-partner projects or fixed DOE sites. Potential sites include the central United States, southern Florida, tropical Pacific, Maritime Continent, Amazon, India, etc. The length of deployment will be location-dependent.

Potential Deployment Locations

- **Central United States** – Mesoscale convective systems are generally initiated in the Rockies and propagate downstream to the Great Plains and further eastward. Several GCM biases including the diurnal cycle of precipitation and dry and warm biases in the central United States are associated with the models' failure to predict MCSs there. Multiple sites between the Rockies and SGP would be needed to capture the propagation of those mesoscale convective systems. At least one and a half years would be needed, starting in March, to sample summertime organized convection twice.

Organized convection is typically large in size and can propagate over long distances. For the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign, the ARM Aerial Facility deployed with the AMF1 to the Sierras de Córdoba mountain range of north-central Argentina in the fall of 2018.

- **Southeastern United States** – Many of the most intense and large mesoscale convective systems in this region occur in the winter season. It would be particularly useful to deploy AMFs in both the southeast and central United States to sample a full transect across the geographical region in coordination. A deployment of one year would be needed to capture both strong MCSs in winter and weaker MCSs in summer.
- **Tropical Pacific** – Tropical convection continues to be a major prediction challenge for climate models. Convection often occurs in organized form in this region. Although the Darwin ARM site has been used in the past, a revisit to the tropical western Pacific focusing on organized convection is desirable. Nauru and Manus Islands are good choices. Neither location had a scanning precipitation radar in the past. A multi-year deployment would be needed to capture inter-annual variation such as ENSO.
- **Maritime Continent** – Here Maritime Continent refers to the land masses of southeastern Asia. This is a region with strong interactions between organized convection and the MJO. Past observations show that MJO convection weakens over the Maritime Continent. Some MJOs survive the Maritime Continent and continue to propagate eastward, and some do not. One-year deployment would be needed to capture multiple MJOs.
- **Amazon** – The Amazon is also another continental region where global models underestimate precipitation. Although the Observations and Modeling of the Green Ocean Amazon 2014/15 (GoAmazon) campaign had an AMF1 deployment there for two years, there was no scanning precipitation radar. The mesoscale convective systems occur predominantly in austral spring and summer. A six-month deployment in the wet season focusing on organized convection would be needed.

Modeling Impacts

A better characterization of the pre-storm environment is critical for prediction of initiation and propagation of convection in models. Identification of the most important factors in organizing convection after it has initiated would help direct model parameterizations, including convective parameterizations in coarse-resolution models and microphysical parameterizations in high-resolution models. In the central United States, organized convection often initiates over the Rockies in the afternoon and propagates downstream. At the SGP, precipitation from organized convection often occurs in late night to early morning. However, models typically fail to capture the propagation, diurnal variation, and sometimes even initiation of precipitation from organized convection. Large-scale forcing data sets considering temporal and spatial scales of forcing would be essential for driving single-column models for parameterization evaluation and for cloud-resolving model/LES simulations. Furthermore, nested Weather Research and Forecasting Model (WRF) can be run at LES scales using the large-scale forcing data to drive or evaluate it. Regionally refined mesh (RRM) with CAPT hindcasting could also use the ARM data to evaluate model parameterizations. Data assimilation of scanning radar data could be used for prediction of organized convection by forecasting models.

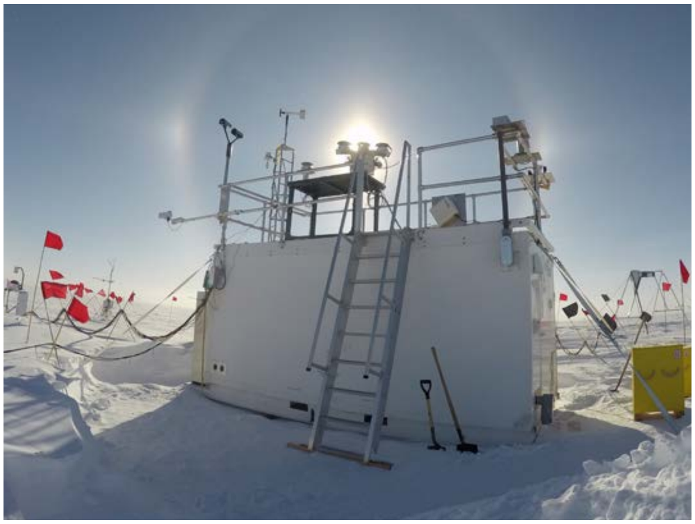
Potential Collaborations

Mobile deployments could collaborate with other DOE programs, institutions, and/or federal agencies. Specifically, DOE's Earth System Model Development program would be a potential user of the AMF observations to improve convection and cloud parameterizations in its E3SM model, particularly considering earlier work has been carried out under the Climate Model Development and Validation (CMDV) program. An example would be the implementation of an organized convection parameterization in E3SM. Participation in aircraft observations of convection from guest aircraft such as the NSF/Wyoming King Air, NASA DC-8, NOAA P3, NSF A1, French Falcon, and German HALO (High Altitude and Long Range Research Aircraft) could be explored. NOAA and other agency research vessels (R/Vs) could be involved for observations of oceanic convection. The Oklahoma Mesonet would be valuable for documenting mesoscale circulation in the boundary layer associated with organized convection. One of the important factors in the success of past field experiments was the participation of other national or international agencies. This mode of operation should be retained to maximize the outcome of any AMF deployment. Auxiliary data from other sources, such as the NASA GPM precipitation data, geostationary satellite data, NWS WSR-88D radars, operational NWP products, and European Centre for Medium-Range Weather Forecasts (ECMWF) forcing data, could be used.

High-Latitude Regions

The high-latitude cryosphere is particularly sensitive to climate change. Sea ice is rapidly decreasing in the Arctic, as are the ice sheets of Greenland and western Antarctica. This is consistent with high-latitude surface temperatures that are rising at a faster rate than in other parts of the globe. The melting of ice sheets contributes to sea-level rise globally. Should the stability of the west Antarctic ice sheet change, it could become a much more significant contributor to sea-ice melt. The changing high-latitude environment and notably the speed of the changes, affects all marine life, with the loss of arctic ice in the Northern Hemisphere also affecting the human economy through fishing and shipping. The physical changes are part of feedbacks with the atmosphere and ocean that also interplay with an evolving larger-scale circulation. Yet, despite the significance of changes within the high-latitude regions for current and future climate, much is still not well understood or even well characterized. This reflects in part the unique challenges for satellite remote sensors, and sparse observational networks, so that available data sets from reanalyses and satellites are not necessarily reliable. Antarctica is particularly poorly observed because of its size and remoteness. The physical processes affecting the Southern Hemisphere high latitudes are not necessarily similar to those of the Northern Hemisphere, in part because there is more open ocean and more precipitation.

ARM has made important contributions to high-latitude research through dedicated field studies that include participation in SHEBA within the Beaufort Sea, the aircraft Mixed-Phase Arctic Clouds Experiment (MPACE) and Indirect and Semi-Direct Aerosol Campaign (ISDAC) campaigns off of the northern slope of Alaska, the upcoming COMBLE campaign in the northern Atlantic, and the upcoming Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) campaign on a more northerly ice breaker. The high-latitude boreal forest, an important component of the global aerosol cycle, and contributor of aerosols to the Arctic, was sampled in Finland as part of the Biogenic Aerosols–Effects on Clouds and Climate (BAECC) campaign. ARM has hosted two long-term sites in Alaska, one at Barrow (known officially as Utqiaġvik) and another at Oliktok Point. The southern high-latitude open-ocean regions have been sampled by



In November 2015, a set of ARM instruments was deployed to the West Antarctic Ice Sheet to make the first well-calibrated climatological suite of measurements seen in this extremely remote, but globally critical, region in more than 40 years.

MARCUS and Macquarie Island Cloud and Radiation Experiment (MICRE), and the ARM West Antarctic Radiation Experiment (AWARE) was based on the West Antarctic Ice Sheet. No multi-year ARM deployment has been based south of 60S latitude.

However, despite these previous high-latitude campaigns, many science questions remain, with those highlighted by the workshop detailed below.

Science Questions

- High-latitude clouds are often mixed phase, with both liquid and ice particles present at temperatures below 273 Kelvin. The proper representation and characterization of mixed-phase clouds in ESMs remains a high priority, as these clouds are complex and are radiatively significant for the surface energy budget. Their precipitation can be composed of both liquid and ice, but a tantalizing feature remains, e.g., the longevity of mixed-phase clouds. While the behavior of single-layer mixed-phase clouds is well understood through large-eddy-scale simulations, they remain poorly represented in climate models. The formation, lifetime, and dissipation of mixed-phase clouds in more complex situations, e.g., within multi-layered systems, and as part of a feedback to changing underlying surfaces and horizontal advection, is less well known. How do mixed-phase clouds respond to changes in CCN and INPs, including in the aerosol vertical structure? What processes affect the development of precipitation (liquid or ice) and mesoscale organization? How well can the small-scale processes affecting mixed-phase clouds be represented in ESMs?
- How much do arctic aerosol, cloud, precipitation, and radiation characteristics vary from year to year? It is well recognized that arctic inter-annual variability in cloud properties can be large, masking longer-term changes. A unique contribution for ARM deployments is their ability to characterize the seasonal cycle in aerosol and cloud properties. This strength can be extended to document inter-annual variability. In this manner the effect of internal cloud-surface feedbacks can be discriminated from those encouraged by inter-annual changes in circulation.
- The Greenland ice sheet, one of two major ice sheets, is increasingly important for sea-level rise. Its surface energy budget is sensitive to the presence of clouds and is also importantly modulated by storm tracks that bring in moisture and differing aerosol types (e.g., eastern seaboard pollution, wildfire smoke, biological aerosols). What are the connections between the atmosphere and surface melt rates?
- Many model parameterizations of secondary organic aerosols from boreal forest are now based on data from northern Finland. How representative are those conditions of other boreal forests? How do the emissions and uptake of carbon evolve across the seasonal cycle as a function of boreal forest location?
- To date, the high-latitude boreal forest aerosol and gas environment has only been sampled in detail in Hyytiälä, Finland, as part of the BAECC campaign. Mixed-phase clouds in both the northern and southern high latitudes are important for the radiative energy balance, with their relationship to local aerosols and dynamics not yet fully resolved.
- Much of the focus on high-latitude change is on the Northern Hemisphere, and much less is known about processes in the interior of Antarctica. How do changes in surface melt rates relate to atmospheric changes in clouds, aerosol, radiation, and precipitation? How well do model improvements relevant to the Arctic also apply to Antarctica?

