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Leveraging ARM Data to Improve Models for Predictive Understanding of Energy and Security Challenges

November 2025 Virtual Workshop Report

January 2026

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DISCLAIMER

An initial draft of this report, particularly the discussion summary in Section 3, was generated from meeting notes using artificial intelligence (AI). All sections were carefully reviewed and edited and most saw substantial revision from that initial draft by the authors.

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Virtual Workshop – November 4 and 14, 2025

JH Mather, Pacific Northwest National Laboratory
A Theisen, Argonne National Laboratory
JM Comstock, Pacific Northwest National Laboratory
N Hickmon, Argonne National Laboratory
G Prakash, Oak Ridge National Laboratory
M Spychala, Argonne National Laboratory
M Prichard, Pacific Northwest National Laboratory
K Dorsey, Pacific Northwest National Laboratory
M Wasem, Pacific Northwest National Laboratory
White Paper Authors (Appendix D)

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Executive Summary

Extreme weather and natural hazards can disrupt the energy sector, affecting demand, generation, transmission, distribution, consumption and operational planning at regional and national scales. These disruptions stem from a broad range of atmospheric phenomena, including winter storms, freezing rain, wet snow loading, severe convection, flooding and landslides, wildfires, prolonged heat, and drought. Many of these same phenomena can also affect national security through impacts to transportation and infrastructure. To support the U.S. Department of Energy (DOE) focus on energy resilience and national security, the Atmospheric Radiation Measurement (ARM) User Facility is uniquely positioned to contribute measurement data, analyses, and modeling frameworks that can significantly improve predictive understanding of these hazards to mitigate their effects.

To explore this opportunity, ARM convened a two-part virtual workshop in November 2025. The workshop engaged interdisciplinary experts in atmospheric science, energy systems, modeling, and operations. The goal of the meeting was to engage with these interdisciplinary experts to address three questions:

- What are examples of atmospheric processes that represent significant risks to energy security or national security and where are those risks greatest?
- What measurements or measurement strategies would improve ARM's capacity to address these issues?
- How can ARM and users of the ARM facility better work with the Energy Exascale Earth System Model (E3SM) and multi-sector modeling communities to apply ARM data to improving E3SM simulations of these phenomena?

Participants were asked to submit white papers ahead of the meeting to initiate thinking on these themes and to help organize discussions. Workshop sessions were then organized around themes identified in the white papers.

First from the white papers and then through subsequent discussions, workshop participants identified many examples that address the three questions listed above.

Participants called out energy system vulnerabilities to weather phenomena such as the impact of freezing rain, strong winds, and excessive heat on power grids. They also noted the effects that weather phenomena could have on energy demand or supply (e.g., through effects of extreme temperatures). They called out security vulnerabilities such as impacts to crops from aerosol-borne pathogens and risks to industry due to melting permafrost in the Arctic. In all, over a dozen meteorological phenomena were linked to energy or security vulnerabilities.

For many of the identified phenomena, participants pointed out where ARM was well poised to address issues (e.g., through measurements of cloud microphysics to inform studies of freezing rain) but also noted needs for additional measurements or modified measurement strategies. For example, adaptive scanning of severe weather would be valuable for probing winter storms or severe convection.

Participants pointed out the value in integrating external observations with ARM measurements and with applying artificial intelligence (AI) to ARM observation analysis and they advocated for using model simulations to help optimize measurement strategies through Observing System Simulation Experiments (OSSEs).

It was clear from the workshop that there are many ways that ARM observations can be used to mitigate energy and security concerns, but meeting participants were also asked to identify what they considered to be the greatest opportunities by ranking issues pertaining to the three workshop questions. This was accomplished through a survey administered to participants between the two virtual sessions.

The highest-priority phenomena identified were winter storms, severe convection, and arctic processes. Discussion in the second session, therefore, focused primarily on these three areas, which were most fully developed in exploring ARM opportunities. Nevertheless, it was also clear that ARM has opportunities to contribute to all the identified topics.

This report describes the workshop, including input from discussion and white papers (Sections 2 and 3) and a list of priority recommendations (section 4). Many other ideas for ARM contributions are discussed in individual white papers (Appendix D).

Acronyms and Abbreviations

AI	artificial intelligence
AMF	ARM Mobile Facility
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
CoURAGE	Coast-Urban-Rural Atmospheric Gradient Experiment
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DUSTIEAIM	Desert-Urban SysTem IntegratEd AtmospherIc Monsoon
E3SM	Energy Exascale Earth System Model
EESM	Earth and Environmental Systems Modeling
EESSD	Earth and Environmental Systems Sciences Division
ENA	Eastern North Atlantic
ENSO	El Niño/Southern Oscillation
ERF	Energy Research and Forecasting
LASSO	LES ARM Symbiotic Simulation and Observation
LES	large-eddy simulation
MJO	Madden-Julian Oscillation
MWR	microwave radiometer
NAO	North Atlantic Oscillation
NEXRAD	Next-Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
OSSE	Observing System Simulation Experiment
PNA	Pacific/North American
RRM	Regional Refined Model
S2S	subseasonal-to-seasonal
SAIL	Surface Atmosphere Integrated Field Laboratory
SCREAM	Simple Cloud-Resolving E3SM Atmosphere Model
SGP	Southern Great Plains
TCAP	Two-Column Aerosol Project
TRACER	TRacking Aerosol Convection interaction ExpeRiment
WRF	Weather Research and Forecasting

Contents

1.0 Introduction

The Atmospheric Radiation Measurement (ARM) User Facility provides continuous, high-quality measurements of clouds, aerosols, precipitation, radiation, and surface processes across a global network of observatories. These measurements are enhanced by derived data products and observationally constrained, high-resolution model simulations to enable scientific discoveries across atmospheric physics, modeling, and earth system science. As the nation faces growing challenges from weather-driven energy disruptions and national security concerns, ARM’s observational and modeling capabilities can play a critical role in advancing scientific understanding of atmospheric phenomena that pose a risk to energy systems.

Recognizing this opportunity, ARM held a virtual workshop on November 4 and November 14, 2025, to explore how ARM observations can be better aligned with the needs of the energy and national security communities. The workshop brought together subject-matter experts, model developers, AI/machine learning (ML) researchers, and operational stakeholders to discuss observational gaps, modeling challenges, and strategic opportunities.

The workshop’s overarching objectives were to (1) identify energy-relevant atmospheric processes for which improved observations or data sets could substantially advance predictive understanding; (2) characterize the gaps that limit current modeling capabilities; and (3) articulate actionable pathways for ARM to enhance its scientific impact through measurement strategies, data products, and model integration.

White papers were solicited from workshop invitees to refine the scope of the workshop and develop initial topics for discussion. Twenty-three papers were received, covering phenomena ranging from winter storms to teleconnections to aerosol transport.

2.0 Workshop Design

The workshop comprised two three-hour virtual sessions, each structured around short presentations, guided discussions, and thematic breakout groups. Approximately 30 invited participants contributed expertise across atmospheric science, energy modeling, data assimilation, boundary-layer processes, microphysics, aerosols, severe weather, and arctic meteorology. Invited participants were joined by the ARM management team and DOE stakeholders.

Session 1 focused on meteorological phenomena that could destabilize and/or adversely impact energy systems or national security. Topics explored included how these phenomena impacted energy systems and security, the ability of models to represent these phenomena accurately, and the degree to which ARM was positioned to provide measurements to help address these measurement challenges.

Session 2 provided an opportunity to discuss a subset of the meteorological phenomena in greater detail, with an emphasis on how to link ARM observations and models more effectively. A survey was sent to participants between sessions 1 and 2 to help select phenomena.

The combination of structured white-paper inputs and interactive discussion allowed the workshop to capture a broad set of perspectives and develop a detailed, multi-phenomenon set of recommendations for ARM's future planning.

The meeting agenda, participants, and survey are included in Appendices A-C. White papers are provided in Appendix D.

2.1 Session Descriptions

2.1.1 Session 1: Science Drivers

Sessions on the first and second days were organized around breakout and large-group discussions. Session 1 began with a pair of short presentations on the motivation for the workshop, to demonstrate clearly the ways in which ARM measurements can advance science understanding of atmospheric phenomena that pose a risk to energy systems and national security. Following these overview presentations, the group split into two breakout sessions. Participants were assigned to a breakout to ensure a balanced distribution of subject representation in each virtual room. Each breakout evaluated a set of phenomena that had been suggested by participants in their white paper submissions. Each of these phenomena had the potential to impact energy systems or national security. Many of the phenomena were meteorological events that had the potential to damage the energy grid or affect energy demand and supply; however, there were other phenomena discussed, including the effects of a nuclear explosion and the spread of biological pathogens.

Discussion points included how these phenomena could impact energy systems and security, pose modeling challenges, and would benefit from additional measurements. A summary of the meteorological phenomena and related discussion points is provided in Section 3.

2.1.2 Intersession Survey

The first session covered a wide range of topics and consequently did not delve into specific topics in great depth. For the second session, there was a desire to get into greater detail for a subset of the meteorological phenomena. Workshop organizers felt that the most appropriate phenomena for detailed discussion would be those that simultaneously meet three criteria:

1. Have a significant impact on energy systems and/or national security.
2. Pose a significant challenge to models.
3. Are well-suited to ARM's measurement capabilities.

Phenomena that meet all three of these criteria represent strong opportunities for ARM to have a positive impact on the energy and/or security sectors.

To identify which meteorological phenomena offered the best opportunities for ARM, a survey was sent to meeting participants to rate nine phenomena (highest, medium, lowest) across the three categories listed above. The results of those surveys are provided in Appendix 3. The three phenomena that scored highest across the three criteria were:

1. Winter storms

2. Severe convection
3. Arctic processes

Discussions in Session 2 were organized around these three phenomena.

2.1.3 Session 2: Model Linkages and Deep Dive into Phenomena

Session 2 began with a brief overview of Session 1 and of the results of the survey. Participants were then assigned to one of three virtual meeting rooms, in which discussion focused on one of the three highest-ranking phenomena that emerged from the survey. Participants were encouraged to explore opportunities to improve linkages between ARM observations and models to advance understanding and simulation of each phenomena. They were also invited to discuss other opportunities to advance the application and utility of ARM data to these phenomena.

3.0 Summary of Discussions and Participant Input

3.1 Science Drivers and Energy-Sector Impact Synthesis

From the participant-submitted white papers and subsequent discussion in the breakout sessions, a set of phenomena emerged that could affect national security, energy generation or distribution systems, or energy demand. This section includes brief summaries of the phenomena discussed along with material presented in the white papers (Appendix D.

3.1.1 Extremes of Heat and Cold

Extreme heat and cold conditions affect energy systems in various ways. High temperatures can reduce the transmission efficiency of the electric grid and can decrease production of thermoelectric power. High and low temperatures (including elevated apparent temperature [or heat index] influenced by high relative humidity) also affect energy demand, which has the potential of overloading energy production and transmission systems.

In short-term (< 1 week) operational weather forecasts, temperatures can be predicted reasonably well. For long-term planning, there is a need to understand a variety of temperature parameters that are more challenging. These include the likelihood of maxima and minima temperatures exceeding some thresholds and the time or area exceeding those thresholds. These parameters identify the potential for damage to the electric grid. Additionally, urban environments significantly complicate and exacerbate heatwaves due to lack of vegetation and preponderance of materials such as concrete and asphalt that absorb solar radiation. Studying urban environments requires high-spatial-resolution observations that are able to resolve processes within urban areas on the scale of 10s to 100s of meters. The need to understand the probability of occurrence and associated damage was a recurring theme across all phenomena.

3.1.2 Winter Weather and Cold-Season Hazards

Winter storms pose numerous risks to energy systems, including conductor icing, wet snow loading on transmission lines, visibility reduction for aviation and transportation, and increased electricity demand.

These hazards arise from complex microphysical processes that remain difficult to represent in models, especially during transitions between precipitation types. Participants noted that freezing rain and drizzle events require detailed quantification of supercooled liquid water content – an area where ARM has strong observational potential but limited integrated products.

The workshop emphasized the need for improved synergy among radars, lidars, microwave radiometers, and surface precipitation sensors. Participants recommended developing targeted scanning strategies, common output formats, and enhanced retrievals that capture microphysical signatures of freezing precipitation including gradients in the region where liquid precipitation transitions to frozen precipitation. ARM could also support model development through curated benchmark data sets that include full metadata and provide multi-year event statistics.

3.1.3 Severe Convection, Tropical Cyclones, and other High-Impact Storms

Severe convective storms produce damaging winds, large hail, lightning, and heavy rainfall, all of which pose threats to energy infrastructure and operational continuity. While ARM operates powerful scanning radars at some sites, participants noted that high-frequency dual-polarization observations are needed to improve microphysical parameterizations, especially those governing hail formation and cold-pool dynamics. ARM's surface meteorological network, combined with radar-lidar observations, can provide unique constraints for modeling severe storms and validating convection-permitting models. Participants noted that spatially distributed measurements to characterize heterogeneous surface properties over spatial scales relevant to severe storms are needed to resolve land-atmosphere interactions driving storm initiation and development.

Participants recommended exploring new scanning strategies during severe weather events and enhancing observational coordination with nearby operational agencies such as the National Oceanic and Atmospheric Administration (NOAA)'s Next-Generation Weather Radar (NEXRAD) and Mesonet systems.

Tropical storms represent particularly damaging events. As targets for study, these storms would be challenging for ARM due to their rarity at any one location and due to their severity. However, work on convective processes should be valuable for informing the study of these storms.

3.1.4 Arctic Processes

The Arctic, and specifically the region around the North Slope of Alaska (NSA), is critical for energy and security because of the oil and gas natural resources it contains and its potential importance for international shipping. Atmospheric changes are driving changes in the tundra and sea ice, which have a direct effect on these activities.

Arctic conditions driven by storms, polar lows, and cyclones introduce additional complexities due to unique cloud regimes, extreme cold, low solar angles, and persistent mixed-phase cloud layers. These conditions impose operational challenges that affect aircraft operations, hydropower potential, and infrastructure reliability. For example, cloud radiative effects influence the state of permafrost, which affects infrastructure stability. Supercooled fog and freezing precipitation pose a significant hazard to aviation, communications, and other infrastructure. Workshop discussions highlighted significant model errors related to arctic mixed-phase cloud microphysics, fog formation, and blowing snow processes.

ARM's NSA site is ideally suited to address these gaps, particularly if measurements from the main ARM observatory are supplemented with additional measurements (including offshore measurements) to capture spatial heterogeneity. These measurements would help to predict and quantify features such as freezing fog and arctic storms. Additional measurements of surface fluxes over permafrost, snow, and ice packs and characterization of atmospheric stability were also highlighted as measurement gaps important for modeling studies.

Participants emphasized the value of arctic fog and blowing snow case bundles, which could be developed for the modeling community as part of an expanded LES [large-eddy simulation] ARM Symbiotic Simulation and Observation (LASSO)-like framework.

3.1.5 Drought, Water Scarcity, and Winter Snowpack

Drought reduces hydropower output, impacts thermal power plant cooling, reduces water available for crop irrigation, and amplifies heatwaves that increase electricity demand. Land-atmosphere coupling plays a major role in drought evolution, yet models often suffer from soil moisture biases and poorly constrained evapotranspiration. ARM's existing flux towers, soil moisture arrays, and energy-balance measurements offer important observational anchors. Still, participants suggested greater coordination across sites and improved spatial metadata to support land-model evaluation.

3.1.6 Wildfires and Aerosol Impacts

Wildfire smoke directly affects visibility, solar radiation, snow/ice melt, and air quality. These factors in turn impact transportation hazards (visibility) and water availability (due to reduced snow pack). Participants emphasized the need to better understand transitions from fresh to aged smoke, to improve understanding of aerosol-cloud interactions, and to quantify impacts on downwelling radiation. ARM's extensive aerosol measurement capability – including long-term Aerosol Observing System (AOS) deployments – can provide highly valuable data sets for model initialization and validation. Participants encouraged ARM to develop wildfire-specific data bundles that combine aerosol microphysics, optical properties, boundary-layer structure, and cloud fields.

3.1.7 Dust Storms

Dust storms are prevalent throughout the western and central United States, occurring in dry, drought-prone regions. Dust storms are difficult to predict and can impact power transmission by reducing solar input, damaging the electric grid through direct effects of strong winds and electrical short circuits caused by accumulation of dust, and disrupting transportation corridors. ARM's upcoming deployment to Phoenix, Arizona, the Desert-Urban SysTem IntegratEd AtmospherIc Monsoon (DUSTIEAIM) campaign, and long-term measurements at the Southern Great Plains (SGP) observatory have the potential to provide information about these storms.

3.1.8 Blocking Events and Compound Extremes

Blocking events, which occur when stationary high- or low-pressure areas prevent significant weather systems from moving, can generate compound extremes such as prolonged heat waves, cold waves, or flooding due to stalled precipitation systems. Compound events result from the convergence of multiple phenomena at one place and time, creating a significant amplification effect. These phenomena operate across spatial scales that exceed individual ARM sites, yet ARM's long-term surface fluxes, cloud measurements, and aerosol data can provide ground-truth constraints for understanding how these events manifest locally. Participants emphasized the need for ARM to develop composite data sets from regional-scale distributed networks, likely external to ARM, measuring atmospheric, land, and hydrologic variables, and contribute to research on predictability and event attribution.