ARM Deployments in the High Latitudes

In addition to its long-term fixed atmospheric observatory on the Alaskan North Slope, ARM has made important contributions to high-latitude research through recent, dedicated field studies. This includes the extended deployment of the AMF3 at Oliktok Point, as well as these recent and upcoming field campaigns below. However, no multi-year ARM deployment has been based south of 60S latitude.

Lidar Support for ICECAPS at Summit, Greenland

15 April 2010 – 31 August 2018

Beginning in May 2010, the Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation over Summit (ICECAPS) project deployed a suite of remote sensors at Summit, Greenland, including a micropulse lidar and ceilometer from ARM.

ARM Airborne Carbon Measurements (ARM-ACME V)

1 June 2015 – 15 September 2015

The ARM Aerial Facility deployed the Gulfstream-159 research aircraft to fly over the North Slope of Alaska, with occasional vertical profiling to measure trace-gas concentrations between Prudhoe Bay, Oliktok Point, Barrow, Atqasuk, Ivotuk, and Toolik Lake.

Evaluation of Routine Atmospheric Sounding Measurements Using Unmanned Systems (ERASMUS)

2 August 2015 – 31 October 2016

Using instrumented unmanned aerial systems during two-week campaign periods in 2015 and 2016 at Oliktok Point, Alaska, this campaign supported the collection of a detailed set of atmospheric measurements designed to complement those concurrently obtained by AMF3.

ARM West Antarctic Radiation Experiment (AWARE)

23 November 2015 – 5 January 2017

Beginning in late November 2015, a set of ARM equipment, including basic radiometric, surface energy balance, and upper air instrumentation, was deployed to the West Antarctic Ice Sheet (WAIS) to make the first well-calibrated climatological suite of measurements seen in this extremely remote but globally critical region in more than 40 years. In addition, AMF2 was deployed at McMurdo Station from January 2016 to January 2017 for a campaign data set that covered 14 months in total from the two locations.

Macquarie Island Cloud and Radiation Experiment (MICRE)

1 March 2016 – 31 March 2018

Measurements of surface radiative fluxes as well as cloud and aerosol properties over the Southern Ocean are in high demand. As such, ARM deployed a variety of ground instrumentation to Macquarie Island, ideally situated at 54.61 degrees south latitude and 158.87 degrees east longitude, to meet this need for a two-year deployment.

Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS)

1 October 2017 – 1 April 2018

For six-months, AMF2 was installed on the Australian Antarctic supply vessel *Aurora Australis* as it routinely traveled between Hobart, Australia, and the Antarctic, visiting the Australian Antarctic stations Mawson, Davis, and Casey.

Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC)

1 September 2019 – 31 October 2020

In support of the major international effort known as MOSAIC, ARM will operate AMF2 and a mobile aerosol observing system on the icebreaker-based observatory as it drifts through the central Arctic for up to 14-months, starting in September 2019.

Cold-air Outbreaks in the Marine Boundary Layer Experiment (COMBLE)

1 January 2020 – 31 May 2020

COMBLE will involve the deployment of the AMF1 and a satellite site to the far North Atlantic to study boundary-layer convection (BLC) and air-mass transformations in cold-air outbreaks (CAO) over open water in the Arctic..

Deployed at McMurdo Station, AMF2 gathered sophisticated data with cloud radars and high spectral resolution lidar, and a complete aerosol suite. The green beam shooting into the sky is the high spectral resolution lidar instrument. *Image by Joshua Swanson, United States Antarctic Program*

Sea ice is rapidly decreasing in the Arctic, as are the ice sheets of Greenland (shown) and western Antarctica. A small collection of ARM instruments is deployed to Summit, Greenland, in support of the Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation over Summit (ICECAPS) project, funded through the National Science Foundation's Arctic Observing Network.

Deployment Strategies

To address the science questions above, measurements would need to include thermodynamic profiling, aerosol (CCN and INP) measurements and their vertical structure, cloud and precipitation properties by phase, surface fluxes, and surface snow/ice properties. A sense of the spatial organization of the cloud and precipitation structure is necessary, particularly for cold-air outbreaks, warm moist intrusions that introduce air-mass boundaries, and synoptic circulations. This requires spatially distributed observations, not only of the atmosphere but also of the surface energy budget. The vertical structure information can be gathered through a combination of sondes, tethered balloons, UAS, and aircraft campaigns selecting for specific regimes.

High-latitude inter-annual variability is large, and distinguishing the processes contributing to long-term change from inter-annual variability requires longer-term measurements. Any given year or season is likely to be an anomaly from a multi-year mean. For this reason, longer-term deployments exceeding the typical AMF deployment length of one year are preferred. The routine measurements would also need to be routinely integrated with information on the larger-scale synoptic circulation.

Modeling Impacts

Earth system models have well-known problems with their representation of mixed-phase clouds, most notably in their under-prediction of supercooled liquid, which plays a critical role in determining the surface temperature. Dedicated site-focused modeling activities, similar to LASSO, can provide a process-modeling bridge between the local ARM measurements on mixed-phase clouds to the larger-scale ESMs. In turn, experimentation with relevant microphysical and mixing parameterizations can be done with site-specific single-column versions of the ESMs. CAPT frameworks also facilitate comparisons to the measurements. Both SCM and CAPT frameworks require adequate forcing data sets.

The modeling of surface-melt processes by ESMs is incompletely linked to the modeling of the overlying low-altitude clouds. The surface budget in ESMs, their synoptic, seasonal, and inter-annual variability need to be evaluated and connected to the other changes in the cryosphere. In boreal forests, new observations provide an independent assessment of new parameterizations of gas and aerosol emissions.

The evaluation of the seasonal cycle in ESMs using observations from new AMF sites in Antarctica helps balance model advancements based primarily on Northern Hemisphere measurements.

Potential Collaborations

The high latitudes naturally lend themselves to international collaborations, because of the proximity to other nations (in the Northern Hemisphere) and sense of common interests. This is likely to increase, as economic interests become more intertwined with increased scientific understanding. Other agencies also possess expertise that is essential to a holistic characterization of the high latitudes and lacking within DOE, such as in sea-ice and ocean processes. Another important collaboration is to incorporate ARM measurements into developing arctic reanalyses. Collaborations with NASA are useful in that ARM observations can improve satellite remote-sensing algorithms for arctic conditions. Collaborations with NSF and with research-sponsoring government organizations in Arctic-bordering nations, or with the nations currently vested in Antarctica, increase available expertise on local conditions, and on cryosphere processes.

Other Regimes/Regions

In addition to the major regimes and regions already presented, a number of others were suggested in the white paper submissions. Although these regions were mentioned less frequently, they serve as viable options for AMF deployments to address questions important for the improvement of ESMs. These regions were each discussed briefly in a combined session during the workshop.

Great Lakes

The Great Lakes region of the east-central interior of North America is an understudied region with a pronounced seasonal cycle that can be used as a laboratory to study a wide range of climatically important atmospheric processes in a location where deployment logistics are more straightforward than in remote regions.

Science Topics

- Cold-air outbreaks – The frequent advection of cold continental air masses over the Great Lakes results in low-level instability and the formation of large regions of low-level, often mixed-phase, cloudiness whose dynamics and microphysics are poorly understood. Related lake-effect snow events seriously impact transportation and safety but remain poorly forecast.
- Surface transitions from open water to ice covered – Changes in surface conditions (including leads, melt ponds, and open water) of ice-covered bodies strongly influence surface fluxes, resulting in changes to thermodynamic, aerosol, and cloud properties. The feedbacks among the surface and atmospheric conditions are not well quantified despite significant impacts.
- Aerosol spatial variability – Aerosol conditions in the Great Lakes region are impacted by a wide variety of local sources, including boreal forest biogenic emissions, industrial regions, lake surface emissions, and ship traffic. The local budgets and gradients in aerosol conditions are a complex interaction of these emission sources, and atmospheric aerosol formation and removal processes. Further, this variety of aerosol conditions offers an excellent location for the study of cloud-aerosol interactions, particularly downwind of the major industrial areas on the windward side of the lakes.

The Great Lakes region of the east-central interior of North America is an understudied region with a wide range of climatically important atmospheric processes that could be easily accessed for study.