3.1.9 Pathogen and Aerosol Transport

Several white papers addressed aerosol transport relevant to agricultural pathogens and food and biofuel security. Although not traditionally part of ARM's mission, participants noted that ARM's aerosol and meteorological measurements could play a valuable role in understanding atmospheric transport pathways for airborne plant pathogens. This could include controlled tracer studies and multi-scale aerosol case bundles that link surface and remote-sensing measurements.

3.1.10 Environmental Impacts of a Nuclear Incident

As with pathogen transport, the study of nuclear incidents has not been part of ARM's mission; however, there are similarities between such events and convective storms and there is the potential for ARM to inform the study of the environmental impact of these events. Two phenomena of interest were called out in one of the white papers: 1) the pattern of fallout; and 2) solar dimming. It was noted that calculations of fallout are currently based on parameterizations that need updating, much like the parameterizations of deep convection. Similarly, solar dimming resulting from the lofting of aerosols and their interactions with clouds involves some of the same processes that ARM users study in aerosol-cloud interactions, though some of the aerosols would reside in the lower stratosphere where ARM has limited observing capability. In both cases, there is potential for ARM to contribute either directly or indirectly.

3.2 Cross-Cutting Themes

3.2.1 Data Accessibility and Multi-Instrument Integration

Across all groups, the most frequently cited challenge was the difficulty of integrating ARM's vast and diverse data sets into workflows used for model evaluation and energy forecasting. Many ARM instruments generate high-frequency observations that are invaluable for process-level understanding but require substantial user effort to synchronize and interpret. Participants recommended the creation of standardized, phenomenon-specific "data bundles" that combine radar, lidar, surface meteorology, flux, precipitation, and aerosol measurements into time-aligned, uncertainty-quantified packages. These bundles should include clear documentation, model-ready formats, and metadata describing instrument limitations and expected uncertainty ranges.

Participants also noted the value of improved visibility into data quality statements, calibration, metadata, and known instrument limitations. Enhanced discoverability and accessibility of these resources would significantly lower barriers for energy-sector modelers and researchers.

3.2.2 Mixed-Phase Cloud Processes and Cold-Season Microphysics

A dominant theme of the workshop was the need for a better understanding and representation of mixed-phase microphysics. Mixed-phase (liquid/ice) microphysics is important in the development of freezing drizzle, freezing rain, and wet snow, which have significant potential for damaging energy infrastructure and pose travel hazards. Understanding these processes require detailed characterization of liquid water content, hydrometeor size distributions, and temperature structure in the near-0°C environment. Models that rely solely on thermodynamic profiles often misclassify precipitation type, resulting in errors that directly affect energy prediction and infrastructure risk assessment.

ARM's suite of radars, lidars, and surface instruments provides a unique capability to observe these transitions. Participants emphasized the need for targeted scanning strategies, enhanced radar-lidar synergy, and improved retrievals that explicitly quantify microphysical fingerprints associated with freezing precipitation. Aerial measurements could also be used to observe these gradients while LASSO simulations would be valuable for providing an observationally constrained description of the region. Participants noted the opportunity to make use of observations at NSA and SGP to develop benchmark data sets around icing events.

3.2.3 Scaling Observations to Modeling Needs: Digital Twins, OSSEs, and LASSO

Model developers stressed the need for curated case studies, OSSEs, and systematic integration of ARM observations into digital-twin frameworks. ARM's long-standing LASSO program was highlighted as an effective model for supporting cloud-process research, and several participants recommended expanding LASSO to include additional phenomena such as mixed-phase clouds, arctic fog, wildfire smoke intrusions, and severe convection. Participants also noted the value of linking ground-based measurements with aerial measurements and linking ARM measurements with observations from other networks and with satellite measurements – and the need for ARM to take on this complex work of integrating diverse data sets. These integrated three-dimensional data sets were highlighted as important for understanding spatial heterogeneity when comparing ARM observations with model simulations.

Digital-twin environments, which require high-quality inputs and synthetically generated fields for controlled experiments, present a major opportunity for ARM to shape future energy resilience research and build on the work ARM has been doing with LASSO. Creating OSSE-ready data sets – complete with uncertainty characterization – will be essential for supporting these efforts.

3.2.4 Land-Atmosphere Coupling and Drought

Participants identified land-atmosphere coupling as a critical driver of drought severity, heatwave persistence, and hydropower predictability. Soil moisture biases are known to amplify heat extremes and impact evapotranspiration and boundary-layer growth. ARM's flux tower networks, soil moisture sensors, and surface energy balance instruments are well positioned to provide valuable observational constraints.

However, users expressed a need for better harmonization across sites and improved temporal and spatial metadata to support land-model integration.

3.2.5 Wildfires, Aerosols, Smoke, and Air Quality

Wildfire smoke has become a persistent risk to solar power, air quality, health, and visibility. Participants highlighted the need for coordinated aerosol microphysics measurements – including size distribution, chemical composition, optical properties, dry and wet deposition rates, and aging processes – to better constrain model behavior and forecast the operational impacts of smoke intrusions. ARM's capabilities in aerosol optical depth, lidar backscatter, and cloud-aerosol interactions are uniquely suited to address these gaps, particularly when combined with targeted case studies and event-driven data bundles.

3.2.6 Teleconnections and Subseasonal-to-Seasonal Predictability

Teleconnections such as El Niño/Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), Pacific/North American (PNA) pattern, and the North Atlantic Oscillation (NAO) – along with blocking events – serve as key predictors of energy demand and hazard frequency on subseasonal-to-seasonal (S2S) timescales. ARM's long-term data sets, particularly at SGP, Eastern North Atlantic (ENA), and NSA, offer unexplored opportunities for evaluating how model biases in clouds, radiation, surface fluxes, and circulation patterns contribute to subseasonal-to-seasonal (S2S) forecast errors. Participants stressed the importance of leveraging these data sets for multi-site, multi-year analysis of atmospheric regimes to evaluate climatological event likelihoods across S2S timescales.

3.3 Modeling Needs, Gaps, and Integration Pathways

A major outcome of the workshop was the identification of specific modeling gaps that ARM could help address. These include challenges in representing convection within the convective gray zone (around 1-10 km), microphysical biases in cold-season precipitation, inaccurate representations of aerosol-cloud-precipitation interactions, insufficient handling of surface-atmosphere coupling, and inconsistent boundary-layer dynamics across model resolutions.

Participants emphasized the need for ARM to support OSSEs and to adopt data formats consistent with model output to facilitate more streamlined integration with E3SM, Weather Research and Forecasting (WRF), Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM), and other high-resolution modeling systems. Participants also discussed the new Energy Research and Forecast (ERF) model as a possible bridge between the atmospheric and energy communities. Improved uncertainty quantification and the creation of AI-ready data sets were also identified as priority areas. For example, ARM observations from long-term observatories could be used to develop models for predicting the likelihood of specific types of events. Expanding the LASSO framework to include wildfire smoke, arctic fog, severe convection, and winter storms would significantly strengthen model evaluation capabilities across multiple phenomena.

3.4 ARM Observational Opportunities

3.4.1 Instrumentation Enhancements

Participants suggested several enhancements to ARM's observational capabilities that could better support energy-relevant scientific goals. These include refining radar-scanning strategies for mixed-phase clouds, expanding aerosol microphysics characterization – particularly at NSA and the third ARM Mobile Facility (AMF3) – improving vertical profiling of cloud and fog boundaries, increasing the density and consistency of flux tower deployments across sites, and hardening instruments to operate during extreme weather conditions. Distributed and adaptive measurements, measurements whose operational parameters adapt to environmental conditions, were noted as essential for capturing the strong spatial and temporal variability that governs high-impact weather and energy-relevant processes – features that fixed, single-point observations may miss. By enabling flexible, multi-platform sampling (remote sensing, aerial measurements, mobile systems), ARM can better resolve evolving storm structures, surface-atmosphere exchange in a heterogeneous environment, and localized hazards that drive model uncertainty and operational risk.

3.4.2 Data Products and Bundles

Across all phenomena, participants identified the need for integrated data bundles that combine observations from multiple instruments. Examples include winter weather bundles (with radar, lidar, microwave radiometer [MWR], precipitation, and surface meteorology), wildfire smoke bundles (with aerosol microphysics and cloud-radiation measurements), arctic fog bundles, and drought/land-surface bundles. These bundles should include standardized time grids, consistent quality flags, and clear documentation of limitations.

3.4.3 Site-Specific Opportunities

Different ARM sites offer unique strengths for addressing energy-sector needs.

- SGP can support convection, drought, severe convective and winter storms, and long-term teleconnection evaluation.
- NSA provides unmatched insight into arctic cloud processes, blowing snow, and cold-season microphysics.
- ENA offers valuable marine boundary-layer measurements supporting teleconnection research.
- AMF1 and 2 offer opportunities to deploy ARM instruments in regions affected by priority meteorological phenomena (e.g., winter storms in the mid-west or northeast United States). Historical deployments also provide an opportunity to study these phenomena (e.g., convective systems during the TRacking Aerosol Convection interaction ExpeRiment [TRACER] in Houston or winter storms during the Coast-Urban-Rural Atmospheric Gradient Experiment [CoURAGE] in Maryland, the Surface Atmosphere Integrated Field Laboratory [SAIL] in Colorado, or the Two-Column Aerosol Project [TCAP] in Massachusetts).
- AMF3 provides opportunities to observe convective cloud systems and land-atmosphere interactions.

4.0 Recommendations

The goal of this workshop was to identify opportunities for ARM to advance science understanding of atmospheric phenomena that pose a risk to energy systems and national security. Through the submission of white papers and discussion, participants identified many phenomena that pose risks to the energy or security sectors, and which ARM has the capability to help study. The survey provided to meeting participants helped to identify which phenomena best met the three meeting criteria: 1) have a significant impact on the energy or security sectors, 2) pose a challenge to earth system models, and 3) are well aligned with ARM capabilities.

Input from participants also identified steps ARM can take to improve its ability to provide support for a better understanding of these phenomena and the threats they pose to energy and security. Meeting organizers extracted ideas from this participant input that seemed to have support from the group and have potential for ARM to increase its impact. White papers and other materials will continue to be reviewed for other possible opportunities.

Specific phenomena of interest are discussed in Section 3 and in the white papers (Appendices 4 and 5). A few examples and associated recommendations for ARM include:

1. **Arctic processes**: ARM has a long history of measurements on the North Slope of Alaska. ARM should continue to provide measurements to improve the study of microphysical processes and the surface energy balance, as they impact the tundra and sea ice, which, in turn, affect energy production and exploration along with navigation in the region.
2. **Winter storms**: Winter storms, and particularly freezing precipitation, can have a large impact on the electric grid, causing widespread power outages. The predictability of these events is poor and there is often limited information about the details of events (e.g., accumulated ice amounts). There is an opportunity for ARM to apply its microphysics remote-sensing and in situ aerial measurement capabilities to significantly improve the understanding of these systems.
3. **Severe convection**: Severe convection has significant potential to impact energy infrastructure through heavy rain, hail, strong downdrafts, and lightning strikes. Convection can also be part of larger systems (e.g., mesoscale convective systems or tropical cyclones) that amplify these effects. ARM should continue its long history of providing measurements of convective systems with a focus on impacts of land-atmosphere interactions, surface heterogeneity, and cloud microphysical processes on severe convection.

These first three phenomena were most highly rated in the participant survey. They meet all three criteria (for impact, modeling challenge, and alignment with ARM). Other phenomena also have potential but scored lower in one or more criteria. Two examples, which nevertheless may present opportunities for ARM are wildfires and extreme heat, particularly heat in an urban environment.

4. **Wildfires**: These events can be devastating and require studying both environmental precursors and the downwind effects of aerosols. ARM is not currently well suited for ground-based studies of these issues due to the transient nature of wildfires and ARM's fixed-location, single-point deployment strategy. ARM should explore strategies to increase its measurement agility to support the study of these events.
5. **Extreme heat**: These events, which can combine high temperatures and humidity, can significantly impact energy demand, transmission, and production. There was a particular emphasis on urban

environments. ARM has begun adapting its measurement strategies for urban environments and can contribute to understanding urban heat. Further development of small-scale deployable systems would help characterize the small-scale interactions in the complex urban environment.

In support of these phenomena, measurement capability needs were identified. These include specific measurements and deployment strategies. Several key needs include:

1. **Freezing precipitation**: Measurement of freezing precipitation and mixed-phase cloud processes emerged as a critical need in several sessions. These measurements would include parameters such as accumulated freezing rain, the existence of freezing rain, and profiles of properties that contribute to the formation of freezing precipitation. These measurements would be important for the study of winter storms in the continental United States and for systems on the North Slope of Alaska. ARM currently provides some measurements (e.g., radar reflectivity profiles) that provide a good start at this; however, there is a need for improved retrievals and in situ measurements that clearly identify and quantify freezing precipitation.
2. **Sampling of spatial gradients**: Some phenomena, such as freezing rain or severe convection, may exhibit tight spatial gradients in their physical characteristics. To understand these phenomena, it is critical to study these gradients. Mechanisms include:
    a. Adaptive scanning radars could be trained to scan across gradients of interest such as the rain/freezing rain/snow transition and gust fronts or cold pools associated with deep convection. Acquisition and deployment of scanning phased-array radar technology that can more quickly and easily accommodate complicated scan patterns would facilitate this goal. Such scanning would benefit from AI applications to provide optimal sampling of these phenomena.
    b. Deployable and agile observing systems that combine a key set of instruments (e.g., boundary-layer profiling sensors) on a vehicle or trailer that can be deployed during intensive operational periods. These mobile platforms would not necessarily provide measurements while moving, but could be positioned in anticipation of an event of interest.
    c. Judicious placement of supplemental sites across regions of expected gradients. For example, on the North Slope of Alaska, sites could be placed both inland and offshore (e.g., on a ship or drilling platform) to understand the representativeness and regional context of the NSA coastal site.
3. **Sampling spatial heterogeneity**: Continuing efforts to augment ARM's single-point observations is important to relate measurements at ARM locations to larger scales and to improve linkages to larger scales. The techniques listed under sampling spatial gradients are also relevant here as are aerial measurements and coordination with other ground-based networks and satellite-based observations.
4. **Instrument and infrastructure hardening**: The phenomena that are most devastating to energy infrastructure also pose a threat to scientific instruments. It is important to identify critical instruments for observing extreme phenomena (e.g., heavy rain or strong wind) and ensure that the instruments can perform effectively in the extreme conditions of interest.
5. **High temporal sampling**: ARM provides high temporal resolution compared to many observing systems; however, for some phenomena, it is important to provide even higher temporal resolution. For example, damage from wind is often due to transient wind gusts. It is important to obtain measurements of fields such as wind and precipitation at sufficiently high temporal resolution

(e.g., order of one second) to capture these transient extremes and to make those high-resolution data available to users.

In addition to new measurements, several recommendations addressed data products or the organization of data to improve effectiveness. These recommendations include:

1. **Mechanisms for merging ARM data with external data sets**: Participants identified the value in merging ARM data with satellite measurements or measurements from other networks. It was suggested that ARM should develop tools, or better organize existing tools, to enable the flexible merging of these data sets, which may involve linking instruments sampling at varied spatial and temporal resolutions.
2. **Data assimilation**: Techniques for assimilating observations into model simulations have advanced over the past decade. ARM should prioritize new efforts to assimilate ARM and external observations into high-resolution simulations over ARM sites to increase the accuracy of those simulations. Assimilation of ARM data could also help define instrument error distributions.
3. **Use of OSSEs**: OSSEs represent an opportunity to improve the likelihood that ARM observations will capture phenomena of interest and that these measurements will address uncertainties in models.
4. **AI/ML applications**: Several examples were identified as good candidates for AI/ML development. These included the application of ARM data to measurement-based parameterizations and the use of long ARM observation records to develop risk-based analyses for phenomena of interest to the energy and security communities.
5. **Identification of benchmark cases**: For phenomena of interest, ARM should develop benchmark cases with curated AI-ready data sets including merged data bundles and dynamic forcing (observation-constrained boundary conditions needed to run limited area models) and spatially distributed measurements for effective engagement with the modeling community.
6. **Use of a hierarchy of models**: To link ARM observations to global-scale models, it is important to run a hierarchy of models ranging from LES scales (with spatial resolution of 10s to 100s of meters) to the global scale. High-resolution models could include ERF or the new DP-SCREAM, as well as the E3SM Regional Refined Model (RRM), which can be configured at kilometer-scale resolution over regions where ARM observations are available. These models could leverage data assimilation and AI to provide an optimally realistic depiction of the region around an ARM site and a bridge to larger scales.

It was illuminating to bring together a diverse group for this workshop and to collect a variety of perspectives. It was noted that there is a need to continue to do this, particularly by reaching out to sectors with whom we have not traditionally worked to understand their needs. Specific examples include:

1. Reach out to specific stakeholders with operational needs, such as operationally oriented DOE offices, NOAA, the U.S. Department of Defense (DOD), utilities, and others to understand their needs. For example, can ARM inform risk analysis that would benefit these communities?
2. Through these engagements, identify specific metrics of interest to understand what parameters are of greatest interest, what uncertainties are considered acceptable, and where specific thresholds for parameters have been identified (e.g., temperature thresholds associated with damage to an electrical grid).

5.0 Conclusions

The workshop highlighted the growing need for integrated observations, curated data sets, and model-ready products that support predictive understanding of energy-relevant atmospheric phenomena. ARM's long-term sites, combined with its advanced remote-sensing and aerosol measurement capabilities, offer an unmatched opportunity to advance the state of the science for various phenomena including cold-season microphysics and convection. By coordinating strategic updates to measurement strategies, data product development, modeling support, and stakeholder engagement, ARM can substantially enhance its role in improving national energy resilience and security.

Appendix A

Agenda

Day 1 (November 4)

- Opening: 45 minutes
  - Background (why we're here, meeting goals) – Jim
  - Digital Testbeds – Gary
  - Summary of White Paper Input – All
  - Instructions for Breakouts
- Breakouts (planning on two parallel breakouts of about 12 people each): 60 minutes
  - Introduction/Kick-Off from Facilitators – Identify where ARM can best make an impact – How significant is the gap?
  - Work Through Prompts
  - Identification of (~3) Scenarios with Greatest Potential
- Review of Top Scenarios from Each Group: 15 minutes
  - Rapporteurs Can Summarize Top Scenarios
- Breakouts: Discussion of Top Scenarios (each person votes for 1): 40 minutes
  - Merge Ideas, Fill Out
  - Remaining Ideas for Modeling Issues, Measurement Gaps (preferably realistic)
- Closing: 20 minutes
  - Brief Summary from the Breakouts
  - Plans for Day 2 (Jim)

Day 2 (November 14)

- Opening: 15 minutes
  - Brief Summary of Day 1 and the Survey
  - Plans for Day 2
- Group discussion: 20 minutes
  - Thoughts from the Group on the Survey and Points Missed on Day 1
- Breakouts: 75 minutes
  - Discussion of Modeling Frameworks
- Break: 10 minutes
- Breakout Summary and Group Discussion: 50 minutes
  - Summary from Breakouts
  - Full Group Discussion – Priorities, What We Learned? What Did We Miss?
- Next Steps: 10 minutes

Appendix B

Workshop Participants

Invited Participants

Scott Collis	Argonne National Laboratory
Rachid Darbali-Azmora	Sandia National Laboratories
Jorge Gonzalez-Cruz	SUNY Albany
Thrushara Gunda	Sandia National Laboratories
Donatella Pasqualini	Los Alamos National Laboratory
Kate Calvin	Pacific Northwest National Laboratory
Jennie Rice	Pacific Northwest National Laboratory
Paul Ullrich	Lawrence Livermore National Laboratory
Joel Rowland	Los Alamos National Laboratory
Peter Caldwell	Lawrence Livermore National Laboratory
Yan Feng	Argonne National Laboratory
William Gustafson	Pacific Northwest National Laboratory
Rao Kotamarthi	Argonne National Laboratory
Erika Roesler	Sandia National Laboratories
Hailong Wang	Pacific Northwest National Laboratory
Shaocheng Xie	Lawrence Livermore National Laboratory
Yunyan Zhang	Lawrence Livermore National Laboratory
Xue Zheng	Lawrence Livermore National Laboratory
Jeffrey Anderson	National Center for Atmospheric Research
Jerome Fast	Pacific Northwest National Laboratory
Chongai Kuang	Brookhaven National Laboratory
Raghu Krishnamurthy	Pacific Northwest National Laboratory
David Romps	University of California, Berkeley
Christine Chiu	Colorado State University
Gijs de Boer	Brookhaven National Laboratory

Scott Giangrande	Brookhaven National Laboratory
Michael Jensen	Brookhaven National Laboratory
Zach Lebo	University of Oklahoma
Greg McFarquhar	University of Oklahoma
John Mecikalkski	University of Alabama Huntsville

ARM Management Team

James Mather	Pacific Northwest National Laboratory
Jennifer Comstock	Pacific Northwest National Laboratory
Nicki Hickmon	Argonne National Laboratory
Adam Theisen	Argonne National Laboratory
Giri Prakash	Oak Ridge National Laboratory
Beat Schmid	Pacific Northwest National Laboratory
Heath Powers	Los Alamos National Laboratory
Andrew Glen	Sandia National Laboratories
Mark Spychala	Argonne National Laboratory

DOE Observers

Sally McFarlane	ARM Program Manager
Gary Geernaert	EESSD Director
Shaima Nasiri	ASR Program Manager
Jeff Stehr	ASR Program Manager
Renu Joseph	EESM Program Manager
Daniel Winkler	EESSD Program Manager

Appendix C

Intersession Survey

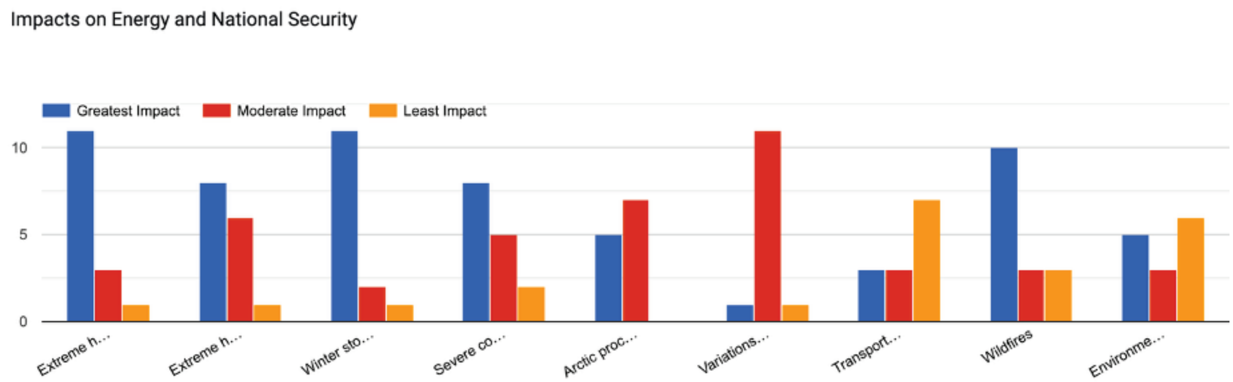
Meeting participants were asked to complete the following survey to help prioritize the phenomena for discussion on the second day of the workshop. The survey preamble as presented to participants read as follows:

> ***Rating of phenomena impacts, modeling challenges, and alignment with ARM***
>
> *Listed below are many of the meteorological phenomena we discussed in the ARM workshop on Tuesday. For each phenomenon, we would like the group's input on three areas: 1) the impact of the phenomena on energy and national security, 2) the challenge the phenomena pose to modeling, and 3) the alignment with ARM. The highest priority would be problems that represent a high impact on energy or security, pose significant modeling challenges and are well aligned with ARM.*
>
> *In filling this out, we do not expect you to fill out every line – just those topics you are comfortable addressing. But we would be quite interested in a few sentences explaining your reasoning. We recognize that all of these phenomena have an impact on energy and security and likely all of them pose modeling challenges – so we are asking for relative responses, which represent the greatest impact or challenge – or the least.*
>
> *If possible, please complete the survey by COB Tuesday November 11. We will use your responses to help us select topics for our second meeting next Friday, November 14.*

1. Extreme heat/cold across a region
2. Extreme heat/cold in an urban setting
3. Winter storms (freezing rain and snow)
4. Severe convection (e.g., downdrafts, lightning, hail, heavy rain)
5. Arctic processes impacting permafrost, coastal erosion, and sea ice
6. Variations and trends in mountain snow pack
7. Transport of pathogens via bioaerosols
8. Wildfires

9. Environmental impacts of a nuclear event

Fifteen meeting attendees responded to the survey. Results are presented below for the nine phenomena for each of the three areas (impact, model challenge, ARM alignment). Comments for each of the three areas are also included.



Comments regarding impacts on energy and national security:

Different phenomena will operate at different scales. Urban settings enhances the complexity and the impact.

Just want to add: drought-induced water scarcity severely impacts energy production, especially hydropower, and national security (food)

Overall impact is very much tied to spatial and temporal scales. Larger/longer scales lead to greater impact.

I voted for the meteorological phenomena that have both high energy and security impacts and a high frequency of occurrence.

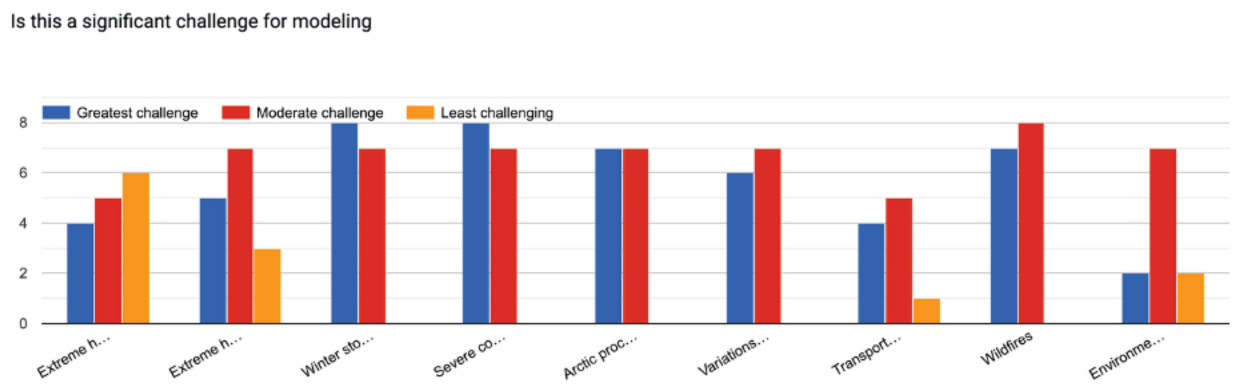
The word "Extreme" is always subjective, so I would propose looking more at individual technology and application where higher temperatures would reduce the efficiency of the energy convertor or impact transmission lines, etc. Some of these extreme events are connected: for example, high temperatures and dry winds can lead to Sundowner/Santa Ana wind events in California, which leads to wild fires. The scales (temporal and spatial) at which the extremes occur also matters.

Extreme heat/cold present major challenges from the demand/generation side. Extreme heat events in particular are increasing in frequency and intensity, and magnified in urban settings where the demand is already high. As we evolve into renewables in the generation portfolio, extreme heat will also diminish the wind resource for generation, presenting challenges of load parity. Better understanding of the origins of heat waves, contributing components (adiabatic, diabatic, advection, sinking air masses), interactions of these with cities, and spatial extent are all crucial variables to research. An emerging variable that needs more research is the role of marine heat waves on atmospheric heat waves. On the other hand, cold snaps present a growing challenge to the electric grid, leading to increasing winter demands under mean and extreme conditions.

I think this question should have been worded as: "Are there facts to be learned about these phenomena that would change how we operate our energy systems or protect national security?" That is the question I have answered here, interpreting the three categories as yes/maybe/no.

The larger regions have significant impacts. Plant pathogens have the potential to be a "catastrophic impact" event for both food and energy crops. More localized phenomena may be impactful locally, but less so to the entire nation. A nuclear event would of course be very impactful, but likelihood is very low, reducing net impacts.

All of these have impacts and are quite important. However, I equally distributed my check marks to prioritize some items over others.



Comments regarding modeling challenges:

For wildfires and nuclear event, the heat source and emission data, especially those high-resolution data, are the challenging part.

I had a bit of trouble answering these without also being able to link the answers to timescales, e.g., near-term forecast, seasonal prediction, versus longer scales. I leaned toward the weather timescale where appropriate.

The meteorological phenomena that present the greatest challenges for modeling are primarily those involving key processes missing from conventional models. Those posing moderate challenges have been studied for some time but still require further model improvements.

It really depends on the time scales and region here for many of these events, and if we want an accurate answer to the above, I recommend analyzing the existing weather forecasts for their ability to model such phenomena. You'll be surprised to see how good the short-term operational weather forecasts are in certain areas, due to enhanced data assimilation techniques currently in place.

1. Modeling the multi-scale manifestation of heat waves remain the major challenge as it manifests both regionally and locally. At local scales, urban processes need to be properly represented in tandem with the regional elements. Case study research may be most appropriate for present-time understanding. From the long-range perspective, fully coupled ocean-atmospheric modeling with

multi-scale capabilities will be most useful to advance our understanding of heat waves, including prediction of marine heat waves.

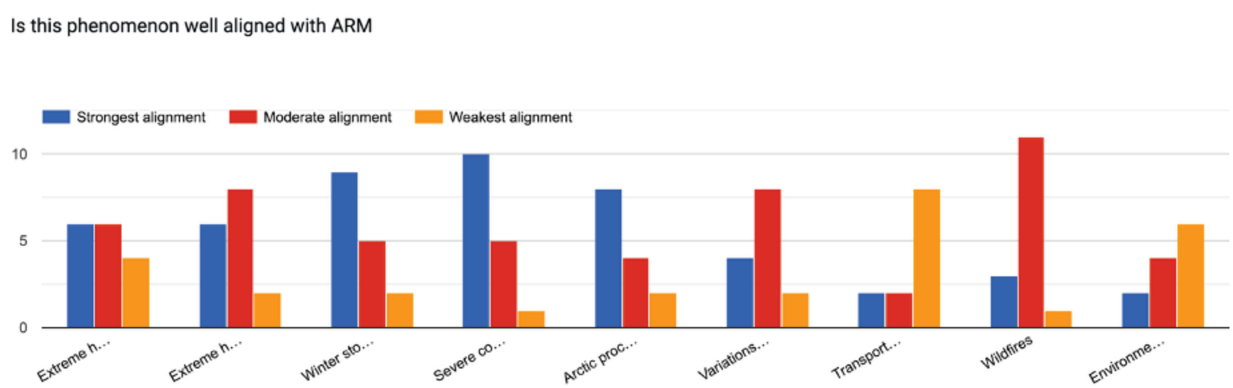
2. Thunderstorms, particularly urban thunderstorms and related precipitation, remain elusive to be properly modeled (and observed!). We need a comprehensive modeling/observation strategy to advance this topic given the number of complex variables involved: urban convection, vapor transport, aerosols and microphysics. The overall impact on the energy infrastructure is less clear.

Some of the challenges depend on model scales. For example, severe convection is very challenging for global earth system models, but it's less of a challenge to regional weather models.

Heat and cold are generally well predicted. While the exact values may be off by a degree or two, the large-scale patterns that largely govern these phenomena are typically simulated well. Clouds and precipitation (and cloud phase) continue to be challenging, impacting the middle four items.

Transport of pathogens is difficult due to the current lack of pathogen/bioaerosol parameterizations (though the transport pathways are generally well constrained). I'm not sure what to put for the last one as I haven't considered the simulation of such an event.

I do not have adequate knowledge to answer the degree of challenge for all of the scenarios, so some are just guesses.



Comments regarding alignment of phenomena with ARM capabilities:

Convective cloud properties are in ARM's wheelhouse. ARM needs to consider which of these are tractable. Regional phenomena will be challenging to link to ARM measurements and challenging to measure the actual improvement achieved through ARM observations.

Whatever the case is, it would be most impactful if support comes from across DOE's Earth and Environmental Systems Sciences Division (EESSD) as ARM observations alone cannot address these challenges. Research support is needed.

Even in areas with strongest alignment above, the current ARM paradigm of having AMFs will not help unless certain processes that are consistently prohibiting from accurate forecasts are identified. These are very broad-brushed processes, and not enough detail to really see any value. The current distributed network of sensors from NOAA provides a lot of this data near-surface – and radars provide upper-level processes - so the boundary-layer process representations is really missing – so perhaps that is where ARM can add value? Most of these processes are synoptically driven.

Sorry, I have given answers above, but I am not sure what "ARM Alignment" you are referring to, so if ARM is thinking more AMFs, it's a weak alignment. If ARM is thinking more a distributed network, there are areas of strong alignment.

ARM observing capabilities are optimized for cloud/aerosol interactions, and boundary-layer processes. They may need to be adapted to measure surface energy balance (including urban contributions), vapor transport, and local convective processes.

I think this question should have been worded as: "With some programmatic guidance, what level of contributions could ARM make to studying the following?" That is the question I have answered here, interpreting the three categories as high/medium/low. Categories I have rated as low are those that involve very large-scale atmospheric dynamics or domains considerably outside ARM's expertise. Categories rated as medium are those for which ARM sites could collect useful data if they get lucky (i.e., when severe weather passes through, or if a wildfire sweeps through) or that could collect data related to, but not central to, the key processes (e.g., atmospheric temperature and radiation in arctic problems that are largely controlled by other things like groundwater flow and ocean processes). Categories I have rated as high are those for which ARM could collect valuable data at the relevant scales.