Deployment Strategies

Clouds over the Great Lakes form closer to the coastline than many of the same cloud systems over the ocean, simplifying sampling strategies. However, coastal effects still need to be accounted for, so some combination of land-based and ship-based measurements is likely needed. This could be a coordinated effort with land-based observations and a ship-based AMF. Another possibility would be to locate some instruments on, or next to, near-shore lighthouses. Some important logistical difficulties that must be considered are that ship-based measurements will only be possible when the lakes are unfrozen, and that optimal land-based sites for the study of lake-effect snow might be buried in snow. The significant inter-annual variability in key drivers (e.g., lake temperatures, ice cover, synoptic forcing, precipitation) will make a single year not wholly representative for development of parameterizations, so a multi-year (or at least a multi-winter) deployment would be preferable.

Modeling Impacts

Large-scale models suffer significant radiation biases for cold-air-outbreak cloudiness over bodies of water. In addition, models struggle with the downstream impacts of the lakes, particularly the simulation of lake-effect snowfall. Increased computing power permits the use of LES to resolve small-scale features resulting from coastal interactions.

Potential Collaborations

The NSF has funded previous studies in this region, particularly focused on lake-effect snows and local hydrology. Ongoing research as part of the NSF-funded Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-Density Extensive Array of Detectors (CHEESEHEAD) study will provide useful surface flux data. NOAA, the Illinois Water Survey, and Canadian agencies would also be potential collaborators in this region. The NOAA Great Lakes Environmental Research Laboratory focuses on the coastal ecosystems in the region.

South and Southeast Asian Monsoon

The monsoon circulation of south and southeast Asia is an important seasonal source of precipitation for the Indian subcontinent and the mainland and maritime regions of southeast Asia. The processes that drive the origin, propagation, and strength of the summer monsoon rain are still poorly understood. The frequent, yet relatively weak, deep convection may be useful for detecting influences of aerosol perturbations in relatively clean locations (i.e., not India or China).

Science Topics

- Monsoonal cloud and precipitation variability – Variability of cloud, aerosol, radiative, and precipitation changes associated with the El Niño-Southern Oscillation remains a challenge for large-scale models.
- Aerosol-convection interactions – The influence of aerosol on the strength of convective updrafts remains a topic of debate. South Asian monsoon convection is relatively weak (compared to mid-latitude convection) and experiences a wide range of aerosol conditions, thereby providing an excellent framework in which to investigate aerosol-convection interactions through both observational and modeling studies.

Deployment Strategies

Careful consideration must be given to deployment in the South Asian monsoon region. Scientifically, a region should be chosen that experiences significant variability in aerosol conditions and a regular progression of the monsoonal front. A land-based deployment must consider the political stability of the country, and relations with the United States. A ship-based deployment, capturing the transition from pristine to polluted conditions over the Indian Ocean, would be a scientifically viable option. In this case, security issues with ship traffic in the region must be considered. In either case, at least one active monsoon season should be sampled, but multiple active seasons would be preferable.

ARM staff stood amidst the AMF2 instrumentation installed on Gan Island for the ARM Madden Julian Oscillation (MJO) Investigation Experiment on Gan (AMIE-Gan). These instruments collected measurements of the initiation, propagation, and evolution of convective clouds within the framework of the MJO.

Modeling Impacts

The representation of the South Asian monsoon remains a challenge for large-scale models, likely related to the coupling of the land, ocean, and atmosphere. Simulation of the current monsoonal circulation is a necessary step towards understanding the changes that will result under climate change scenarios. Further, the South Asian monsoon represents an ideal regime in which to further investigate aerosol-deep convection uncertainties in models..

Asian Pollution in South Korea

The South Korean peninsula experiences a wide variety of aerosol conditions, including a natural background state, locally generated anthropogenic aerosol, and pollution aerosol transported from China and the surrounding region. This variety of aerosol conditions makes this region an excellent location to study aerosol life cycle and cloud-aerosol-precipitation interactions.

Science Topics

- Aerosol emissions and impacts on clouds and radiation – Interactions of aerosols with clouds and radiation remains an important topic for the understanding of global radiative balance. Changing radiative and chemical properties as a function of aerosol aging and sources needs to be quantified under a variety of environments. The variety of aerosol properties and source regions experienced on the South Korean peninsula makes it an excellent region to study aerosol impacts on clouds and precipitation.

Deployment Strategies

There have been previous studies of aerosol and clouds in the South Korean region; however, significant changes in emission rates and profiles make new observations necessary. The ideal deployment location would be a land-based, regionally representative location that experiences a variety of aerosol air masses but is not always heavily impacted by local emissions.

Modeling Impacts

Cloud-aerosol-precipitation interactions remain a significant challenge for models across many scales. Careful observations of meteorological and aerosol properties would help constrain the parameter space for formulating process-model simulations.

Potential Collaborations

The Korean Meteorological Administration operates a network of 11 weather radar systems that could provide quantitative precipitation mapping and a large-scale context for AMF observations. There are also possible plans for a new phase of the Korea-United States Air Quality (KORUS-AQ) study that could offer partnerships for an AMF deployment in the region.

Urban Areas

More than half of the Earth's population currently lives in urban areas, and that fraction is increasing with time. This underlies the importance of understanding climatic impacts to the urban environment and the associated feedbacks. Urban areas serve as important sources of aerosol emissions, localized heating, and variations in surface fluxes. While these urban impacts are well documented, important questions still remain regarding the influence of urban perturbations (e.g., increasing population, changing land cover) on cloud, precipitation, and radiation processes.

Science Topics

- Urban heat island – Changes in land cover affect the partitioning between latent and sensible heat flux and result in increased temperatures in urban areas compared to surrounding rural areas. The heat island has further impacts to the local aerosol, cloud, precipitation, and thermodynamic properties including feedbacks that are modulated by localized circulations. These impacts significantly affect the large populations in the urban centers and have important consequences for health, energy, and environment.
- Aerosol sources and budgets – Cities offer a well-defined aerosol perturbation, both on the local and downwind environment. Particularly in high-latitude locations like Fairbanks, Alaska, interactions with local meteorology (e.g., stable boundary layers, lack of wintertime synoptic influences) have a significant impact on the aerosol budget and air quality. The aerosol perturbations from cities also may have important impacts on downwind clouds and precipitation.
- Boundary-layer meteorology – Interaction of radiation with the complicated urban landscape and the influence of buildings on localized flow and turbulence results in a complicated boundary-layer wind and thermodynamic structure that has important implications for atmospheric dispersion, clouds, and precipitation.

Important questions still remain regarding the influence of urban perturbations (e.g., increasing population, changing land cover) on cloud, precipitation, and radiation processes.

Deployment Strategies

An AMF deployment in an urban area would likely require a complementary distributed network of sensors to capture the variability across the complicated landscape. Seasonal and inter-annual variability likely has a strong influence on urban meteorology, and therefore a multi-year deployment at a location that experiences large enough cycles is preferable. It was also noted that the largest cities are likely too complicated to be able to identify specific urban influences on aerosol and cloud life cycle, and therefore a mid-sized city might offer a preferred location. St. Louis, Missouri; Minneapolis, Minnesota; and Dallas, Texas; were offered as suggestions.

Modeling Impacts

The complicated urban land surface, and particularly the interaction of radiation and turbulence with the urban infrastructure, was noted as a particular challenge for models. Recent advances in the representation of coupling with the urban land surface from tracer modeling studies may make this more feasible in coming years.

Potential Collaborations

Local municipalities often operate networks of meteorology and air-quality measurements that would provide important complementary observations for any AMF deployment. Connections within DOE, for example, Office of Electricity Delivery and Reliability or the Office of Energy Efficiency and Renewable Energy, may provide excellent partnerships. There may also be opportunities across other government agencies, such as NOAA, the Environmental Protection Agency (EPA), and the Department of Homeland Security (DHS).

Wildfires

Wildfires, fueled by a combination of low precipitation, persistent winds, and dry vegetation, present serious threats to property and life. Wildfires also represent significant perturbations to the environment through the release of aerosols, heat, and changes in the land surface. These perturbations strongly impact air quality, cloud and precipitation properties, and land-atmosphere interactions.

Science Topics

- Aerosol life cycle and air quality – Characterizing the evolution of biomass burning aerosols emitted from wildfires remains an important target from both atmospheric science and health perspectives. The life cycle of the chemical and radiative properties of these aerosols has important consequences for their interactions with radiation and clouds. Given the frequency of wildfire events, these represent an important aerosol source. The downwind impacts to air quality and health are also an important component of this question.
- Impacts on cloud and precipitation – Wildfire events impact cloud systems through direct heating of the lower atmosphere, the development of pyrocumulus clouds and associated precipitation, and aerosol-cloud interactions.
- Recovery of burn scars – Wildfire events have a significant impact on the land surface including changes in the surface roughness, albedo, and biogenic emissions. As the burned region recovers after a wildfire, these properties also recover and there is an evolution in the land-atmosphere interactions that is not well quantified.

Deployment Strategies

There are significant challenges to deploying an AMF for the study of wildfire regions. Naturally occurring wildfires are too unpredictable to target in any significant way, and risks to property and personnel would always be a concern. Coordination with prescribed burns by forest services is a

The Gulstream-159, operated by the ARM Aerial Facility, headed toward a smoke plume during a research flight for the Biomass Burning Observation Project in the summer of 2013. Wildfires represent significant disturbance to the environment through the release of aerosols, heat, and changes in the land surface and continue to need to be studied.

more feasible target. If ARM developed a quick deployment strategy, there may be options to deploy immediately after fires to study the recovery phase.