The current state of ARM isn't ideal for some of these phenomena. Many require more mobile, agile forms of observing. The top phenomena may be considered "NOAA problems", and the link to DOE is limited. Clearer arguments can be made for Arctic, snowpack, and bioaerosols. These are things that ARM is well equipped to measure (and in some cases is or recently has measured). Wildfires are very challenging to observe (again, need highly mobile and flexible measurements). The topic of the last item is well aligned because of DOE, but I'm not sure that ARM is well equipped to measure all of the appropriate processes.

Appendix D

White Papers

Ensemble Data Assimilation for ARM Data

Jeff Anderson, NSF NCAR, Data Assimilation Research Section

Atmospheric data assimilation (DA) is the process of combining estimates of the state of a numerical weather predication (NWP) model with observations to produce an analysis, the best possible model estimate of the current atmospheric state. DA produces the initial conditions used for operational NWP for many space and time scales. DA can also be applied to other Earth system component models like the land surface, ocean and sea ice to produce initial conditions for longer forecasts in which the evolution of all components can be important. Ensemble DA combines an ensemble (a sample) of model forecasts with observations to produce an ensemble of analyses. Ensemble methods enable detailed statistical analysis of the relation between model skill and observations. Ensemble DA systems are available for many forecast models including a number of DOE models. Studies called observing system experiments (OSEs) could be used to assess the impact of the novel observations available at ARM sites on forecast situations of interest on scales ranging from local convection to decadal prediction.

The process of ensemble DA has sometimes been described as confronting models with observations in a statistically rigorous fashion. In addition to providing initial conditions, DA can reveal systematic model deficiencies. Novel observations like those at ARM sites provide more information about the physical system and so can reveal model shortcomings that may not be resolved with traditional observations. DA can be used to directly obtain estimates of uncertain model parameters by finding values that produce forecasts that are most consistent with observations. DA experiments can also evaluate the error characteristics of observations. This can include identifying both systematic errors between disparate types of observations and making quantitative estimates of the observational error distributions associated with a particular instrument.

DA can also be applied in observing system simulation experiments (OSSEs). As the name implies, this involves studying the impacts of hypothetical instruments. Carefully designed OSSEs can provide estimates of the impacts of instruments that are not yet deployed, or not even built, on model state estimates. What would be the impact of new observations on forecast skill? Would a new class of observations improve estimates of model parameters? What would be the impact if existing instruments at ARM sites were more widely deployed? Where should a set of instruments at a site be deployed to deliver the maximum amount of new information? All of these questions are aspects of observing system design which can be studied with DA.

The use of DA using existing and proposed ARM observations could help DOE achieve a number of its goals. At present, DA systems are under development for several DOE model components and could be available for application in the near future.

E3SM Suggestions for ARM
Peter Caldwell

E3SM is pivoting to focus on higher resolution (~10 km dx or higher) and shorter timescales (~30 yrs or less). This alters the types of ARM observations E3SM is interested in. Happily, higher resolution means that ARM's pointwise measurements are now much more appropriate for comparison against E3SM grid columns. The fact that E3SM now partially resolves convection has caused a resurgence of interest in understanding the model's strengths and weaknesses in simulated convection across cloud-resolving (< 1 km) and convection-permitting (1 km – 3 km) scales.

In particular, E3SM is interested in exploring (1) the structure of clouds and storms and the associated updraft/downdraft, mass fluxes, cloud microphysical and aerosol processes, and diabatic heating, (2) spatial heterogeneity of meteorological fields and surface fluxes, and (3) spatial heterogeneity of land surface states such as soil moisture and temperature, vegetation, and snowpack. All of this data is needed at resolutions of ~1 km or finer. LASSO can play an increasingly important role in providing such data, especially if its realism is increased by adding new capabilities for cloud-scale atmospheric data assimilation and land data assimilation.

E3SM's move to higher resolution has also resulted in the replacement of the E3SM single column model (SCM) with a doubly-periodic cloud-resolving model (called DPxx). Initial analysis suggests that this new model is a much better proxy for global-model behavior than the old SCM. Both DPxx and E3SM's regionally-refined model (RRM) capability have been run down to 100 m dx, which raises interesting questions about E3SM's future relationship with LASSO. E3SM is currently gearing up for a series of 200 m RRM simulations over CONUS; areas where E3SM behaves poorly would be useful targets for ARM mobile facility locations.

In addition to convection, E3SM is likely to be focused on anvil clouds, km-scale land/atmosphere interactions, microphysics, and shallow convection in the next few years. The team is also testing a Modal Aerosol Model in C++ (MAMxx), so km-scale measurements of aerosol/cloud interactions will be useful. E3SM is also leaning into machine learning (ML), so ARM datasets - which could be used to develop ML subgrid parameterizations for individual physics processes - would be valuable.

In conjunction with its move to higher resolution, E3SM is also increasing focus on extreme events that cause damage to energy infrastructure and disrupt energy production and use. ARM data could be used to improve and evaluate the ability of E3SM to simulate extreme events such as severe convective storms (hail and ice storms, derechos, and tornadoes) and extreme orographic precipitation, and to model the contributions of land-atmosphere interactions to floods, droughts, heatwaves, and wildfires. While ARM is traditionally configured to collect long-term measurements most relevant for modeling clouds and aerosols that have important radiative
effects, making measurements relevant for

modeling extreme events may require reconfiguration of ARM, particularly the mobile components, to collect data of opportunity at event-scale. Interagency collaborations with NSF, NOAA, and NASA could go a long way in leveraging multiple observing platforms and instruments for this new endeavor.

Mismatch between the radiative bands used by the atmosphere and surface models is another topic of interest to E3SM. Tolento et al. (2025) recently showed that a small change to sea ice partitioning of visible versus near-infrared radiation could change polar temperatures by up to 1.5 K. Measurements of snow and ice spectral albedo and absorptivity in the face of metamorphosis of water crystal influenced by rain (increasingly common in polar regions) would be helpful. Improved understanding of radiative transfer for melt ponds and liquid-saturated snow is also needed. It would also be useful to have observations of albedo and radiative absorption over heterogeneous snow, ice, and ponded surfaces accumulated to the 100m-to-10km scales currently targeted by E3SM.

Team members emphasize that making it easier to compare ARM and E3SM data would be welcome. EMC^2-EAMxx was called out as a particularly useful tool. Extending arm_diags to work with the new C++ atmosphere model (EAMxx) is a natural next step. Estimates of observational uncertainty and clear descriptions of observation limitations are also highly valued. E3SM members also need long-term observations which enable probabilistically robust conclusions and tests that E3SM gets the correct frequency distribution of events.

The Need For Observational Agility To Observe Deep Convective Storms That Drive Destructive Wind Gusts

ARM Workshop on Energy Security Issues

Scott Collis Environmental Science Division
Argonne National Laboratory
Lemont, IL 60439
scollis@anl.gov

Robert Jackson Environmental Science Division
Argonne National Laboratory
Lemont, IL 60439
rjackson@anl.gov

Joseph O'Brien Environmental Science Division
Argonne National Laboratory
Lemont, IL 60439
obrienj@anl.gov

Matthew Tuftedal Environmental Science Division
Argonne National Laboratory
Lemont, IL 60439
mtuftedal@anl.gov

Paytsar Muradyan Environmental Science Division
Argonne National Laboratory
Lemont, IL 60439
pmuradyan@anl.gov

October 29, 2025

Abstract

The United States grid is vulnerable to storm driven winds. The study of deep convective systems, especially classes of mesoscale convective systems such as derechoes, improves the representation of these systems in models across scales and can improve our planning of the grid of the future. However, we need new measurements. To this end, this white paper will discuss the need for a more agile mobile facility for ARM. A facility designed for autonomous, solar-powered operation, enabling rapid deployments in complex terrains such as heterogeneous topography and in the urban fabric where grid disruptions can lead to cascading hazards affecting critical infrastructure and public safety in areas where most Americans live. The white paper authors expect others to discuss pertinent processes, this paper focuses on observational systems using the CROCUS U-IFL as an example.

Keywords Energy · Thunderstorms · Observations · Agile

1 Introduction

Organized convection such as derechoes are particularly damaging to energy infrastructure (e.g. the 2020 midwest derecho [Bell et al., 2022]). These systems can damage energy infrastructure and due to their widespread nature also create hazards that can hinder restoration and lead to cascading failures of critical services. This is particularly exacerbated in urban areas where more than half of the US population lives [Dijkstra et al., 2021].

Understanding the underlying physics of large Mesocale Convective Systems (MCSs) will lead to better representation of these systems in models across scales which in turn will enhance understanding of the range of winds produced and their coupling to damage models for overhead high-voltage lines and other critical energy infrastructure. This white paper leaves detailed discussion of MCS modeling to other authors and instead focuses on new observing systems aimed at investigating convective systems, particularly in complex settings around grid infrastructure and in urban settings.

2 Measurement Needs

Derechos are prevalent in the Midwest of the United States, primarily along a corridor between Nebraska and Illinois, with branches that touch on the domain of ARM's Southern Great Plains site [Li et al., 2025]. This corridor represents a gradient between semi-arid lands that require irrigation through corn lands to the urban-rural interface in Illinois.

This provides an opportunity to investigate and better represent the changing land-atmosphere feedbacks and their impact (or lack of) on the formation, maintenance and dissipation of MCSs, particularly derechoes.

Observing these systems, particularly in the urban-rural gradient region demands a new approach to deploying an ARM Mobile Facility to allow increased agility. A new AMF aimed at studying storms that bear destructive winds would need to be:

- Modular, allowing distributed sensing that can utilize a MODEX approach to target different zones in the storm complex. **Note that this white paper does not advocate for a *mobile* facility, rather a facility that is re-deployable on a shorter timescale than the full AMF**
- Intelligent, leveraging AI and a digital twin (AI or physics driven such as WRF) allowing real-time MODEX. Key examples are rules based adaptive scanning of LIDAR and radar systems such as in [Jackson et al., 2025 forthcoming].
- As independent of utilities as possible. Avoiding construction. Several components need to be on solar + battery and all components need to leverage advanced wireless and satellite internet.

Figure 1: The ADM deployed at University of Illinois Chicago during CROCUS' Urban Canyons 2024 (left) and at NEIU CCICS during the CROCUS Urban Flooding and Rainfall field campaigns (right). From [Muradyan et al., 2025 forthcoming]

Figure 1 is an example of re-deployable instrumentation. The Argonne Deployable Mast (ADM), funded as part of the CROCUS Urban Integrated Field Laboratory, is a solar/battery powered 5G connected platform that uses Waggle [Beckman et al., 2016] for data collections, ingest and to allow adaptive operations of any reconfigurable instrumentation. Another example is the University of Wisconsin-Madison SPARC trailer [Wagner et al., 2019]. While all instrumentation can not be made rapidly re-deployable (e.g. HSRL, KaZR, etc.), many components can. The engineering of a new, agile AMF would include a central facility with a traditional container setup and then the re-deployable component consisting of several units of various levels which could follow the CROCUS conventions shown in Figure 2. The exact instrument configuration will depend on the science question being asked. But for convective systems that impact the grid, questions such as *How do rear-inflow jets and downdraft acceleration influence near surface winds?* would necessitate instruments like a scanning Doppler LIDAR (run adaptively), while questions like *What role do agricultural practices play in modulating moisture fluxes into convection and in the initiation and maintenance of organized convective systems? (e.g. Whitesel et al. [2024])* would require enhanced flux measurements.

Finally, ARM should continue to invest in UAV measurements but focus on smaller units, including rotor aircraft. It should also invest in smaller sonde systems such as the windsonde system to get thermodynamic and wind profiles in the near storm environment.

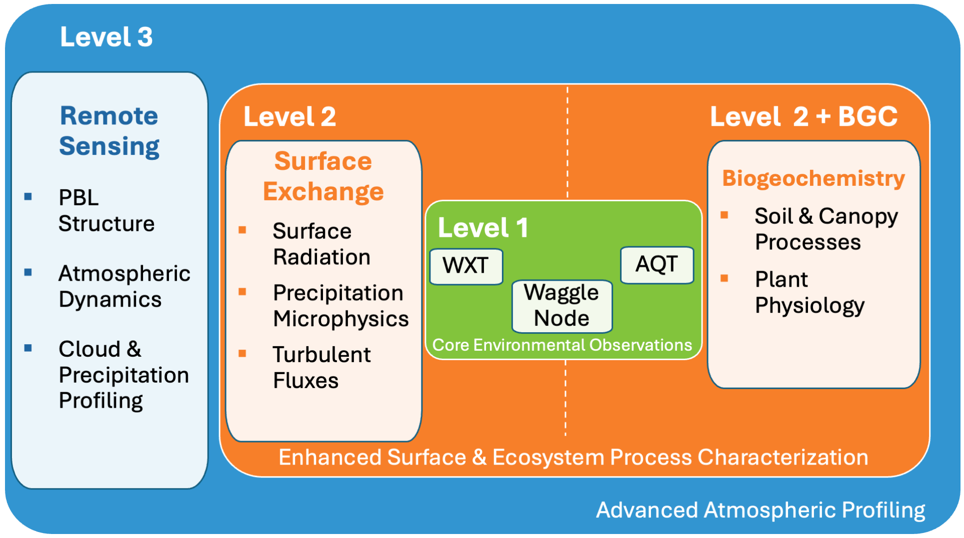


Figure 2: The hierarchy of CROCUS nodes. From [Muradyan et al., 2025 forthcoming]

3 Partnerships and Deployments

Having an agile fleet of nodes will allow a highly configurable observatory. By engineering nodes that can be deployed without construction, ARM can work with site access agreements (through the operation laboratory or entity) to non-profits, utilities, and other institutions. It can partner with utilities in rural settings to co-locate instrumentation, leverage national labs in settings that are prone to organized convection (Argonne and Ames labs are key examples, taken with the ARM SGP site they form a triangle around derecho hotspots) and university partners. By leveraging model output and historic derecho cases, configurations can be identified and an "A la carte" menu of deployment locations can be developed based on climatology, critical energy infrastructure locations and the energy relevant science question being asked.

4 Conclusions

ARM has a long history of mobile deployments based on a multi-container configuration focused on a single site plus a limited number of extended facilities. Deployments, especially the AMF3, require construction and are not readily re-deployable. In order to study energy impactful organized systems such as Midwest derechoes, ARM needs a new approach to deployments with a re-deployable node strategy to allow opportunistic siting at partner locations as directed by a MODEX approach.

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Sandia National Laboratories

Leveraging DOE Atmospheric Radiation Measurement (ARM) to Enhance Grid Planning and Control

Rachid Darbali-Zamora

Introduction

The growing demand for electricity and the transition to distributed energy resources (DERs) have driven the development of decentralized and more resilient electricity systems. Microgrids have emerged as an efficient solution to integrate DERs for energy generation, storage, and consumption. The concept of a microgrid is shown in Fig. 1. This requires a clearer understanding of how atmospheric conditions affect both long-term planning and real-time operations. This creates a need for grid planners and operators to account for the complex interaction between atmospheric factors and grid stability.

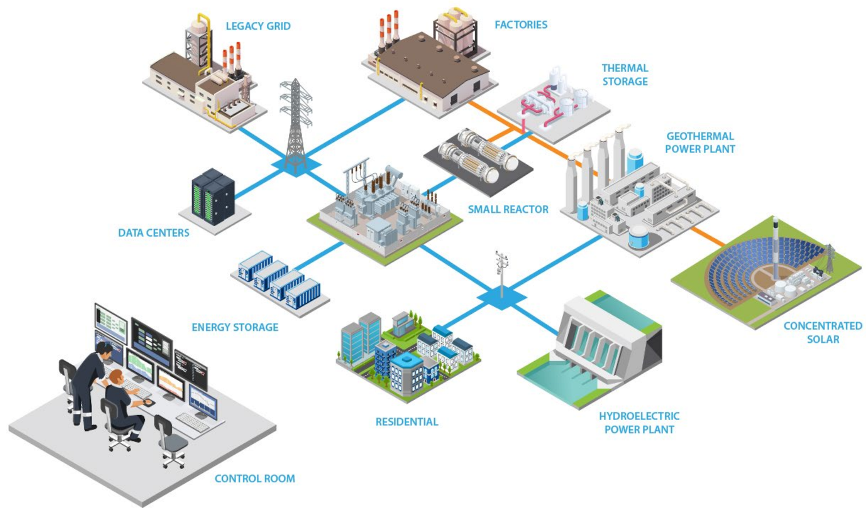

Fig. 1. Concept of a microgrid consisting of a diverse generation set, including geothermal, small nuclear reactors and thermal storage as well as diverse load demand, including data centers.

The Atmospheric Radiation Measurement (ARM) User Facility, supported by the U.S. Department of Energy's Office of Science, provides one of the world's most comprehensive sources of high-resolution atmospheric data. Its observations of radiation, wind profiles, aerosols, temperature, and cloud microphysics can be directly applied to enhance the reliability, resilience, and adaptability of modern power systems. This paper outlines how ARM data can support two critical domains in grid modernization, risk-informed grid planning and advanced grid controls. ARM operates a network of fixed and mobile observatories across diverse geographic and meteorological regions. These sites continuously measure key atmospheric variables relevant to power system operations, such as radiation fluxes, cloud optical depth, aerosol concentration, temperature, humidity, and wind velocity. ARM also deploys aerial and mobile facilities to collect localized, high-resolution data in areas characterized by complex terrain or operational challenges.

Grid Planning Applications

Integrating ARM data into the Microgrid Design Toolkit (MDT) framework provides a unique approach for advancing data-informed grid planning and resilience analysis. MDT, developed by Sandia National Laboratories, supports the design and optimization of microgrids through multi-objective analyses that evaluate tradeoffs among cost, performance, and reliability.[1] The effectiveness of these simulations depends heavily on the accuracy and resolution of the environmental and operational data used to represent site-specific conditions. ARM's comprehensive atmospheric datasets, which include radiation, wind profiles, humidity, and cloud characteristics, can directly enhance the fidelity of these models. By incorporating ARM data, MDT users can simulate microgrid behavior under realistic atmospheric and environmental conditions, improving the accuracy of both generation and load forecasts. ARM's radiation measurements can refine profiles for variable energy generation, while wind and temperature data can inform load models by capturing the influence of environmental conditions on energy demand. This enables planners to assess system performance across a wider range of operating scenarios and evaluate resource adequacy.

ARM's long-term observations can be leveraged for conducting probabilistic and risk-based planning studies within MDT.[2] Historical atmospheric records provide an empirical basis for modeling the frequency and duration of conditions that may

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create vulnerabilities in the grid, such as strong winds that could lead to extreme weather events as shown in Fig. 2.[3] These data-driven insights can inform decisions about storage sizing, backup generation capacity, and component hardening to ensure continued operation during adverse conditions.

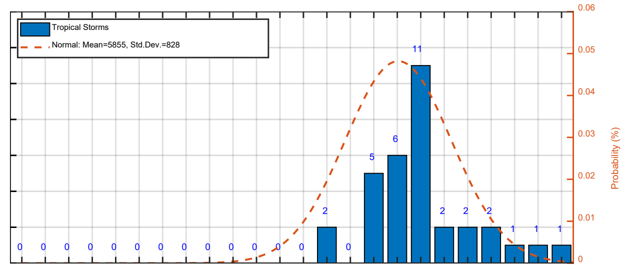

Fig. 2. Half-Month Tropical Storm Occurrence and Normal Distribution.

In regions with limited site-specific meteorological data, ARM's mobile facility deployments and geographically diverse observatories can fill critical information gaps. Planners can leverage ARM's datasets to characterize potential project sites and validate assumptions before field measurements are available. This approach enables more robust microgrid designs, particularly for rural or remote areas where environmental data are scarce.

Grid Control Applications

ARM data can also advance the development of AI-driven grid control systems capable of predictive, adaptive decision-making. The detailed atmospheric measurements captured by ARM provide an ideal training environment for reinforcement learning (RL) algorithms that forecast generation variability and optimize operational responses. AI models trained on ARM's radiation, wind, and cloud data can anticipate fluctuations in variable energy output, enabling grid operators to dispatch storage systems, manage demand response actions proactively, and adjust inverter settings to provide grid services.[4, 5]

These same datasets can support hybrid physics–AI models that combine atmospheric understanding with power system dynamics. Integrating ARM's real-time or near–real-time meteorological data with grid sensor data such as Supervisory Control and Data Acquisition (SCADA) and Phasor Measurement Unit (PMU) feeds would allow developing control algorithms capable of mitigating instabilities caused by sudden natural hazards. ARM data can also be used to simulate a range of environmental disturbances for testing resilience-oriented control strategies. In areas subject to severe storms or operational uncertainty, ARM's mobile facilities could also provide localized atmospheric data to help microgrids and distributed systems maintain uninterrupted services under challenging conditions.

Synergistic Value and Strategic Integration

The ARM user facility offers an opportunity to connect atmospheric science with power system by integrating ARM data into both long-term planning and real-time control. This would enable a grid that is efficient and adaptable, as well as intelligent, resilient, and responsive to operational variability. This integration will strengthen national security in predictive planning, adaptive control, and system reliability. The integration of ARM's atmospheric datasets with grid science offers both immediate and long-term benefits.

- **Grid planning:** ARM data enhances the precision of MDT-based assessments and supports proactive investment in infrastructure resilience and DER siting.
- **Grid controls:** Development of AI models that leverage ARM data to improve forecasting accuracy, operational efficiency, and stability under variable generation and environmental conditions.

The combination of these applications demonstrates how ARM can support data infrastructure for initiatives focused on operational reliability, system flexibility, and advanced distribution management. To realize this, efforts research should focus on integrating ARM data into MDT-based grid planning tools as well as developing advanced controls that support the resilient AI-driven algorithms trained on ARM's high-resolution datasets, emphasizing predictive dispatch, resilience optimization, and fault mitigation. Finally, an "ARM–Grid Data Integration Platform" can be developed to streamline access and interoperability between atmospheric datasets and power system simulation tools, ensuring that both planners and operators can leverage this data resource effectively.

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Understanding the High-Latitude Earth System for Energy, Security, and Community

Gijs de Boer, Hailong Wang, Erika Roesler

The High Latitude Imperative

High-latitude regions, and Alaska in particular, are integral to the Nation's energy systems, national security posture, and community well-being. These regions host critical infrastructure for energy generation, transmission, and distribution, provide key logistical hubs for defense and emergency operations, and support communities whose safety and prosperity depend on reliable environmental forecasts. Operating effectively in these environments requires a detailed understanding of atmospheric processes that are key to sub-seasonal, seasonal, and multidecadal variability in quantities such as temperature, radiation, winds, and surface conditions. Variability in these factors affects not only energy production and distribution, but also transportation safety, infrastructure durability, and community preparedness. The Department of Energy's Atmospheric Radiation Measurement (ARM) program, through its North Slope of Alaska (NSA) observatory and mobile/partner assets, provides comprehensive, process-level measurements needed to characterize and predict these environmental conditions. ARM's long-term observations of clouds, aerosols, radiation, and surface–atmosphere exchange make it uniquely suited to inform understanding of the complex Arctic environment, and the development of energy- and security-relevant predictive models and decision tools.

Energy: Production, Distribution, and Demand: Alaskan energy infrastructure, from the Trans-Alaska Pipeline System to village-scale microgrids and coastal fuel depots, faces operational risk from permafrost thaw, icing, and surface instability. Reliable energy systems depend on accurate prediction of temperature, ground heat flux, and radiative balance.

The key physical uncertainties affecting energy systems are embedded in the Arctic's atmosphere:

- **Mixed-phase cloud persistence** governs longwave radiative surface warming. Partitioning between ice and supercooled liquid -- controlled by **ice nucleation mechanisms, habit growth, and fall speeds** -- helps to dictate whether permafrost remains stable or begins to degrade. Misrepresentation of these processes leads to errors in ground temperature forecasts, threatening infrastructure stability. ARM radars, lidars, and radiometers directly measure **phase evolution and glaciation timescales**, providing data that close these radiation budget gaps.
- **Stable boundary-layers** limit vertical mixing, trapping heat and moisture near the surface. In models, small biases in **turbulent kinetic energy (TKE)** and flux-gradient relationships translate into large differences in **frost depth and structural stress** on roads and pipelines. ARM's eddy-covariance and stability measurements support studies of **flux intermittency and mixing efficiency**, improving earth system models (ESMs) and infrastructure design models.
- **Aerosol composition and optical properties** influence both solar energy availability and heating demand. The hygroscopicity and absorption of Arctic aerosols determine cloud droplet number and optical depth—affecting both renewable generation and the energy needed for winter heating. ARM's Aerosol Observing System (AOS) provides real-time data on **black carbon, sulfate, and organic compounds**, informing models that optimize energy planning.

Such measurements let ARM connect atmospheric processes to the energy system, helping forecast when, where, and why the Arctic environment strains generation, distribution, and demand.

National and Homeland Security: National and homeland security in the Arctic depend on accurate forecasts of visibility, icing, coastal erosion, sea ice properties, and storm evolution. Military and emergency missions, coastal defense operations, and aviation logistics rely on environmental intelligence limited by uncertainties in atmospheric processes.

- **Icing and supercooled fog** represent a major hazard to aviation, radar, and communications systems. These events arise from **droplet activation on aerosols, ice-nucleating particle concentrations, and weak boundary-layer turbulence**. When ESMs or forecast models fail to represent these interactions, icing potential is severely misjudged. ARM's lidars, microwave radiometers, and aerosol measurements inform studies of **liquid water content and microphysical structure**, enhancing prediction of flight and communications safety windows.
- **Arctic storms and coastal cyclones** threaten infrastructure and operations with intense winds and heavy snow. These systems draw energy from temperature gradients and heat and moisture fluxes near the marginal

ice zone. Model errors in representing **air–sea exchange coefficients, sea-spray generation, and surface roughness transitions** often lead to underestimation of storm intensity and surge potential. ARM's radars, flux towers, and microwave profilers guide model improvement and evaluation, guiding coastal readiness and maritime operations.
- **Sea-spray aerosols and associated cloud and riming feedbacks** further complicate storm evolution. Variability in aerosol source strength and **ice nucleation efficiency** determine cloud glaciation and precipitation development, affecting visibility, radar performance, and vessel icing.
- **Sea ice concentration and coastal erosion** impact operation of military facilities, including ship navigation, ice-based transportation, and coastal infrastructure. Understanding processes that drive variability in these quantities can help improve prediction of future states, informing planning and operational performance.

By linking these observations to model parameterizations, ARM directly supports the forecast accuracy and risk mitigation necessary for secure Arctic operations and defense logistics.

Community Strength and Resilience: Arctic communities face challenges that stem from environmental predictability—air quality degradation, transportation hazards, and infrastructure stability. These are driven by small-scale atmospheric processes that models struggle to represent.

- During the long Arctic winter, **strong inversions** trap pollutants near the surface. ARM's active profilers capture **inversion depth, frequency, and turbulence intensity**, improving forecasts of air quality and visibility that guide community health and emergency planning.
- **Aerosol composition and optical feedbacks** influence both health and energy use. Aerosols can alter surface radiation balance, changing near-surface temperature variability and consequently **heating demand and building stress**. ARM's AOS characterizes these aerosol properties and their radiative impacts and cloud activation ability, enabling improved community energy modeling.
- **Snow and ice radiative processes** affect transportation and infrastructure stability. The growth of snow grains and deposition of impurities such as soot modify **albedo and surface energy absorption**, determining how quickly snow melts. ARM's surface energy budget instruments provide critical data to evaluate and forecast these changes.

Through these measurements, ARM not only illuminates the fundamental physics of Arctic variability but also contributes to equitable resilience and energy security for northern communities.

The Path Forward, and Measurement and Data Priorities

ARM's Arctic facilities and datasets bridge the gap between atmospheric process science and mission-critical societal applications. By focusing measurement and analysis capabilities on high-impact uncertainties, ARM can most effectively advance DOE's goals in the Arctic:

- Quantify ice nucleation and phase partitioning that impact icing and surface warming.
- Constrain radiative transfer under complex cloud conditions and aerosol loading.
- Evaluate turbulent fluxes and boundary-layer intermittency controlling surface–atmosphere coupling.
- Link aerosol chemistry to optical and cloud activation properties.
- Observe air–sea exchanges and storm energetics that define operational risk along Arctic coasts.

To achieve these objectives, ARM should:

- Leverage advanced radar capabilities, including multi-frequency, phased-array and bistatic systems, and in situ sensors to measure cloud properties, atmospheric motion, and stability, partnering with other agencies as needed to support the radars.
- Expand aerosol instrumentation to characterize cloud and radiation relevant properties and evaluate models.
- Establish extended spatial networks and deploy mobile assets across coastal–inland gradients to quantify energy and momentum exchange under a variety of environmental regimes.
- Extend UAS and tethered platforms to bridge surface and cloud-layer observations of turbulence, microphysics, and radiation.
- Provide process-oriented data products aimed at processes relevant to energy, security, and societal well-being to accelerate ESM improvement

By grounding atmospheric process understanding in the real-world needs of energy reliability, national security, and community well-being, ARM enables a new generation of predictive capability for the Arctic—turning complex environmental variability into actionable knowledge.

Leverage ARM Observations for Energy and Grid Resilience

Yan Feng (Argonne National Laboratory)

Opportunities. The increasing frequency and intensity of weather and extreme weather events are disrupting energy production, transmission, and consumption across the U.S. At the same time, rapid growth in AI and data center construction is driving unprecedented electricity demand. These converging pressures amplify the vulnerability of the nation's energy infrastructure. By improving the predictability of atmospheric phenomena at regional and local scales, DOE can better assess risk exposure and implement data-driven adaptation strategies to strengthen long-term U.S. energy security and competitiveness. ARM provides observations to inform the improved understanding of atmospheric processes and support the representation of those processes in earth system models for breakthroughs in S2D predictions.

Problem. Utilities[1] have identified major atmospheric hazards that the industries are most vulnerable to:

- **Water supplies**: for power generation systems, **extreme heat or cold and drought** events may result in cooling water shortages, diminished thermal efficiency, or icing of water supplies.
- **Transmission/distribution infrastructure**: **High winds, heavy precipitation and flooding** associated with severe storms pose significant threats to equipment, power lines and maintenance operations.
- **Operation**: Heat or cold especially **icing conditions** can also reduce line ampacity and degrading insulation, potentially leading to overloading, flashover and excessive sag. Debris such as **snow**, **aerosols from wildfires or dust storms** may accumulate or fall onto power lines, leading to line breakage/short-circuiting, excessive sag, damage to insulators or connectors, or increased fire risk.

Actionable predictions of these high-impact events at the kilometer and S2D scales for energy sector remain scientifically and technically challenging, as this timescale falls into the weather-climate gap where model predictive capabilities are weakest[2-3]. *ARM observations can play a critical role in model initialization, data assimilation, and improvement of process representation***.** Here, I will focus on process improvement.

Key Processes and Observational Limitation. The table is an attempt to summarize the key processes that Earth system models struggle to accurately represent, in the context of downstream impact and observational limitation to address these challenges.

High-impact phenomena	**Key Processes**	**Observational Limitation**
Extreme heat or cold	Compounded, e.g., interactions with large-scale circulation, land surfaces, aerosol-radiation-CBL interactions	*Coverage*: data representativeness in critical regions, e.g., water-limited Southwest US and cold climate zones like Midwest.
Severe storm and related high winds (derechos), heavy precipitation, dust storms (haboobs)	Unresolved convection, boundary layer dynamics, surface interactions and aerosol emissions, aerosol-convection-cloud interactions	*Coverage/instrument*: storm life cycle, spatial coverage, vertical profiling (turbulence, aerosol, heating, water vapor), surface and sub-surface measurements especially soil moisture levels
Ice storms/snow accumulation	Ice and mixed-phase microphysics	*Readiness*: ice nucleating particle and ice particle habit characterization, turbulence measurements
Freezing rain	Very little information produced by numerical models, and most of the approaches are empirical	*Coverage/Readiness*: lack of characterization of these events and training datasets in critical zones

Integrating Observations with Modeling.

- **Deployment of AMF to critical regions** for energy sector where models also struggle the most, e.g., targeting at water-limited Southwest US (e.g., DUSTIEAIM), or Midwest such as Iowa, which is prone to severe thunderstorms (derechos, torrential rainfall, haboobs) in summer and snow/ice storms and freezing rain in winter.
- **Develop AI-enhanced adaptive 3D observing approaches** that, for example, target surface energy fluxes, and boundary layer profiles to better capture land-atmosphere interactions, convection and boundary-layer cloud development for improved predictability of severe storms. Argonne has developed a workflow from surface (mironet) -> volume (NEXRAD) -> lidars with better spatial and temporal resolution.
- Leverage long-term ARM data for **observation-driven regime-based analysis to better characterize model biases** by regime (e.g., Zheng et al., 2025) or reanalysis-based regime analysis for **pre-campaign siting and sampling strategies**.
- Leverage AI in **developing data-driven model for processes** lack of fundamental understanding or numerically challenging to model, such as aerosol mixing state, freezing rain, primary and secondary ice nucleation parameterizations.
- **Build benchmark datasets for detection of extreme events** (such as severe storms, extreme cold/heat events, droughts) for model evaluation and training datasets for building foundation models for mapping grid vulnerability.
- **Build an automated data assimilation workflow** to ingest observations such as soil moisture, vertical profiles of aerosol, turbulence to a large-eddy simulation digital testbed, e.g., LASSO or DP-SCREAM. It helps develop siting strategy and can be further extended to the data assimilation framework for km-scale Earth system models.

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ARM Measurement for Peak Energy Demand Drivers in Urban Centers for Efficient Forecast of Loads and Long-Term Planning

Jorge E Gonzalez-Cruz[1,2] and Mike Jensen[2]

[1]University at Albany, Albany, NY
[2]Brookhaven National Laboratory, Upton, NY

What are examples of atmospheric processes that are relevant to energy security?