Modeling Impacts

The modeling targets are mostly likely associated with impacts of changes in the land surface and carbon cycle.

Potential Collaborations

A wildfire-based deployment could build upon a number of previous studies including the ARM Biomass Burning Observation Project (BBOP), NOAA's Fire Influence on Regional and Global Environments Experiment (FIREX), NSF Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (WE-CAN), and the Fire and Smoke Model Evaluation Experiment (FASMEE). This could also provide an opportunity for DOE's Environmental System Science's portfolio in BER to leverage ARM assets to study ecological disturbance.

Convection in Arid and Semi-Arid Environment

Building upon one of the most challenging, but successful, deployments of the AMF at Niamey, Niger, Africa, as part of the Radiative Divergence using AMF, GERB and AMMA Stations (RADAGAST), there is still a need for additional observations of convective systems in arid and semi-arid environments. Advances in measurement and modeling technology could provide new insights on this important convective regime. The Southwest United States or the West Africa Sahel region are possible deployment locations to address this challenge.

Science Topics

- Impact of soil moisture on convection – Convective initiation, propagation, and redevelopment are all impacted by interactions with the land surface, particularly soil moisture content. In arid and semi-arid regions, the role of soil moisture-precipitation feedbacks is magnified but still in need of quantitative assessment.
- Aerosol impacts on convection – The impact of aerosols on convective strength remains an area of active research and an important uncertainty in model simulations. The subsequent upscale influence of the aerosols on the monsoonal circulation is also an important consideration.

In 2006, AMF1 was deployed to Niamey, the capital of Niger, West Africa, for its second field campaign. Instruments, such as this aerosol stack, sampled absorbing aerosols from desert dust in the dry season and deep convective clouds and large column moisture loadings during the summer monsoon. There is still a need for additional observations of convective systems in arid and semi-arid environments.

Deployment Strategies

An important consideration for a deployment to study convection in an arid or semi-arid is the need for characterization of the spatial variability in land cover and soil moisture. This likely requires a distributed network of surface sensors around an AMF central facility. Due to the stochastic nature of convective precipitation events, a multi-year deployment is needed to capture enough events for statistical significance. An important logistical consideration, particularly for a deployment in West Africa, is security of the site. This is even more challenging for a distributed network.

Modeling Impacts

Coupling between land surface and atmosphere is particularly important for convective processes. As discussed above for the Korean peninsula, careful observations of meteorological and aerosol properties in semi-arid regions would help constrain the parameter space for formulating process-model simulations.

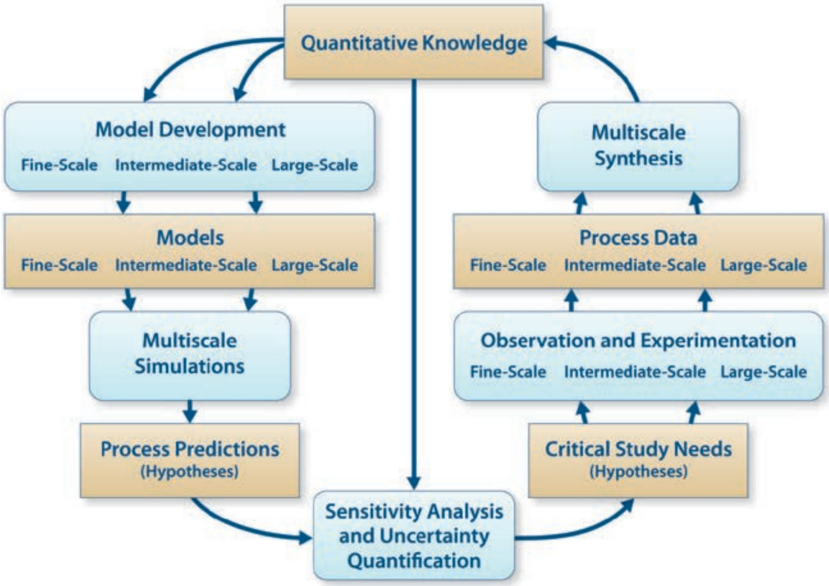
Potential Collaborations

There may be opportunities to build upon collaborations with European partners, particularly those who were involved in the RADAGAST campaign, and the accompanying AMF deployment in Niamey, Niger.

Modeling Coupling/Integration

Integration of AMF Science with Modeling

In order to achieve DOE's Climate and Environmental Sciences Division mission to enhance predictability of Earth's system, the observations collected by the AMF must be integrated with the development and improvement of predictive models for Earth's system. According to the Integrated Model-Observation-Experiment Paradigm, AMF process measurements are coupled with models of these same processes in an integrated loop to ensure that models incorporate state-of-the-science knowledge about atmospheric processes, and the resulting improved models can be used to guide subsequent observational campaigns and to inform future policy decisions. Participants at the workshop discussed general strategies to connect AMF science with models, the opportunities for various modeling frameworks, and the desired AMF data products that would more tightly couple AMF observations with modeling.



According to the Integrated Model-Observation-Experiment (ModEx) Paradigm, described in this flow diagram from DOE's Climate and Environmental Sciences Division Strategic Plan 2018–2023, AMF process measurements are coupled with models of these same processes in an integrated loop to ensure that models incorporate state-of-the-science knowledge about atmospheric processes.

Strategies to Better Engage Modeling with AMF Science

A high priority is to involve modelers from the very beginning—namely, on a team that proposes an AMF campaign. That way, the design of AMF campaigns will have considered the challenges of connecting the unique AMF measurements to modeling interests. These early efforts to connect modelers to an AMF campaign can subsequently be reinforced by proactive outreach steps taken at ARM meetings and beyond. Recruiting modelers beyond the ARM community is easier if an AMF campaign is part of a larger international deployment with high visibility.

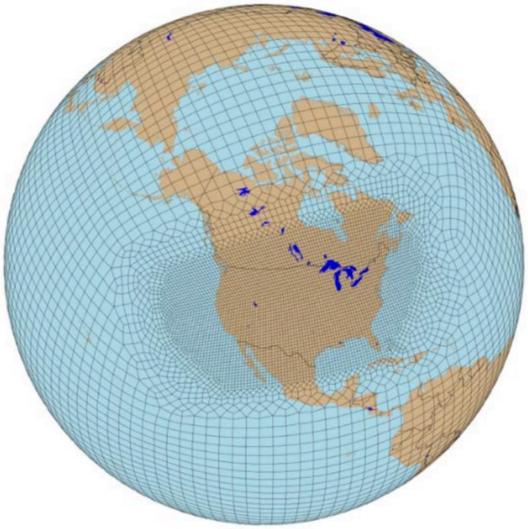
As early as possible, it is highly desirable to have a clear concept of how the AMF measurements can constrain uncertain aspects of model processes representations. One strategy is to have aspects of AMF campaigns target specific model development issues and questions. For example, can further observations be collected to understand why cloud-resolving models tend to overestimate the vertical velocity in deep convective updrafts? Or, to understand why large-scale models tend to simulate marine low clouds that are "too few, too bright"? For these efforts to succeed, close collaborations between modelers who understand the details of model process representations and observationalists who understand the characteristics and limitations of the observations are necessary. One specific strategy is that large-eddy simulations or cloud-resolving model simulations with forward operators can be performed in advance of a deployment to assess the suitability of any proposed campaign to provide meaningful constraints.

Opportunities for Specific Modeling Frameworks

Models vary widely in aspects such as model resolution and how and which processes are represented. A number of specific opportunities were identified according to model type:

For global models, their coarse grid-spacing—typically 10 to 100 km in the horizontal—means that many critical processes are represented with parameterizations that approximately simulate the aggregate effects of these processes. Improving these parameterizations based upon the understanding of processes gained through AMF observations is a high priority. One well-established technique of continuing value is to connect AMF observations to models via “single-column model” simulations that are integrations of the global model at one horizontal location (e.g., the AMF site) with only the column “physics” driven by boundary conditions of the large scale that were observed at the AMF site. When driven by a data set of the large-scale forcing, the behavior of the model physical parameterizations can be compared to the AMF observations, providing important tests of the model representation of processes. A high priority is to make available large-scale forcing data sets for as many AMF campaigns as is practical. These data sets can also be used to force simulations of limited-area models.

Another well-established strategy to connect global models to AMF observations is to perform simulations with global models in weather-prediction mode so that the model is simulating the conditions not only at the AMF site but in the surrounding environment. The strategy has been well used for many past ARM campaigns and is one foci of the DOE Cloud-Associated Parameterization Testbed project that performs such simulations with DOE’s E3SM. This model has the additional capability to add extra resolution in portions of the globe and if these regions are located over AMF sites, model processes can be evaluated with AMF observations for finer model resolutions that may be typical of future models.