Extreme heat and cold snap events are major drivers for peak energy demands, particularly in dense urban environments, often placing the generation system and transmission grid at high risks to meet these excessive demands. Our understanding of the interactions of local and regional atmospheric processes of these events and the built environment is limited. Heat waves are characterized by regional high-pressure systems with dry sinking air masses. These events are further exacerbated by the built environment on what is known as the Urban Heat Island (UHI). Moisture transport plays a key role in increasing demand in these events as energy systems will be driving demand for moisture removal processes. Further, the nexus and feedback processes associated with extreme heat (cold)-energy demands are further complicated by coupled air quality influences affecting human health and comfort. The built environment will respond to extreme heat to manage human comfort, leading to emissions of heat and mass -from exhalation of the buildings- into the natural environment which in turn will further elevate the outdoor thermal state. The rates of these heat emissions in form of latent or sensible fluxes and not directly known, nor the composition in terms of indoor pollutants making it into the outdoor environment. It has been hypothesized that anthropogenic emissions of Volatile Organic Compounds during extreme heat events are major precursors of urban ozone production. The surface energy balance will also influence the levels of UHI and implications on energy demands, thus, cloud dynamics and aerosol concentrations may play key roles in controlling surface radiation balance.

More specifically, key atmospheric heat (cold) wave processes that drive the power grid demand include:

(1) *Urban-Heat Dome:* Extent of the urban-heat dome along the transect of the urban-rural landscape with Micro-Wave Radiometers (MWR) and Surface Thermal Observations;
(2) *Boundary Layer Dynamics* in and outside the urban centers: thermal stability, wind-profilers, heights, with Doppler lidars, radiosonde launches, and Ceilometers;
(3) *Convective* motions and sinking air masses via combinations of Doppler lidars and MWR;

(4) *Surface Energy Balance* via flux gradients in and outside the city centers; sensible and latent heat fluxes, net radiation, turbulence fluxes;
(5) *Cloud Dynamics* that may influence surface energy balance via radars;
(6) *Mass/pollutant emissions* from buildings via ground observations along the gradient urban-rural, and in-situ observations if/when possible;
(7) *Vapor Transport* via the above observations that may influence the energy demands for moisture removal;
(8) *Ozone Levels* and precursors in/outside city centers;
(9) *Aerosols Concentrations* that may influence energy and mass balances.

What additional measurements are needed?

The current suite of ARM instrumentation already measures many of the atmospheric variables needed to understand extreme heat and cold processes that drive the energy demand and cascading consequences. The key aspect is to organize observations in the context of gradients urban-rural.

1. Distributed measurements (over an area the size of a typical city-rural domain) of 3D winds (near-surface and vertical), thermodynamic profiles (thermal and moisture), turbulence, and surface fluxes of heat (sensible, latent, net radiation), and turbulence.
2. Suite of air quality measurements to include Ozone and precursors (NOX; VOC; VCP) along the urban-rural gradient;
3. Cloud cover and height along the urban-rural gradient.
4. Aerosol concentrations along the urban-rural gradient.

What data products and/or analysis frameworks or methodologies are needed?

1. Pre-campaign observing system simulation experiments (OSSE) need to be performed to define the ideal number and location of distributed networks.
2. Complementary high-resolution modeling activities are needed, constrained and/or validated by distributed observations towards a 4-D data cube that will provide the highly-granular data needed for understanding the variability in the urban heat island dome and the atmospheric processes that drive that variability.

Opportunities to Address Gaps in Atmospheric Phenomena for Energy Operations and Planning

Thushara Gunda, Nicole D. Jackson, Zach Kilwein, Kate Klise, and J. Kyle Skolfield

Energy operations and planning span various activities including supply/generation, transmission, distribution, and loads. Each of these activities is influenced by different weather phenomena, driven by both the specific infrastructure involved, geographic location, and associated weather exposures. For example, icing can impact various infrastructure assets (e.g., pipelines, conductors, ground wires) leading to operational issues and safety concerns. Similarly, wildfire smoke, lightning, hail, persistent temperature conditions, and dust storms can result in adverse impacts to energy systems (Allen-Dumas et al., 2019; see Table 1 for more details). It should be noted that while some of these may be geographically isolated within the United States (e.g., dust storms in the arid Southwest), their occurrence in other parts of the world could influence energy production relevant for national security (Chen, 2025; Varga et al., 2025).

Table 1. Examples of energy sector concerns from atmospheric phenomena. Non-exhaustive list.

Atmospheric Phenomena	Examples of Energy Sector Concerns	Additional Resources
Icing	Supply challenges from natural gas pipelines Mechanical and electrical issues in power network equipment (e.g., conductors, ground wires and insulators)	Cherynk et al., 2025 Farzaneh, 2024
Wildfire smoke	Interference with solar radiation Outages to network equipment from charged atmospheric particles	Gilletly et al., 2023 Panossian & Elgindy, 2023
Lightning	Flashover between phase and neutral/ground conductors Interruptions to connected loads (due to event itself or associated sensors being tripped)	Balijepalli et al., 2005 Gunda et al., 2020
Hail	Physical damage to glass panels, electrical equipment, and other structures Safety concerns for operators	DOE FEMP, 2025 Clark, 2025 MacDonald et al., 2015
Temperature extremes	Decreased efficiency, capacity of power lines	Zainuddin et al., 2020 Garimella et al., 2023
Dust storms	Interference with solar radiation Outages from high winds knocking out power lines	Smith & Chow, 2025 Varga et al., 2025

While these atmospheric phenomena concerns are well-recognized, there are notable gaps in being able to effectively address them in the energy sector, including: 1) limited ability to forecast exactly when and where these phenomena may occur; 2) extension from single point measurements towards area-based extrapolations; and 3) development of scenarios (both realistic and tail ends). The first two gaps impact energy operations while the latter two are relevant for energy planning, with the scenario development especially relevant for stress testing or informing resilience analyses.

There are various ways that the monitoring and scientific capabilities of ARM could be leveraged to address some of these gaps. Namely, this could be through development or design of value-added datasets (e.g., through coordination with multiple agencies), leveraging LASSO (e.g., for point-to-areal measurement conversion), or even informing new campaigns (e.g., for characterizing cloud intensification to produce lightning). The geographic distribution of ARM facilities would be especially valuable for developing insights into different extreme weather phenomena, which also vary in space. Longitudinal analyses that are able to characterize shifts in patterns over space and time would be especially useful for energy planning activities. Insights that ARM may generate regarding where weather measurements (for above phenomena) can be taken, how they can be processed, or used for both real-time and seasonal or decadal analyses would provide valuable science-backed insights to the energy community.

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Using ARM and LASSO to Facilitate Observation–Model Integration for Energy-Related Kilometer-Scale Processes

William I. Gustafson Jr. (PNNL), Scott E. Giangrande (BNL), and Yunyan Zhang (LLNL)

A White Paper for the US DOE ARM Workshop
"Leveraging Data to Improve Models for Predictive Understanding of Energy and Security Challenges"

Virtual Workshop Series, November 2025

The ability of earth system models (ESMs) to faithfully reproduce processes important to the energy system is critical for infrastructure planning, forecasting, and scenario testing of interactions between the atmosphere and the energy infrastructure. Weather events impact energy generation and demand, as well as infrastructure placement, maintenance, and longevity. Interaction scales for the energy–atmosphere system range from local to continental due to complex interactions and feedbacks between system components. DOE needs accurate models that can span this complexity and accurately handle the interactions.

Examples of impactful weather for the energy system include lightning, wind gusts and downdrafts, heavy precipitation, icing events, and organized storm systems such as mesoscale convective systems and hurricanes. ESMs struggle to accurately simulate the cloud systems critical to these phenomena. And, lightning, which is strongly coupled to the clouds, is typically completely neglected in ESMs, yet should be included when applying the models for energy applications.

The US DOE ARM user facility has over 30 years of observations targeting clouds and related processes, and ARM continues to collect observations for priority data gaps so modelers have the data necessary to improve, evaluate, and deploy atmospheric models. Opportunities exist to better integrate ARM observations and coupled atmospheric modeling efforts with the large-scale and applications-driven ESMs that operate on regional to global scales. Leveraging ARM's suite of observations and high-resolution modeling can directly support improving clouds, boundary layer, and other processes in earth-system and numerical-weather-prediction models that are critical for the impactful weather phenomena noted above. In particular, DOE has active development of two models, the Energy Exascale Earth System Model (E3SM) and the regional Energy Research and Forecasting (ERF) model.

ARM produces large-eddy simulations (LESs) to complement its observations through the LES ARM Symbiotic Simulation and Observation (LASSO) activity, which has been impactful in furthering process understanding of clouds, radiation-cloud interactions, and related parameterization development. LASSO simulations target specific weather phenomena, which, to date, include continental shallow convection, orographically forced deep convection, and marine shallow clouds. Future LASSO simulations will target high-priority phenomena associated with ARM observation sites, such as will be highlighted at this workshop.

Combining the complementary E3SM, ERF, and LASSO atmospheric/earth-system models enables a synergistic model hierarchy that can be used to enable E3SM and ERF to more readily simulate the conditions important for energy system applications. This is particularly true when the coarser models require fine-scale detail for improving physics processes, of which many can be well-resolved in the LASSO LES. The recent push for kilometer-scale and smaller grid spacings in E3SM makes the connection between models particularly timely, as the new E3SM features require evaluation and cross-model validation, and can benefit from detailed case comparisons, such as is produced by LASSO. Likewise, the ERF model is quickly evolving to include the physical processes required to simulate real-world weather conditions from local to continental scales, and it too is heavily in need of careful validation frameworks.

We propose developing software libraries and modeling workflows to leverage a model hierarchy from the LASSO LES to regional ERF to E3SM high-resolution and regionally refined methodologies. We envision facilitating model configurations that span LES, regional, and global-model grid spacings using periodic domains, nested "real-world" domains with in/outflow boundaries, global domains, and global regionally refined domains. Fair comparisons between the models and their various modeling approaches can be enabled by consistently using input and boundary data and carefully communicating recommended model configurations that optimize the model comparisons. Developing consistent post-processing and plotting software to compare output from the models with ARM observations will facilitate model development and physics-process research that spans the model hierarchy. With these capabilities, libraries of cases can be shared across the models, with the benchmark LES informing understanding of E3SM and ERF behaviors and leading to improved physics parameterizations, ultimately enabling E3SM and ERF to address current United States priorities in energy research and applications. As these models evolve and demonstrate accurate simulations, they can also become the primary models used in LASSO, further strengthening the DOE atmospheric model ecosystem.

As part of this multi-model hierarchy, LASSO can be improved to target key variables and processes. For example, a lightning parameterization can be added to the LES model in combination with ARM collecting lightning data to complement its suite of cloud measurements. These can be used to add, evaluate, and improve lightning parameterizations in the coarser atmospheric models that cannot resolve the individual clouds like the LES. More sophisticated treatments of ice-phase clouds in LASSO can also be investigated to assist improvements of multi-phase and ice cloud processes in E3SM and ERF.

The goal is to streamline the model improvement process to quickly adapt the DOE atmospheric model ecosystem to more directly address energy-system priorities. Having interchangeable tools, input datasets, evaluation data, and models of varying complexity that span the relevant atmospheric scales will open new possibilities not possible today for informing the US energy community.

ARM Measurement for Improved Forecasting of Storm Impacts on the Power Grid for Efficient Restoration Response and Long-Term Planning

Michael Jensen[1], Jorge E. Gonzalez-Cruz[2,1] and Meng Yue[1]
[1]Brookhaven National Laboratory, Upton. NY
[2]University at Albany, Albany, NY

What are examples of atmospheric processes that are relevant to energy security?

Hazardous and extreme weather events (e.g., summertime convective storms, tropical cyclones and hurricanes, synoptic and mesoscale windstorms) and associated phenomena are the main causes of damage to the power grid transmission and distribution infrastructure (lines, transformers, towers, sub-stations) leading to power outages. Improved prediction of the **location**, **timing** and **severity** of these events will lead to more efficient short-term preparation and response leading to shorter restoration times and enhanced long-term planning leading to a more resilient grid.

More specifically, key storm processes that drive power grid damage and outages include:

(1) Wind-related damages such as synoptic and mesoscale storms, convective scale downdrafts and microbursts, and tropical cyclones. These wind-related damages occur throughout the United States wherever the transmission and distribution system includes overhead wires. Specific atmospheric variables that need to be measured and modeled include maximum wind gusts, gust duration, wind direction persistence, wind load on structures, boundary layer turbulence, and orographic wind enhancements in complex terrains.

(2) Precipitation and icing such as freezing rain and glaze icing that weighs down and stresses power lines, wet snow accumulation that often damages vegetation around power lines, and heavy rainfall that can flood sub-stations and destabilize ground surfaces. While icing and wet snow conditions are most important in northern portions of the United States, these events have also impacted areas throughout the continental U.S. with the distribution systems being more vulnerable to these events in regions where they are less frequent. Flooding issues are important throughout the U.S. but notably have significant impacts on the power infrastructure in regions that use underground wires (including urban areas) and areas prone to landslides. Specific atmospheric variables that need to be measured and modeled include thermodynamic profiling to capture 0^oC isotherm, warm nose aloft, frontal overrunning events, and rain rates.

(3) Convective and lightning activity which in addition to strong winds can include damaging hail and lightning strikes that cause line trips and transformer damage. Specific atmospheric variables that need to be measured and modeled include convective available potential energy (CAPE), vertical wind shear, convective initiation and growth, location and timing of cloud-to-ground lightning strikes.

What additional measurements are needed?

The current suite of ARM instrumentation already measures many of the atmospheric variables needed to help improve forecasting of storm impacts on the power grid (e.g. winds, precipitation, thermodynamic profiles, storm structure), however the traditional “soda-straw” view of the single column above the ARM site is insufficient for these needs.

1. Distributed measurements (over an area the size of a typical grid service area or high-resolution model domain) of 3D winds (near-surface and vertical), thermodynamic profiles, precipitation, turbulence and lightning are needed.
2. Adding a lightning mapping array to the ARM suite of instrument would be beneficial to help in quantifying convective properties and constrain process studies. Continuing development of parameterization of lightning frequency and occurrence in Earth System models (especially at high-resolution) will help improve representation of mixed-phase precipitation processes and offer the opportunity to couple with power outage prediction and damage forecasting models.
3. Adaptive measurement capabilities, particularly for radar systems, to observe the dynamical structure and precipitation microphysics of storm systems. Mobile capabilities, at least on a field campaign basis, would also be beneficial.
4. At assets (e.g. towers, poles, wires) wind and precipitation conditions to better understand the separate and combined mechanical and thermal stresses of winds, precipitation, snow and temperatures.

What data products and/or analysis frameworks or methodologies are needed?

1. Pre-campaign observing system simulation experiments (OSSE) need to be performed to define the ideal number and location of distributed networks.
2. Complementary high-resolution modeling activities (LASSO-like) are needed, constrained and/or validated by distributed observations towards a 4-D data cube that will provide the highly-granular data needed for precise timing and location of weather disruptors of the grid.

What are specific examples of meteorological phenomena that pose a risk to energy infrastructure, drive energy demand, and/or pose a risk to national security? Identify examples and include some explanation of the risk.

Extreme weather events, including extreme temperature (hot or cold), tropical cyclones, wildfires, flooding, and other severe weather, can lead to power outages, by damaging electricity generating infrastructure and/or transmission lines. Increased air and water temperatures can result in reduced production from thermal power plants or even temporary shutdowns. Hurricanes can damage refineries and other energy infrastructure. Increases in average temperatures lead to increased demand for cooling and decreased demand for heating; the net effect on energy use varies by region. Droughts, flooding, and extreme temperature can affect the production of crops used for bioenergy (e.g., corn, soybean, etc.).

Some examples:

- In 2005, hurricanes Katrina and Rita led to the shutdown of eight refineries and hundreds of drilling rigs.[1,2]
- In summer 2025, extreme heat led to a temporary shutdown of some nuclear reactors in Europe, due to elevated cooling water temperatures. Such events have occurred in other regions and years (e.g., Connecticut in summer 2012).[3,4]
- In California, utilities have pre-emptively turned off portions of the electricity grid to reduce the risk of wildfires.[5]
- In winter 2021, freezing temperatures in Texas left millions of customers without electricity for several days.[6]

Where in the United States are these phenomena expected to have the greatest potential impact?

The part of the USA most impacted by these events depends on the specific events. While hurricanes can make land fall on the gulf coast or the eastern seaboard, the largest potential impact on refineries is along the gulf coast, due to the amount of infrastructure in this region. Wildfires are more common in the western United States, though smoke from wildfires can impact communities across the USA. Increases in air and water temperatures occur across the United States, though the effect those increases have on energy systems may vary.

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[3] Sergio and Colelli, 2025. "Weather-induced power plant outages: Empirical evidence from hydro and thermal generators in Europe." *Energy Economics* 148 (108549), doi:10.1016/j.eneco.2025.108549.
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[6] Busby et al., 2021. "Cascading risks: Understanding the 2021 winter blackout in Texas." *Energy Research & Social Science* 77 (102106), doi:10.1016/j.erss.2021.102106.

ARM for Energy Resilience and Security

Rao Kotamarthi, Argonne

ARM is designed to (a) perform multiscale measurements that span the spatial resolution of climate models, available and in development (b) develop data that provides insights for the development of process scale models that could be considered sub-grid scale to climate models. These measurements have served this purpose well and as the models becomes increasingly high-resolution and the atmospheric process that could be considered sub-grid to these models now moves to scales that would be considered LES and cloud resolving. I propose that instead of asking how these measurements can support energy sector, we should ask what the key environmental/atmospheric constraints and challenges to this sector are and how can the ARM program reconfigure itself to support the energy sector and address these challenges.

I can identify two topics that could be of relevance to the energy sector that ARM could provide data/information (1) the ultimate sink for the existing conventional and SMR Nuclear Power plants is either water (river, ocean) or air. Air cooled SMRs will be cheaper to build. Understanding atmospheric conditions at local (LES) scales in the lowest 0-50 m. temperature, moisture, winds or more correctly the microscale atmosphere will benefit the reactor designers develop efficient heat sinks. This may also help with wind and solar energy planning, if we shift focus to the lower 0-50, 0-100 and 0-200m portion of the atmosphere (2) improving S2S and inter-annual forecasts, how can we use ARM to probe these forecasting challenges? The primary issue to be addressed is the predictability at time scales beyond the medium range weather forecasting. ARM as designed now is a Eulerian sampling system, where we stary at a place and expectation that the Taylor hypothesis holds and we can look at longer time/spatial patterns using the point datasets. One possible idea would be to consider what I would call ‘conditioned’ predictability problem, where weather conditioned by ENSO yields predictable forecasts for S2S over Western USA. There are many such predictability manifolds in global system that we could systematically address with ARM measurements that are setup in a tele-connected spaces.

Enhanced ARM Observations to Improve Energy Infrastructure, Resources, and Demand Variability and Predictability

Raghu Krishnamurthy,
Pacific Northwest National Laboratory

The white paper provides some potential ideas for ARM to align its mission with the current administration priorities. The ideas should be discussed with a larger group of scientists to assess its importance, feasibility, and DOE's interest in such topics.

1. **Supporting a DOE Digital Twin System or Speed to Power Initiative**
   Building a small modular network of key atmospheric observations incorporating all-in-one surface meteorological (met) sensors (includes bulk precipitation), Doppler Lidars (DL), Microwave Radiometers (MWR), Ceilometers (CL), surface radiation, visibility sensors, lightning detection systems, and Portable Optical Particle Spectrometer (POPs) monitoring instrumentation in proximity to energy infrastructures or urban areas could significantly improve the conversion of meteorological conditions to energy supply/demand estimates.
   Examples include:
   - **Small Modular Nuclear Reactors (SMRs):** As SMRs are increasingly planned to be located near urban areas or densely developed cities, real-time dispersion modeling and risk mitigation planning become crucial. Direct ingestion of real-time observational data into local high-resolution dispersion models, paired with robust analytics, would support decision-making and safety initiatives. This approach may appeal to the Department of Energy (DOE).
   - **Infrastructure Resiliency Modeling:** Extreme weather events, such as intense storms, droughts, fires, and floods, necessitate high-resolution infrastructure modeling using real-time observational data. This would help assess and improve resiliency for hydropower systems, solar plants, hybrid energy plants, power grid line installations, and other energy sources.
   - **Impact of Adverse Atmospheric Conditions:** Fires and smoke, fog, lightning, derechos can disrupt energy infrastructure operations. Observations paired with improved local high-resolution forecasts could support predictive systems and mitigation measures (such as deployment of micro-grids), fostering operational reliability.

   As shown in Figure 1, regions such as the mid-west and DC area are expected to have low anticipated reserve margins of power by 2030 and high growth/demand for data centers. Therefore, these regions will be heavily impacted by variability in weather conditions or extremes and would need hybrid energy systems supporting the near-term and long-term growth of energy demand.

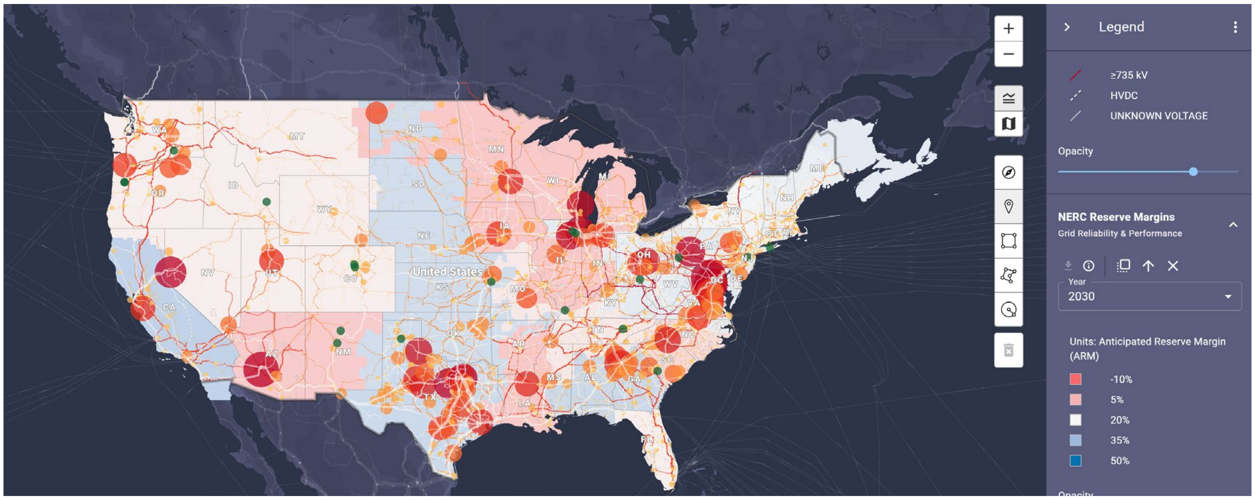

Figure 1: Anticipated reserve margins (ironically also known as ARM) in 2030 at each state (red indicating low energy reserves for supporting the grid), with overlays of total data center capacity (circles, including planned data centers at each state), and power grid lines at various regions showing interconnection lines. Data from Accelerating Speed to Power website (here).

2. **Analysis frameworks: Novel Machine Learning Techniques to Integrate Multi-Source Observations**
   Advanced machine learning approaches could be developed to efficiently merge field observations, data from polar and geostationary satellites, and numerical weather prediction outputs. Automating data collection, processing, and analysis through these techniques would ensure seamless integration, accelerating insights for energy resource management.

3. **AI-Based Cataloguing for Energy Assessment**
   Implement AI-powered systems to catalog atmospheric conditions that impact energy infrastructure. This would include extremes such as strong winds, droughts, heavy precipitation, atmospheric turbulence, and cloud conditions (e.g., stratiform versus convective states). Automated classification can identify days or events potentially critical for infrastructure assessment and planning.

4. **Data Assimilation for Enhanced Modeling Capabilities**
   Harness observational networks to support data assimilation into computational models. For example, hindcast model updates using GPU-enabled high-resolution models such as Energy Research Forecasting (ERF) or E3SM-driven LASSO modeling studies could

incorporate observational data to refine forecasts, providing enhanced predictive capabilities for energy infrastructure planning and risk management.

5. **Edge Computing Systems for Event-Based Observational Characterization**
   The development and application of edge computing systems for adaptive sampling of atmospheric observations could enhance event-based characterization. This would be particularly impactful for dynamic instruments such as radars or lidars, allowing real-time responsiveness and targeted data acquisition during critical atmospheric events. But such changes in scan patterns would impact data assimilation strategies mentioned earlier.

6. **Risk Assessment Studies Using AI-Based Synthetic Models**
   High-precision observational datasets are essential to train AI-based synthetic models for risk assessment. For instance, accurately modeling precipitation during atmospheric rivers requires deploying networks capable of measuring droplet size distributions along coastal regions. Such precision guarantees reliable risk models for extreme weather events impacting energy systems.

Elevator pitch: Observational Dome Supporting National Defense and Infrastructure Goals
Establishing an observational "Dome" aligns with the Pentagon's vision for an American Golden Dome. By integrating NEXRAD radar capabilities (Figure 2) with modular next-generation ARM instruments, this initiative could provide an interconnected system capable of monitoring critical atmospheric processes. Such a system would benefit national defense strategies while doubling as a robust framework to protect energy infrastructures from adverse weather conditions.

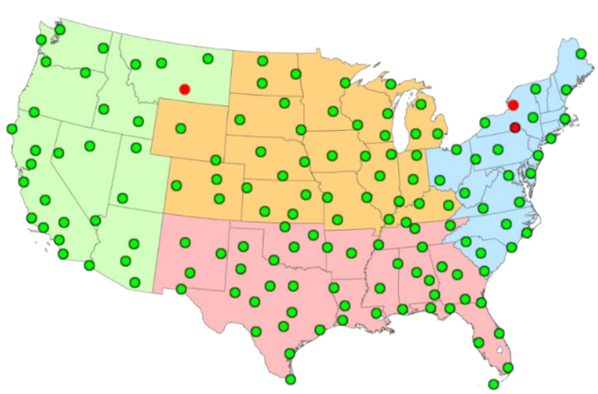

Figure 2: NEXRAD radar locations over US. Aligning with existing networks (including the state-level surface observational networks) for next generation monitoring of the of the nation's weather patterns and dynamics to enhance prediction accuracy and disaster response capabilities.

Advancing Agricultural Food & Energy Security: Confronting the Threat of Airborne Pathogen Transport and Transformation

Chongai Kuang, Tamanna Subba, Maria Zawadowicz, Robert McGraw, Scott Giangrande

Rationale: The US is advancing an agricultural crop economy for a range of uses including not only food, but also bioproducts and biofuels. These agricultural crops face increasing threats from the spread of airborne plant pathogens (e.g., fungal spores, bacterial and viral aerosol particles) and their vectors (e.g., pollen). Understanding their atmospheric transport and interactions with meteorology are essential for forecasting crop disease spread, making disease management decisions, and establishing effective approaches to mitigation - all of which are crucial components for secure and sustainable agricultural supply chains. Pathogen dispersal occurs over multiple spatial-scales ranging from plant-scale pathogen release, to subsequent spread within and between adjacent crop fields, and further to long-range transport across regions and continents. Across these scales, atmospheric process controls on pathogen dispersal include turbulent transport in plant canopies, convective transport and precipitation, and long-range aerosol transport and transformations. The ARM User Facility, with its highly instrumented and advanced surface fixed-, mobile‐ and aerial‐observatories, is well-poised to investigate these controls by leveraging ARM's extensive experience with long-term, spatially-distributed measurements and multi-scale modeling coupled with the adoption of new capabilities in biological aerosol measurement and monitoring.

Observational Approach: Desirable observational locations include agricultural areas already embedded within and around existing ARM fixed sites (e.g., SGP), agricultural areas (e.g., extension/university-managed agricultural test-beds) that are accessible by potential AMF deployments, and sites (e.g., BNF) with substantial biological aerosol activity (e.g., pollen emission/rupture, fungal spore emission/rupture) and multi-scale transport processes (e.g., canopy-driven turbulent ejection, advection, convection). Key observational time-scales range from the diurnal-scale and associated processes (e.g., RH-driven biological aerosol emission and rupture, canopy turbulent ejection) to the seasonal-scale and associated processes (e.g., spring-time maxima in phenological transitions and convective activity). Additionally, the inherent "multi-scale" nature of the threat requires a "multi-scale" approach to observation that links pathogen release, field-scale progression, and longer-range continental transport. A distributed network of profilers for atmospheric dynamics (e.g., DL, RWP), structure (e.g., CEIL, MPL), hydrometeors (e.g., cloud/precipitation radars), and aerosol "layers" (e.g., HSRL), coupled with distributed surface in-situ aerosol sensing (e.g., AOS, AOS-nodes), and mobile aerial assets (e.g., UAS, TBS) would leverage strengths of both Eulerian and Lagrangian sampling to track the emission, transport, and transformation of these biological particles from the source (e.g., infected field) to target "near-range" down-wind locations (e.g., un-infected crop fields) and deposition. Desired measurement capabilities (and institutional collaborations) beyond ARM include: satellite remote sensing (NOAA, NASA) to capture more regional-scale/continental transport, more "direct" biological aerosol sensing via holography, fluorescence, and filter-based analysis (EMSL), and measurements of biological activity/viability/speciation (JGI).

Analysis Framework: Observations would be integrated with high‐resolution transport models to simulate potential pathogen dispersion under a range of meteorological conditions to capture pathogen emission, "lift-off", transport, and deposition for model evaluation. A pollen emission and transport scheme has recently been coupled with WRF-Chem and used to simulate the emission of pollen and impacts on clouds and precipitation at SGP during a period with both pollen emissions and convective activity. Additional effort would be required for model-integration of additional pathogen-specific physiological characteristics (e.g., latent period, spore size, emission rates).

LANL White Paper Topics for ARM Workshop

Power Grid

The electrical power system is highly vulnerable to several weather variables that affect energy demand, generation efficiency, and infrastructure reliability. Severe storms—particularly winter storms, lightning, and hurricanes—can cause outages and large-scale physical damage. Coastal flooding also threatens coastal generation and transmission assets. Forecasting power outages caused by winter storms has been a significant challenge because these events, unlike hurricanes, are not well localized in space or time. Despite their diffuse nature, the impact of a major winter storm on the electrical grid can be severe, with serious consequences for energy reliability and national security.

Several meteorological and surface variables play key roles in determining the grid's vulnerability and resilience to such events. Among the most important are total precipitation, soil moisture, snowfall, temperature, wind speed, wind direction, eastward and northward turbulent surface stresses, 2-meter dewpoint temperature, convective available potential energy, mean sea level pressure, and surface pressure. Together, these variables influence not only the likelihood of power outages but also the ability of grid infrastructure to withstand and recover from extreme winter weather conditions.

In addition, temperature strongly influences both electricity consumption and equipment performance. High heat increases cooling demand, reduces the efficiency of thermal power plants, and limits transmission capacity, while extreme cold can freeze fuel supplies and damage equipment. Precipitation and hydrology also play major roles—rainfall, snowmelt, and river flow determine water availability for hydropower and for cooling thermal and nuclear plants.

Arctic Needs

In addition to sea ice extent and thickness, Arctic navigation and offshore resource development will depend on operational hazards associated with fog and icing on ships and offshore platforms. Fog formation depends on air temperature, humidity, moisture supply, wind speed and turbulence, and cloud cover. Icing of ships and infrastructure is controlled by air temperature, wind speed, humidity, and precipitation. Wind speed also strongly influences wave development and sea spray formation.

Snow cover on the North Slope has a significant influence on the timing and feasibility of exploration and extraction of oil and gas resources on land. Snow depth depends heavily on air moisture content, which is influenced by both local moisture sources, such as the Arctic Ocean, and large-scale atmospheric patterns. Air temperature, radiation, and the deposition of dark aerosols all influence the onset and melting of snow cover on land.

Advancing Hydrometeor Identification and Precipitation Type Forecasting for Energy System Resilience Using ARM Observations

Zachary J. Lebo, Associate Professor, School of Meteorology, University of Oklahoma

1. Atmospheric Processes Relevant to Energy Security and Model Uncertainty

Accurate representation of microphysical processes, particularly those controlling hydrometeor type and precipitation phase, is critical for understanding and forecasting weather-driven energy system vulnerabilities. Transitions between liquid and solid precipitation are often poorly captured in Earth system models (ESMs) of all scales, including even the highest-resolution weather prediction models, leading to uncertainty in forecasts of ice accretion, snow loading, and hail occurrence. These deficiencies have direct consequences for energy infrastructure. For example, freezing rain leads to ice accumulation on power lines and wind turbine blades; heavy wet snow can bring down trees and transmission lines; hail can damage solar panels and turbine blades; and mixed-phase precipitation events challenge surface maintenance, aviation safety, and grid reliability.

These impacts are especially pronounced in U.S. regions prone to rapid temperature transitions or mixed-phase precipitation, including the southern Great Plains, Midwest, and Appalachian regions, as well as coastal and mountainous transition zones. Moreover, in the context of a changing climate, precipitation type will inevitably change, and predicting how and when precipitation types will change is paramount to identifying vulnerable energy systems and providing stakeholders time to prepare and mitigate risk. ***Improved understanding of the microphysical pathways governing hydrometeor formation, growth, and phase changes is therefore essential for enhancing both predictive capability and energy resilience.***

2. Needed ARM Measurements and Deployment Strategies

ARM's suite of active and passive sensors provides an exceptional foundation for studying precipitation microphysics, but targeted enhancements and deployments could significantly improve the community's ability to characterize hydrometeor type and phase. High-priority measurement needs include:

- Collocated multi-frequency polarimetric radar observations (e.g., X-, Ka-, and W-band) to better distinguish hydrometeor type, shape, and phase.
- Vertically pointing Doppler radars and lidars for observing hydrometeor fall speeds and identifying melting layers and supercooled liquid layers.
- In situ microphysical instruments, such as disdrometers, precipitation imaging probes, and multi-angle snowflake cameras, to validate radar-based hydrometeor classification.
- Surface precipitation-type sensors for distinguishing rain, freezing rain, sleet, and snow in mixed-phase conditions.
- Aerial measurements (e.g., UAS or tethered balloons) in mixed-phase and icing conditions to directly observe liquid water content, droplet spectra, and ice habits.