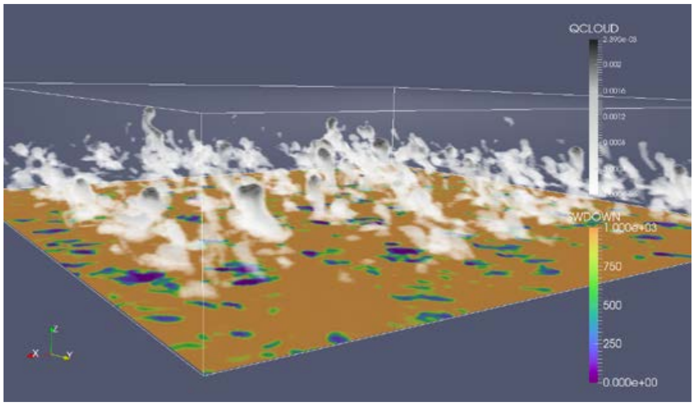


Improving model parameterizations based upon the understanding of processes gained through AMF observations is a high priority. There is potential to pair AMF deployments with model studies performed by DOE’s Energy Exascale Earth System Model (E3SM). Shown here is an example of a regionally refined model, or RRM, over the United States from E3SM.

Limited-area models such as large-eddy simulation (LES) or cloud-resolving models have fine grid-spacing, ranging from 10 to 1000 m in the horizontal, that permits explicit simulation of many critical processes. To the extent that they successfully simulate the variables that AMFs measure, these models can be used to provide information about the variables that AMFs cannot measure. For example, LES are often used to provide information about turbulent vertical fluxes that are represented in parameterizations used by global models. Towards that end, ARM has invested in a project called the LES ARM Symbiotic Simulation and Observation (LASSO) that performs targeted LES for ARM sites.

To date, LASSO has performed simulations for cases of shallow cumulus at the ARM Southern Great Plains atmospheric observatory. The scientific impact of LASSO could be broadened if it could be applied to AMF sites. This is easiest for locations where the phenomenon of interest is low-altitude processes suitable for modeling with periodic lateral boundary conditions over a homogenous surface. A larger impact could be achieved if LASSO developed capability to simulate larger domains in a nested modeling framework with open lateral boundary conditions. This would allow LASSO to perform simulations of AMF campaigns observing deep atmospheric convection. Other ways that LASSO could broaden its impact would be through the development of assimilation capabilities that would allow for the ingest of AMF and other observations.

Analysis models are atmospheric models of either global or limited-area extent that ingest observations to provide an analysis of the state of the atmosphere at a given time. The analyses provided by such models form the initial background fields from which one can derive the large-scale forcing needed to driving single-column models or large-eddy simulations. As a means to enhance the effectiveness of using AMF data by modelers, one could automate the production of large-scale forcing from the analyses or re-analyses of these models so that they are available as early as possible during the campaign. These analyses could be of higher quality if the AMF observations, particularly for the radiosondes, could be ingested into these analysis models in real time. While this effort will be oriented towards the analyses produced by global models, such as those produced



Thanks to LASSO, a cloud model simulation (above) can now more easily than ever be compared with observational data. The scientific impact of LASSO could be broadened if it could be applied to AMF sites.

by the European Centre for Medium-range Weather Forecasts, it is also valuable to ingest AMF observations into limited-area convection-permitting models such as the High-Resolution Rapid Refresh model.

To engage with atmospheric chemistry models, it would be valuable if AMF observations provided measurements of aerosols needed to initialize single-column or limited-area models. For selected campaigns, it would be valuable to perform back-trajectories to identify the source of air over the AMF site and to quantify inventories of regional emissions.

AMF Data Products for Modeling

Timely production of high-quality data products from AMF measurement is key to the engagement of the modeling community. These data products must be "modeler-friendly," generally meaning that they consist of quantities corresponding to model variables, that they are free of as many observational artifacts and as much instrument noise as possible, and that they offer long-term, consistently high-quality data to permit comparison across the full duration of an AMF campaign and with the measurements from other AMF campaigns or ARM fixed sites. These attributes, plus convenient temporal averaging from the timescale of the measurement to longer periods that are more representative of scales approaching the grid size, describe the necessary characteristics of "value-added products" that are created from the raw measurements. Producing such data products for the geophysical quantities requested by modelers in a timely fashion must be a high priority if modelers are to actively engage with the observations collected by AMFs. Input on which data products should be produced first can be collected from the modelers involved in the proposal for the campaign and from other interested modelers in forums such as breakouts at the annual joint ARM user facility and ASR principal investigator (PI) meeting.

Because the science foci of each AMF campaign are distinct, it is difficult to offer specific ideas as to which data products are of most value to every modeling campaign. But generally speaking, the highest priority belongs to so-called "first access" ARM data sets such as (1) the ARM Best Estimate (ARMBE), consisting of elementary geophysical measurements, (2) the Active and Remotely Sensed Cloud Locations (ARSCL), consisting of cloud classifications from the vertically pointing radars and lidars, and (3) the Variational Analysis (VARANAL) consisting of the large-scale forcing necessary to run single-column models and LES. Of nearly equal priority would be vertical profiles of atmospheric state variables from radiosondes or ground-based remote sensors, and some measurements of surface fluxes. Some basic VAPs related to aerosols are also needed. It would be helpful if the production of these "routine" "first access" data sets can be automated as much as possible in order to free up scientists to analyze and produce VAP products from the more advanced and unique measurements for each AMF campaign.

Separately, data simulators for complex measurements (e.g., radar reflectivity) when applied to models allow for comparison of models to more raw AMF measurements and can be helpful when the retrieval of geophysical quantities is very difficult or even impossible. Efforts to provide community data simulators to the modeling community are of value.

Finally, the data product needs of modelers motivate specific actions with regards to the collection of the data itself. The requirements for long-term homogeneous data places extra emphasis on establishing a reliable and repeated calibration of the instruments. In addition, the comparison of geophysical parameters from different instruments places a premium on the co-location of instruments so that they are "viewing" the same portion of the sky at a given time.

Increasing AMF Impact

Different scientific objectives and geographical realities dictate that each AMF deployment carries unique challenges and requires specific strategies. Workshop feedback and discussion of previous deployments highlighted strategies that could make future AMF-based projects more impactful.

Promoting Communication with the Larger ARM/ASR Community to Foster Broader Collaboration for AMF Campaigns

To promote broader scientific participation in AMF-based projects, it would be beneficial to identify and include collaborators, along with potential guest instruments and data products, as early as possible in the deployment planning process. This networking effort would entail little cost if done virtually (i.e., through a public webinar) or at the joint ARM user facility and ASR PI meeting. Previously, this effort to promote the AMF deployments has been left to the PI, but in the future the effort could be co-led by the PI and a representative from ARM to reach out to the community to express project goals.

Broader participation in the AMF deployment could be advertised by publishing a short abstract or white paper associated with proposed campaigns prior to the joint ARM/ASR meeting. This effort to promote broad collaboration early on might also attract modelers (both process and ESM modelers) to include them in the campaign science prior to deployment, as well as a way to obtain feedback on proposed PI value-added products from the broader ARM/ASR community.

Developing In-Country Relationships

Past AMF deployments have demonstrated the importance of establishing strong in-country collaborative relationships, especially with researchers (e.g., GoAmazon). Establishing and promoting these relationships increases scientific engagement and serves to facilitate logistics for an AMF deployment. Working from a pre-existing relationship is ideal, but typically these relationships are built upon years of personal investment and engagement of the PI with the organizations and researchers in the host country. Building a relationship from scratch would likely require dedicated face-to-face engagement. These efforts are naturally PI-led but could benefit from support from ARM.

Performing Modeling and/or Observational Studies Early to Optimize Experimental Design of Prospective AMF Deployments

Modeling and/or observational studies prior to deployment are valuable for quantifying the probability of observing the desired phenomena during the proposed length of deployment. These sampling statistics include both the likelihood of the physical phenomenon occurring in the vicinity of the AMF but also the feasibility of the profiling AMF instruments sampling the structures of interest. Such feasibility assessments might be included in the AMF proposal to help reviewers better estimate the probability of success of the proposed study. Furthermore, such studies could provide guidance on which instruments to deploy—or not to deploy—for a given project. Cost for this effort varies widely depending on the number and depth of pre-deployment activities, and the ARM/ASR infrastructures are not currently set up to do these types of analyses (e.g., the LASSO LES models cannot be simply run for any specified location in the world).

Developing Campaign Log/Field Guide for Intensive Operational Periods of AMF Deployments

Field catalogs, notes, and logs from prior field campaigns have proven highly valuable (e.g., Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment [TOGA-COARE], Dynamics of the Madden-Julian Oscillation [DYNAMO]) for identifying “golden” cases, documenting periods of scientific interest, and providing a quick assessment of which instruments are functioning. Field guides provide valuable context for users by not just identifying the golden cases or periods, but also providing captured satellite imagery, instrument quick looks, model output, and other images such as maps of how instruments are deployed. A project field guide is a natural extension of the field notes from the lead investigators accumulated in the day-to-day operations of a field deployment, which includes PI and collaborator comments on scientifically interesting periods (field notes from the recent AAF deployments in GoAmazon or Aerosol and Cloud Experiments in the Eastern North Atlantic [ACE–

A collection of aerosol observing systems deployed with AMF1 to Cape Cod, Massachusetts, for 12 months starting in the summer of 2012. Smaller off-site campaigns that deploy subsets of the full AMF instrument suite could be beneficial in conducting studies with focused research questions.

ENA] are good examples). As such, it is predominantly a PI effort and need not entail substantial additional cost. There is an ARM role to host the log/field campaign guides with their associated AMF deployment, integrating deployment details (e.g., instrument locations), and establishing best practices for field guide composition.

Ensuring AMF Data Quality

Instrument calibration is a vital component of data quality. One option to provide a calibration period is to build in a short pre-campaign deployment as an option. This period might focus on calibration but also local site micrometeorology and other deployment issues. A focus on calibration and data quality is especially valuable for high-profile periods such as AAF intensive operational period deployments. Maintaining an inventory of critical spares (both parts but also complete instruments where possible) is highly desirable, as is ensuring the quick availability of the spares in the event of instrument malfunction. Deploying instruments with some degree of observational overlap is advantageous, in that it promotes robustness and redundancy in measurements. All these efforts would entail various levels of additional expense, which would predominantly be a responsibility to ARM, except for data quality pertaining to PI products.

Identifying Optimum Timescale for AMF Deployments

ARM is open to longer AMF deployments, and some previous AMF deployments have been lengthy (e.g., 22-month Clouds, Aerosol, and Precipitation in the Marine Boundary Layer [CAP–MBL] campaign in the Azores and 23-month GoAmazon campaign in Brazil). Fewer, longer campaigns may make sense for some regions and scientific questions, but historically the length has been considered on a case-by-case basis. Fewer, longer deployments reduce costs/effort for shipping and set-up and take-down of instruments. For shorter-term deployments, sufficient time must be budgeted between projects to avoid being too rushed in preparations. Benefits of longer deployments would be more opportunity to ensure instruments were all working and calibrated properly, longer sampling time, and more relaxed atmosphere leading up to deployment. However, longer campaigns mean that fewer locations can be sampled overall.

Assessing the Relative Merit of UAS, Tethered Balloon, and Distributed Observational Networks

Distributed observational networks are valuable in providing spatial context to the vertically profiling AMF instruments; however, siting and security incur additional challenges and costs. UAS resources have an advantage in their observational flexibility and responsiveness. Tethered balloon systems are a relatively unique asset for ARM and can provide on-demand lower tropospheric profiling of atmospheric state and aerosol. Despite many desirable features of these different systems; however, their use entails substantial challenges (for example, incorporating UAS observations into modeling frameworks and VAPs). Furthermore, for both the tethered balloon system and UAS, airspace issues may limit the locations over which the systems can be used or the flight plans that can be used. The value of these capabilities should be considered where they can be tied closely to scientific objectives of the PI proposal and challenges can be overcome.

Recognizing Opportunities for Synergistic and Collaborative Field Activities

Previous AMF deployments include both those in which DOE was the sole agency and those in which ARM participated in multi-agency field campaigns with a multitude of other observational platforms. Currently, determining the degree of engagement with entities outside of ARM falls upon the PI. This maximizes flexibility but at the expense of a possible lack of engagement with larger field data collection efforts. Interacting with international (umbrella) organizations (e.g., World Meteorological Organization [WMO], Climate Variability and Predictability [CLIVAR]) may be one pathway towards even greater participation in integrative campaigns.

Formalize Procedures for Deploying Subsets of the AMF Instruments

Previous AMF campaigns have demonstrated some flexibility in instrumentation deployment, particularly for small off-site campaigns that deploy subsets of the full AMF instrument suite (e.g., the Radiative Heating in Underexplored Bands Campaign [RHUBC], MICRE, and Diurnal Cycle Interactions with Madden-Julian Oscillation Propagation [DIMOP] campaigns). The choice of instrumentation depends on the scientific motivation and research questions. This flexibility would especially benefit dedicated aerosol studies (e.g., aerosol observing system [AOS]-only deployments plus gust instrumentation). Furthermore, deploying subsets of radiation, meteorology, surface flux, and aerosol instruments across an area would have considerable benefits for studies where horizontal variability is an important factor.

The tethered balloon system (TBS) operates up to 1.5 kilometers (0.93 miles) above Oliktok Point and AMF3 to collect atmospheric data such as temperature, humidity, and aerosols. Combining TBS measurements with deployments can provide a unique opportunity to collect valuable measurements of spatial context to vertically profiling AMF instruments.

Additional Items

Funding for PI activities associated with AMF deployments – Currently projects funded under the AMF umbrella do not include funding for the PI's time, although ARM does cover some PI travel costs for campaign planning. Funding for PI time is valuable in providing the PI resources needed to engage with the community to rally support for a campaign, perform vital pre-campaign analysis or model simulations, and identify specific needs—e.g., special data products—and communicate those to ARM staff. In the past, ASR has provided initial campaign support to PIs for ASR-relevant AMF campaigns, but this has been on a case-by-case, proposal-driven basis. PIs and other members of the research community have been able to apply for funding from ASR on a competitive basis through ASR's annual funding opportunity announcements. This ARM/ASR approach has the advantage that the AMF proposal is self-contained and not strictly contingent upon PI funding (either from ASR or elsewhere). An alternate approach might follow the NSF procedure for field campaigns whereby multiple proposals are submitted. The advantage of this approach is that if all the proposals are successful, the PI has both scientific and infrastructure support. The disadvantage is substantial; however, in that if one critical piece is not funded then the whole project is at risk of failure.

Rapid-response AMF – In the current AMF process, AMF proposals are submitted at least two years before the proposed deployment. A rapidly deployable AMF would potentially be able to address time-sensitive scientific targets of opportunity. Examples of possible phenomena of interest might be the environment following a major weather event such as a hurricane, along with its short-term climatic impact; wildfires/burn scars; El Niño/La Niña onset; and volcanic eruptions, potentially including associated cloud–aerosol interactions. In principle, a rapid-response AMF could engage with other spontaneous field deployments supported by other agencies. Such an AMF would of necessity contain fewer instruments than the full AMF but might be a set that could fit into a single container or vehicle. It is desirable to have the campaign duration be as flexible as possible—depending on the scientific problem of interest—but could range from a few months to a year. Such a system might also employ other DOE observational resources on an as-needed basis. For example, DOE's TES program has three AmeriFlux systems available for up to three years. A rapid-response AMF system might naturally pair with UAS resources. One issue with deploying small subsets of instruments is the requirement of a better-defined process for deploying single instruments.

However, attendees noted that the potential science questions for a rapid-response AMF were not easily justified relevant to DOE Climate and Environmental Sciences Division (CESD) objectives and run counter to the historical strengths of ARM. Other groups/agencies already do rapid-response applications. Proposed response times of a rapid-response AMF would still be on the order of months, which is probably too long to address most science questions related to the phenomenon of interest. Also, such a system would require an infrastructure framework rather different from that of the current AMF. For example, it would require a ready-to-go infrastructure of instrument configuration and personnel, and a framework in order to rapidly assess scientific merit and feasibility. This rapid-response AMF infrastructure would entail a substantial opportunity cost, both in personnel and deployment, and would draw resources from other AMF platforms.

Summary and Conclusions

A DOE workshop was held in August of 2018 with the objective of gathering input on the highest-priority scientific objectives, research challenges, and opportunities for the AMF capabilities in order to best address the BER goal of improving the predictability of ESMs. The workshop focused input gathered in white papers from the scientific community into workshop discussions, which this report summarizes.

The request for input consisted of these six questions and the additional information included in Appendix A:

- What AMF deployments do you consider the most scientifically impactful?
- What are the highest-priority science questions and/or improvements to ESMs that you feel can be addressed with an AMF?
- How do you think AMF measurements could be more tightly coupled to model development activities?
- What do you consider the highest-priority regions or meteorological regimes (consider both within North America and globally) for a six-month to one-year deployment of an AMF to improve processes in ESMs?
- What do you consider the highest-priority regions or meteorological regimes (consider both within North America and globally) for multi-year deployments of an AMF to improve processes in ESMs?
- Why is a multi-year deployment in this region critical? What length of data set is required to address uncertainties in this region?

The following synopsis include the targeted ESM model bias and deployment strategies, organized around the regions identified below in bold font.

- **Marine regions** are home to large decks of low clouds for which representation in climate models remains a challenge, and for which aerosol-cloud interactions have a disproportionately large global aerosol indirect forcing. Logistical and measurement challenges have restricted measurements. The depiction of stratocumulus, its transition to cumulus, and the mesoscale organization of shallow convection remains a challenge in models at many scales. Marine regions remain under-sampled primarily because of logistics. Many island sites were suggested, with atoll and buoy locations suggested to capture representative surface fluxes upwind and spatially. Shipping lanes may also hold potential regular access to marine regions. The length of deployment depends on location. New techniques may be needed to develop the needed large-scale forcing data sets, in particular the large-scale subsidence.
- The moist **southeast United States** is home to surface-forced convection that poses specific challenges for ESMs and contrasts with the convection experienced at the Southern Great Plains site. During the warm season, a continental inland regime hosts lightly organized shallow and deep convection, while sea breezes at the coast enhance the intensity of the local convection. The cold season experiences synoptically organized cold fronts. The evolution of land convection in a moist environment is poorly parameterized in ESMs. The unique southeast United States aerosol environment consists of biogenic emissions from a typically wooded land surface, interspersed with those from urban environments. A longer-term deployment is preferred to better capture seasonal variations and inter-annual ENSO variability.
- **Mountainous terrain** hosts complex land-atmosphere interactions with strong diurnal variations, capable of initiating substantial convective systems that propagate downwind. ESM model biases in complex terrain are substantial, as land interactions with the large-scale circulation can vary at small scales, and processes driven by large topographic gradients are poorly resolved in models and observations are sparse. Multi-year, distributed-network deployments would be needed to address the inter-annual variability and processes to address these challenges.
- Organized convection in both the **tropics and mid-latitudes** challenge ESMs because relevant processes span a large range of scales and scale interactions and are not all well understood. Parameterization as a function of scale is a further challenge. Measurements require extended facilities, for extended times, to capture the more infrequent highly organized systems. Mobile profiling systems, including Lagrangian cell-tracking using multiple radars and/or multiple sites, are needed, along with large-scale forcing data sets.

- **High-latitude regions** are sensitive indicators of climate change and pose unique challenges for modeling and observing. Mixed-phase clouds are not yet consistently modeled, and inter-annual variability is high. Boreal forest secondary organic aerosols represent significant emissions, with their measurement still limited to Finland. Surface energy budget measurements are important in regions with high melt rates such as southern Greenland and must include aerosol measurements. Conditions in the Southern Hemisphere, e.g., the interior of Antarctica, likely differ from the Northern Hemisphere and are less well known. Longer-term deployments are preferred. The high latitudes naturally lend themselves to international collaborations, with additional expertise needed on cryosphere interactions and the development of arctic reanalyses.
- Other regions and regimes attendees felt were important but did not receive as much emphasis in the white papers, were discussed. These included the **Great Lakes region** of the United States, Asian monsoon, Asian pollution, urban areas, wildfires, and convection in semi-arid regions.

Regions and Regimes of Interest

From the workshop, the following areas were suggested for further study.

- **Marine regions** for trade wind cumulus, shallow-to-deep convection, mid-latitude oceans, western continental coasts, and shipping lanes.
- **Southeast United States** for seasonal and inter-annual ENSO variations, specifically organized shallow and deep convection and the evolution of land convection.
- **Mountainous terrains** for interactions between atmospheric circulation, radiation, and land-surface conditions in the seasonal and diurnal cycle of precipitation and spatial distribution of surface winds within relatively small areas.
- **Tropical and mid-latitude regions** for organized deep convection including mesoscale convective systems, convectively coupled equatorial waves, Madden-Julian Oscillation events, and the monsoon.
- **High-latitude regions** for multi-year measurements of the formation, lifetime, and dissipation of mixed-phase clouds in complex situations through thermodynamic profiling, aerosol (CCN and INP) measurements and their vertical structure, cloud and precipitation properties by phase, surface fluxes, and surface snow/ice properties.

Also of interest were the Great Lakes of the United States, urban areas, Asian monsoon and pollution, wildfires and convection in semi-arid regions.

Locations for which multi-year deployments are desirable towards overcoming inter-annual variability effects include the southeastern United States, high-latitude and ENSO-affected marine regions, and complex terrain (uneven seasonal cycle). Locations requiring spatially distributed deployments include complex terrain and marine regions (towards developing subsidence estimates).

Integration of AMF science with modeling received its own attention. AMF process measurements need to be coupled with models of the same processes in an integrated loop. Ways to improve the integration include involving modelers from the very beginning of an AMF campaign. Proactive outreach steps at meetings can reinforce these relationships. Aspects of AMF campaigns can target specific model development issues. Single-column model simulations are one well-established technique for connecting AMF observations to large-scale models. A high priority is large-scale forcing data sets, and another is the CAPT approach. Extension of the LASSO project, which applies targeted LES to ARM sites, to other locations, is another approach. AMF observations could also be ingested into limited-area convection-permitting models. AMF data products need to be 'modeler-friendly.'

Suggested strategies were examined for making future AMF projects more impactful. Scientific community and in-country collaborations were discussed. Early identification and involvement of collaborators is key to successful deployments. Collaborations could be co-led by the PI and an ARM representative and could be advertised prior to the proposed campaign. Modeling and observational pre-studies can optimize the experimental design of prospective AMF deployments, while campaign 'field guides' can help identify periods of heightened interest. Sufficient transition time between campaigns can allow time for instrument calibrations and to focus on other deployment issues. Maintaining a readily accessible inventory of critical spare instruments and parts, where feasible, lowers the risk related to instrument failures. Relocation costs and science drivers should be balanced when determining length of campaigns. Tethered balloons, UAS, and distributed observational networks provide flexibility and responsiveness, but their observations can be difficult to incorporate into modeling frameworks and value-added products. More integrative campaigns with other agencies, international partners and 'umbrella' organizations can increase participation. The formalization of procedures for deploying subsets of AMF instruments was discussed, as were those for rapid-response deployments.

Appendix A: Workshop Charge

The Office of Biological and Environmental Research (BER) within the U.S. Department of Energy Office of Science research advances the fundamental understanding of dynamical, physical, and biogeochemical processes required to systematically develop earth system models that are needed to inform policies and plans for ensuring the security and resilience of the nation's critical infrastructure. The Atmospheric Radiation Measurement (ARM) user facility is an Office of Science user facility managed by BER that provides the research community with strategically located in situ and remote-sensing observatories designed to improve the understanding and representation, in climate and earth system models, of clouds and aerosols as well as their interactions and coupling with the Earth's surface. ARM data are used to improve fundamental understanding of important atmospheric processes that impact the Earth's radiative balance and limit predictability of the Earth system and to evaluate and improve earth system models. The ARM atmospheric observatories also serve as a testbed for demonstrations of new technology developed by the community and for validation of space-borne sensors. This workshop will focus on input from the scientific community on the highest-priority scientific objectives, research challenges, and opportunities for the ARM Mobile Facility capabilities in order to best address the BER goal of improving the predictability of earth system models.

ARM's current observational capabilities include three fixed sites for long-term measurements, mobile facilities designed to be deployed around the world for shorter campaigns, and an aerial capability. The first ARM Mobile Facility (AMF1) conducted its initial deployment in 2005. The success of the AMF1 led to a second mobile facility (AMF2) designed for marine deployments in 2010, and a third mobile facility (AMF3) designed for multi-year deployments in 2013. Two of the mobile facilities (AMF1 and AMF2) are deployed for campaigns lasting six to 12 months based on peer-reviewed proposals by the scientific community. These facilities have been deployed around the world, including locations in the United States, Europe, Africa, South America, Asia, and Antarctica and on ships in the Pacific and Southern Oceans. The AMF3 was designed for longer (three to five) year deployments in regions with higher variability where multiple years of data are needed. The AMF3 has been deployed to Oliktok Point, Alaska, since 2014.

ARM continually reviews its measurement locations, capabilities, and activities to identify the highest-priority activities for meeting DOE's mission and regularly conducts workshops to get input from the scientific community. The last workshop that considered scientific priorities for the ARM mobile facilities was held in 2007. It is timely to revisit the objectives and scientific priorities for the ARM mobile facilities, and particularly to consider current areas of high-priority observations needed to advance the Energy Exascale Earth System (E3SM) model. The proposed workshop is focused on getting input from the scientific community on the highest-priority scientific objectives, research challenges, and opportunities for the ARM Mobile Facility capabilities to ensure that ARM is well positioned to meet the BER mission of improving the predictive understanding of the earth system.

The workshop will be co-chaired by a committee consisting of the ARM associate director for operations, a scientist representing the observational community, and a scientist representing the modeling community. Participants will include both national laboratory and academic scientists with expertise in atmospheric observations and modeling. Participants may include international scientists so that synergy with ongoing international observational activities can be explored. Participants will include a mix of scientists funded by different DOE programs as well as scientists not currently funded by DOE to ensure a broad range of perspectives.

Suggested Readings

CESD Strategic Plan (2018-2023): https://science.energy.gov/~/media/ber/pdf/workshop reports/2018_CESD_Strategic_Plan.pdf

The ARM Mobile Facilities: Meteorological Monographs: Vol 57: https://journals.ametsoc.org/doi/full/10.1175/AMSMONOGRAPHS-D-15-0051.1

ARM Climate Research Facility Expansion Workshop (2007): https://science.energy.gov/~/media/ber/pdf/Doe_sc_arm_0707.pdf

Recommendations for Implementation of the LASSO Workflow Report: http://www.arm.gov/publications/programdocs/doe-sc-arm-17-031.pdf

Identification, Recommendation, and Justification of Potential Locales for ARM Sites (1991): http://www.arm.gov/publications/programdocs/doe-er-0495t.pdf

Appendix B: ARM Mobile Facility Workshop Input Questions

What AMF deployments do you consider the most scientifically impactful?

- What were the key elements of those deployments that made them impactful?
- Are there any changes (e.g., in instruments, modes of operation, data products) that would make AMF deployments more impactful in general?

What are the highest-priority science questions and/or improvements to earth system models that you feel can be addressed with an AMF?

- What AMF instrumentation and data products do you consider the highest priority for addressing these science questions?
- How could additional instruments/capabilities in an AMF address high-priority scientific questions or improve coupling with process and global modeling?

How do you think AMF measurements could be more tightly coupled to model development activities?

What do you consider the highest-priority regions or meteorological regimes (consider both within North America and globally) for a six-month to one-year deployment of an AMF to improve processes in earth system models?

- Why is this region critical to earth system models?
- What model uncertainties could an AMF deployment in this region address?
- What measurements are critical to addressing these uncertainties?

What do you consider the highest-priority regions or meteorological regimes (consider both within North America and globally) for multi-year deployments of an AMF to improve processes in earth system models?

- Why is this region critical to earth system models?
- What model uncertainties could an AMF deployment in this region address?
- What measurements are critical to addressing these uncertainties?
- Why is a multi-year deployment in this region critical? What length of data set is required to address uncertainties in this region?

Appendix C: Workshop Agenda

ARM Mobile Facility Workshop | August 15 to 17, 2018 | Gaithersburg Hilton | 620 Perry Parkway, Gaithersburg, Maryland

Wednesday, August 15

8:00 **Breakfast available to participants**

8:30 – 8:40 **Welcome** – goals and expectations (DOE)

8:40 – 9:00 **Participant introductions**

9:00 – 9:30 **Brief overview presentation on ARM and AMFs**

Jim Mather, ARM Technical Director

9:30 – 10:00 **Synthesis/summary of white papers** (workshop co-chairs)

10:00 – 10:15 **Coffee break**

10:15 – 10:30 **Introduction to breakout sessions** (workshop co-chairs)

10:30 – 12:30 **Breakout session 1 – region/regime breakouts**

Session 1A – Southeastern United States

- Discussion lead: Steve Nesbitt
- Rapporteur: Sebastien Biraud

Session 1B – High-latitude regions

- Discussion lead: Xiaohong Liu
- Rapporteur: Gijs de Boer

12:30 – 1:30 **Lunch**

1:30 – 2:00 **Reconvene**

- Brief report-outs
- Discussion

2:00 – 4:00 **Breakout session 2 – region/regime breakouts**

Session 2A – Marine regions

- Discussion lead: Paquita Zuidema
- Rapporteur: Rob Wood

Session 2B – Mountains/complex terrain

- Discussion lead: Larry Berg
- Rapporteur: Ruby Leung

4:00 – 4:15 **Coffee Break**

4:15 – 4:45 **Reconvene**

- Brief report-outs
- General discussion

4:45 – 5:00 **Plan for tomorrow** (co-chairs)

6:00 **Group dinner** (optional)

Workshop Agenda (continued)

Thursday August 16

8:00	**Breakfast available to participants**
8:30 – 8:45	**Plan for the day** (co-chairs)
8:45 – 10:45	**Breakout session 3 –** region/regime breakouts
	Session 3A – Organized convection • Discussion lead: Courtney Schumacher • Rapporteur: Guang Zhang
	Session 3B – Open region/regime discussion • Discussion lead: Catherine Naud • Rapporteur: Don Collins
10:45 – 11:00	**Coffee break**
11:00 – 12:30	**Breakout session 4 – topical breakouts**
	Session 4A – Better integration/coupling with modeling • Discussion lead: Maike Ahlgrimm • Rapporteur: Steve Klein
	Session 4B – Open, based on topics from meeting
12:30 – 1:30	**Lunch**
1:30 – 2:00	**Reconvene/discussion**
2:00 – 3:45	**Breakout session 5 – topical breakouts**
	Session 5A – Increasing the scientific impact of AMFs • Discussion lead: Jim Mather • Rapporteur: Dave Mechem
	Session 5B – Increasing the scientific impact of AMFs • Discussion lead: Nicki Hickmon • Rapporteur: Mike Jensen
3:45 – 4:00	**Coffee break**
4:00 – 4:30	**Reconvene** • Report-outs • General discussion
4:30 – 5:00	**Close-out and next steps** (DOE and co-chairs)

Friday, August 17 (Writing team only)

8:00	**Breakfast available**
8:30 – 12:30	**Begin workshop report** • Outline report • Set writing assignments • Set timelines for drafts and review

Appendix D: AMF Instrumentation

Typical AMF Instrumentation

AERI	atmospheric emitted radiance interferometer
AOS	aerosol observing system (AOS: indicates deployed in the system)
AOS:ACSM	aerosol chemical speciation monitor
AOS:AETH	aethalometer
AOS:CCN	cloud condensation nuclei particle counter
AOS:CPC	condensation particle counter (CPC-3772 fine, CPC-3776 ultrafine)
AOS:CO	carbon monoxide analyzer
AOS:HTDMA	humidified tandem differential mobility analyzer
AOS:MET	measurements associated with the aerosol observing system
AOS: NEPH	nephelometer (ambient, wet/dry)
AOS: NOX	nitrogen oxides monitor
AOS:OZONE	ozone monitor
AOS:PSAP	particle soot absorption photometer
AOS:SMPS	scanning mobility particle sizer
AOS:SO2	sulfur dioxide monitor
AOS:SP2	single-particle soot photometer
AOS:UHSAS	ultra-high-sensitivity aerosol spectrometer
CEIL	ceilometer
CSPHOT	Cimel sunphotometer
DL	Doppler lidar
ECOR	eddy correlation flux measurement system
GNDRAD	ground radiometers on stand for upwelling radiation
IRT	infrared thermometer
KAZR	Ka-band ARM Zenith Radar
LDIS	laser disdrometer
MET	surface meteorological instrumentation
MFR	multifilter radiometer
MFRSR	multifilter rotating shadowband radiometer
MPL	micropulse lidar
MWR	microwave radiometer
MWR3C	microwave radiometer, 3 channel
RAIN	rain gauge
RWP	radar wind profiler
SEBS	surface energy balance system
SKYRAD	sky radiometers on stand for downwelling radiation
SONDE	balloon-borne sounding system
TSI	total sky imager

Deployment-Specific Instrumentation

AETH	aethalometer
AOS:APS	aerodynamic particle sizer
AOS:TAP	tricolor absorption photometer
AOS:TRACEGAS	trace gas concentrations
GVRP	G-band (183 GHz) vapor radiometer profiler
HSRL	high-spectral-resolution lidar
KASACR	Ka-Band Scanning ARM Cloud Radar
MAWS	automatic weather station
MWACR	Marine W-Band (95 GHz) ARM Cloud Radar
MWRHF	microwave radiometer - high frequency
MWRP	microwave radiometer profiler
NAV	navigational location and attitude
NFOV	narrow-field-of-view zenith radiometer
SASHE	shortwave array spectroradiometer-hemispheric
SASZE	shortwave array spectroradiometer-zenith
VDIS	video disdrometer
WB	weighing bucket precipitation gauge
WSACR	W-Band Scanning ARM Cloud Radar
XSACR	X-Band Scanning ARM Cloud Radar

Special Request Instrumentation

CSAPR	C-Band Scanning ARM Precipitation Radar
TBS	tethered balloon system

Appendix E: Attendees

Attendee	Institution	Role	Session Lead	Rapporteur
Nicki Hickmon	Argonne National Laboratory	Co-chair	x	
Rob Wood	University of Washington	Co-chair		x
Guang Zhang	University of California, San Diego/Scripps	Co-chair		x
Maike Ahlgrimm	European Centre for Medium-range Weather Forecasting	Attendee	x	
Stan Benjamin	National Oceanic and Atmospheric Administration	Attendee		
Larry Berg	Pacific Northwest National Laboratory	Attendee	x	
Sebastien Biraud	Lawrence Berkeley National Laboratory	Attendee		x
Don Collins	University of California, Riverside	Attendee		x
Aiguo Dai	State University of New York - Albany	Attendee		
Gijs De Boer	University of Colorado	Attendee		x
Virendra Ghate	Argonne National Laboratory	Attendee		
Scott Giangrande	Brookhaven National Laboratory	Attendee		
Mark Ivey	Sandia National Laboratories	Attendee		
Mike Jensen	Brookhaven National Laboratory	Writing team		x
Steve Klein	Lawrence Livermore National Laboratory	Writing team		x
Ruby Leung	Pacific Northwest National Laboratory	Writing team		x
Xiaohong Liu	University of Wyoming	Attendee	x	
Jim Mather	Pacific Northwest National Laboratory	Attendee	x	
David Mechem	University of Kansas	Writing team		x
Catherine Naud	Columbia University	Attendee	x	
Steve Nesbitt	University of Illinois	Attendee	x	
Kim Nitschke	Los Alamos National Laboratory	Attendee		
Courtney Schumacher	Texas A&M University	Attendee	x	
Yuan Wang	Caltech	Attendee		
Shaocheng Xie	Lawrence Livermore National Laboratory	Attendee		
Paquita Zuidema	University of Miami	Writing team	x	
Sally McFarlane	DOE	DOE		
Shaima Nasiri	DOE	DOE		
Rick Petty	DOE	DOE		

Appendix F: White Paper Contributors

Adam Varble
Alec Bennett
Allison McComiskey
Andrew M. Vogelmann
Ben Hillman
Catherine Naud
Cathy Cahill
Courtney Schumacher
Daniel Feldman
Darielle Dexheimer
Dave Turner
David Mechem
Erika Roesler
Ernie Lewis
Evgueni Kassianov
Fred Helsel
Gavin McMeeking
Gijs De Boer
Hailong Wang
Hajo Eicken
Hansi K. Singh
Hugh Morrison
Jarome Fast
Jessie Creamean
Jim Mather
Jim Smith
Jiwen Fan
Joseph Hardesty
Joseph Hardin
Larry Berg
Laura Riihimaki
Lauren Wheeler
Maike Ahlgrimm
Mark A. Miller
Mark Ivey
Martin Stuefer
Matthew Shupe
Mike Jensen
Mikhail Ovchinnikov
Mikhail Pekour
Paquita Zuidema
Paul De Mott
Phil Rasch
Po-Lun Ma
Rao Kotamarthi
Samson Hagos
Sara Lance
Scott Giangrande
Shaocheng Xie
Steve Klein
Steve Nesbitt
Thomas Hill
Tim Gordon
Virendra Ghate
William I. Gustafson Jr.
Xiaohong Liu
Yuan Wang
Yun Qian
Zhanqing Li
Zhe Feng

For More Information

ARM User 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
Shaima Nasiri, shaima.nasiri@science.doe.gov