Strategic deployments of these instruments during winter weather campaigns or transitional season events in the central and eastern U.S. would yield ***invaluable datasets to constrain model***

microphysics and precipitation-type parameterizations, to develop and improve model parameterizations, and thus provide a benchmark for models used to predict precipitation phase both in the short term and long term.

3. Data Products and Frameworks to Support Model Development

To fully leverage these observations, ***integrated data products and modeling frameworks are needed***. ARM could support model development through the following avenues:

- Creation of comprehensive hydrometeor classification datasets, combining radar polarimetric signatures, surface disdrometer data, and in situ particle imagery.
- Expansion of LASSO-style case studies for precipitation phase transitions, designed to benchmark microphysics schemes in models such as SCREAM and E3SM, as well as for the broader community.
- Development of machine learning-based precipitation type retrievals that fuse radar, lidar, and surface data to improve process representation.
- Establishment of scalable observation–model comparison frameworks bridging the 100 m–10 km range, ideal for evaluating ESM microphysics at process-resolving scales.

Such coordinated observational and modeling efforts would enable ARM to play a central role in reducing uncertainty in precipitation microphysics, directly improving energy system resilience to ice, snow, and hail events.

4. Summary and Vision

ARM's unique observational capabilities position it to lead the next generation of atmospheric process studies linking microphysics and energy resilience. Enhanced hydrometeor and precipitation-type observations, integrated with modeling, machine learning, and data assimilation frameworks, will strengthen our understanding of how small-scale microphysical processes translate to large-scale energy impacts. By targeting these research priorities, ARM can substantially advance predictive understanding of high-impact winter and convective precipitation, ultimately supporting more robust and adaptive U.S. energy systems.

- What are examples of atmospheric processes that represent significant risks to energy security and where are those risks greatest?

Processes involved with severe and high impact weather represent the biggest risks to energy security, including winter storms parallelizing the power grid (Texas storms), hurricanes (e.g., possibility of damage to refineries in coastal areas), heat waves (inability to meet nation's power requirements). These risks seem to be inherent to the entire nation, with coastal areas perhaps the most prone given sea level rise and the enhanced impact of flooding.

- What measurements or measurement strategies would improve ARM's capacity to address these issues?

ARM currently has observations at fixed sites and deployments of the mobile facility at select locations at varying times. Currently ARM does not have measurement strategies that are sufficiently flexible to move assets to locations severe and high impact weather is expected to impact. There is some predictability, about on a 1-week scale, to time periods where flooding, winter storms or heat waves are expected to hit. Could ARM's capacity be improved so that it would either have aircraft resources of a quickly-deployable mobile ground-based platform to travel to areas where this weather is expected to hit. This would somewhat follow the model that is currently used for limited-duration field campaigns, but would differ in that the possibility for quick deployment of resources would be available year-long. Part of the analysis of such collected field campaign data involves machine learning and artificial intelligence to search out parameters that most control generated properties, as well as determining those relations. The use of AI should allow for quicker analysis of datasets than has hitherto been possible.

- How can ARM and users of the ARM facility better work with the E3SM and multi-sector modeling communities to apply ARM data to improving E3SM simulations of these phenomena?

Modeling needs to continue to be a central component of ARM moving forward. The need to get more observations in undersampled regions corresponding to severe and high impact weather should help improve parameterizations of cloud microphysics, boundary layer, radiation in these undersampled regions. It is still poorly known how universal parameterizations are, and getting data that can test parameterizations, model performance and remote sensing retrievals in these undersampled regions is needed. It is also critical that modelers need to be developed at the formative stage of all observational campaigns in order to get data that is most needed to confront the models.

White Paper

Leveraging ARM Data to Improve Models for Predictive Understanding of Energy and Security Challenges

John R. Mecikalski
29 October 2025

The following is developed in response to the request for ideas related to the topics below, which I feel most qualified to address given my research experience. I do not have a significant amount of background knowledge in atmospheric aerosols, so will not address that topic.

Topic Answers:

What data products and/or analysis frameworks or methodologies would allow ARM data to more efficiently support earth system model development to address these phenomena?

To address this topic, given my needs to co-locate low-Earth orbiting (LEO) and geostationary satellite imagery and associated products to ARM site locations (e.g., SGP, BNF), an idea for ARM to focus development are on tools and open source algorithms that can perform temporal and spatial matching of these two datasets. Specifically, assuming the scenario of 5-min satellite fields from GOES-18 (West) or -19 (East), or 90-min data from a LEO sensor, it would be helpful to have tools that perform the tasks of temporally matching those datasets to point ARM site ground location instruments, and also to perform temporal averaging of 30-sec to sub-60 min resolution ARM observations to the timing of LEO overpasses and geostationary images. In addition, and of importance, is the need within these tools to perform spatial averaging of satellite imagery (visible, infrared and microwave) channel data and associated derived products (e.g., cloud-top height, cloud fraction) over some region so they can be statistically related to the point ground observations. For example, over a 5-min timeframe between CONUS GOES-19 images, one would be able to time and space integrate the ARM datasets in a manner that allows for the subsequent matching of those time series to the statistical patterns observed in satellite imagery. Admittedly, much more direction would be needed toward forming a tool that would serve the broader community needs, which I can discuss further in the ARM Workshop.

What are examples of atmospheric processes which are relevant to energy system or security vulnerability that represent a source of uncertainty in earth system models and which ARM can usefully inform, what is the associated impact to energy systems, and where is this most likely to occur in the United States?

Toward addressing the area, I feel there is a need to continue to enhance understanding of land surface fluxes, specifically from forest and other ecosystems down to the leave, stem/trunk and ground surface. In humid regions that experience a large amount of convective storm related rainfall, with more widespread forests, a large amount of sensible heat can be stored within the forest canopy, which alters evapotranspiration, longwave cooling, lower level boundary layer structure, and atmospheric stability. The AMF3 site in the Bankhead National Forest would seem like a good location for instrumentation that could be sited to address this topic area. The impacts would be relevant to the Eastern U.S. Without good understanding on how heat and moisture fluxes behave over complex land surfaces, poor NWP model forecasts of warm season high impact are more likely.

The energy system in the U.S. includes the electricity industry (bulk power generation, transmission, and distribution of electricity—see Figure 1) as well as industries dedicated to the mining and distribution of primary fuels (e.g., oil, gas, coal). The energy system is vulnerable to extreme weather events such as droughts, heat waves, cold snaps, hurricanes, wildfires, and flooding (see, e.g., Zamuda et al. 2023 and Figure 2) as well as to non-stationarity in atmospheric processes (e.g., higher average temperatures, lower average rainfall). Energy system vulnerability manifests in the form of the inability of energy system resources to meet energy demands at the necessary time and place due either to insufficient resources, higher than expected demands, or both. Electricity demands need to be met instantaneously. Oil and gas pipelines and storage facilities need to be operational to deliver fuel to power plants or to homes (e.g., an oil-fired furnace) to meet energy demands. Water is necessary for most thermoelectric generation cooling processes and for mining of oil and gas. Water availability is crucial for hydropower generation. Extreme events can damage or disrupt energy supplies and seasonal anomalies, such as drought, can compound with shorter term extremes, such as heat waves, that not only reduce energy supplies but also increase energy demands. Inter-annual variability in weather results in annual bulk power production cost variations of +/-15% in the Western U.S. (Voisin et al. 2018). This variability is primarily associated with hydrological droughts. Extreme events like wildfires and hurricanes can also result in abrupt, local, and more costly disruptions. Floods and wildfires cost system operators billions of dollars every year (NCEI 2025).

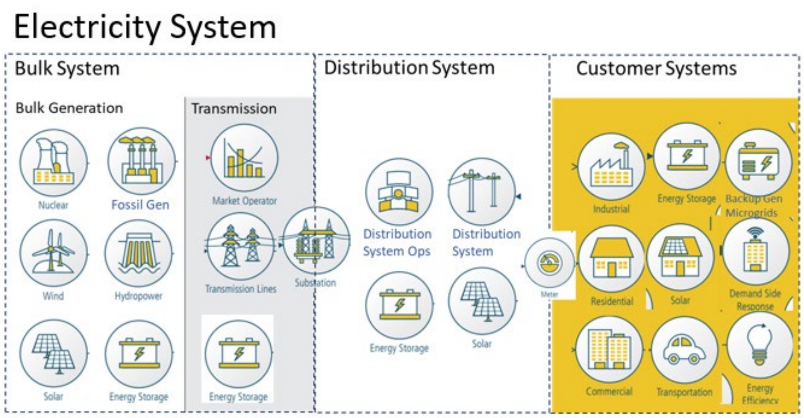

Figure 1. The electricity system is made up of three primary components: bulk, distribution, and customer systems. https://www.energy.gov/sites/prod/files/2017/02/f34/Appendix--Electricity%20System%20Overview.pdf

Predictability of these events and shifts is crucial for the energy sector. And the predictability that is needed spans sub-seasonal to decadal. For example, when the energy sector faces a decision on new infrastructure investment, it needs to understand the likelihood of that infrastructure being damaged due to extreme weather during the investment lifetime, typically 30-50 years. If future peak demands could exceed historical experience (e.g., due to increasing severity of heat waves), infrastructure investment decisions need to understand the likelihood of future temperature extremes over the lifetime of the collective investments in the energy system. For operational decisions, the predictability needs to be on shorter time scales to manage energy storage and maintenance schedules for dispatchable power generation. For example, what is the likelihood of compound renewable energy droughts (reduced hydro, wind, and solar availability) within each year and during what part of the year. What is the likelihood these could happen simultaneously with demand spikes due to heat waves? In the western U.S. this is particularly crucial due to the large penetration of renewable resources in the electricity generation mix.

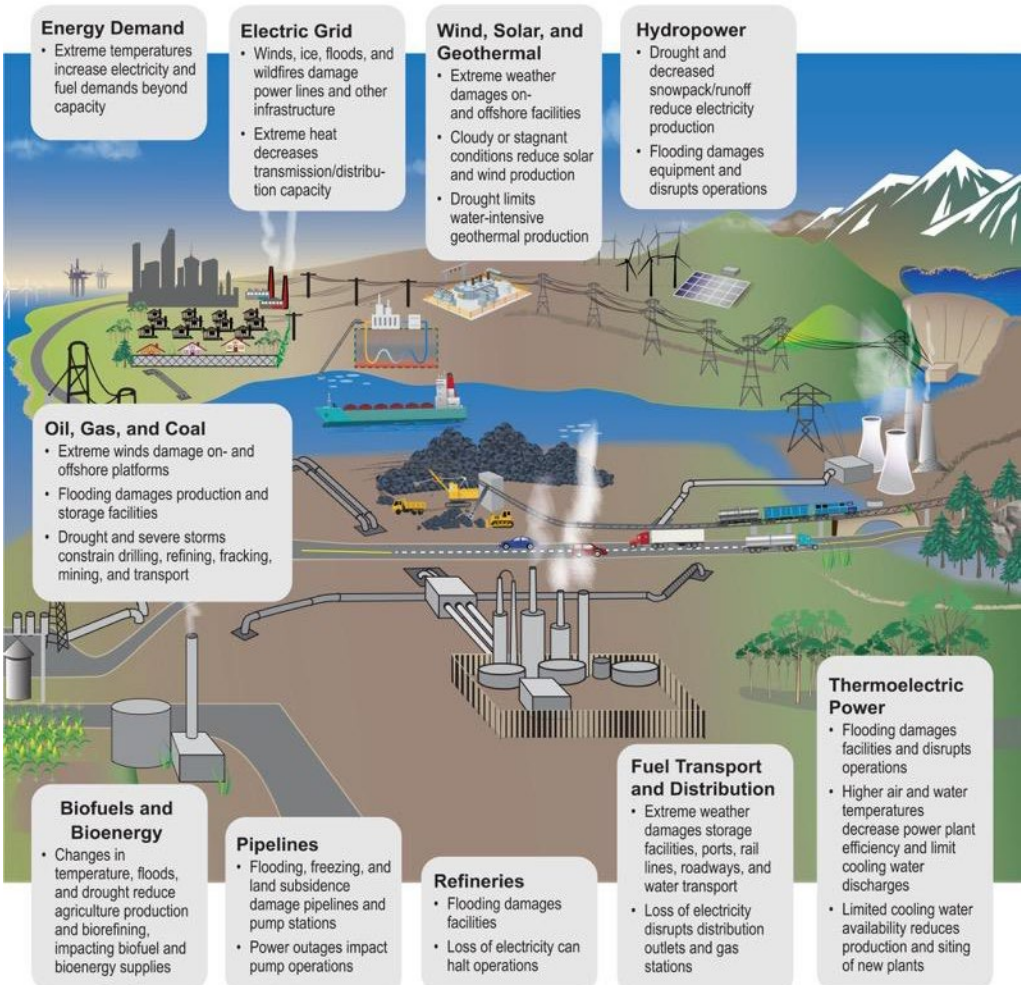

Figure 2. Energy Abundance and Reliability Depend on Human-Earth System Interactions (Zamuda et al. 2023)

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Sandia National Laboratories

Opportunities to Bridge DOE ARM Infrastructure and Data to Global Model Projections to Improve Energy Security across the Continental United States

Erika L. Roesler (elroesl@sandia.gov)

A White Paper for the DOE ARM Workshop on Leveraging ARM Data to Improve Models for Predictive Understanding of Energy and Security Challenges

October 2025

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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To increase American Energy Dominance[1], community-level energy resilience and infrastructure durability and strength need to be understood under meteorological stressors and disruptive events. The Office of Science and Technology Policy priorities include enhancing “capabilities for anticipating, preventing, responding to, and recovering from threats and natural disasters.” [2] For increased understanding, significant research and development investment is needed. The following are suggested ways in which the Department of Energy’s Atmospheric Radiation Measurement (ARM) User Facility can provide valuable data to improve energy security and resilience.

To begin assessing energy risk to the communities within the United States, first identify the areas that have reoccurring power outages. As shown in Figure 1, the Eastern and Coastal United States has the most reported power outages. Causes of these outages should be documented and parsed between meteorological disturbances and other causes.

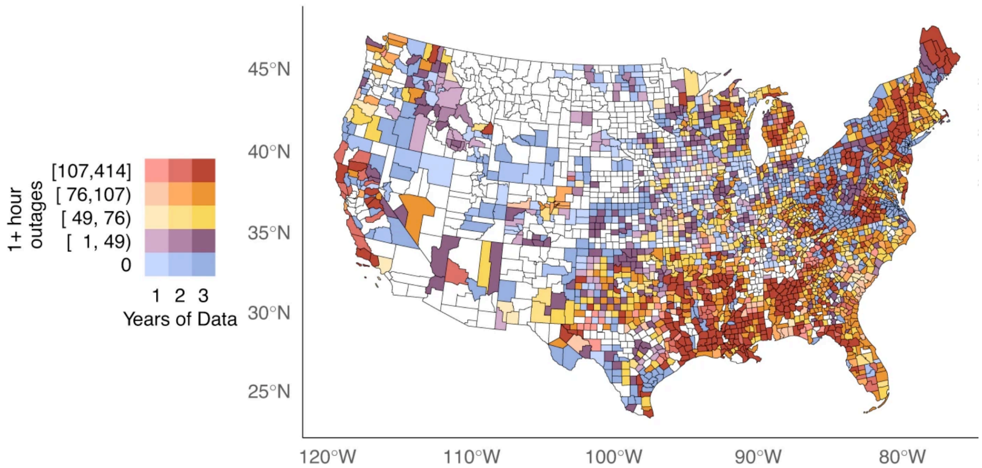

Figure 1: From Do. et al (2003), “Counties shaded in white lacked any reliable data. Geographic distribution for county-level yearly average of 1+ hour outage events. Power outage data was purchased from PowerOutage.us and county basemaps were obtained from the usmap R package version 0.6.1.”[3]

ARM has data collection sites in and near these outage locations. ARM’s Mobile Facility 3 (AMF3) is currently deployed in Bankhead National Forest collecting data since 2024, has had data collection with CoURAGE in Baltimore and in the future with DUSTIEAIM in Phoenix, and ARM’s permeant site near Lamont, Oklahoma as the Southern Great Plains site collected decades of data, near other National Weather Service (NWS) and NOAA sites. The second recommended step to assess energy risk would be to work with ARM’s Infrastructure team to quantify the durability of the instruments and data collection during these outages. The data streams coming from ARM before, during, and after meteorological disruptive is valuable to understanding any changes and impacts from a process level to extremes, as ARM has multidecadal data and able to measure changes.

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[1] “Strengthening the Reliability and Security of the United States Electric Grid,” The White House, April 8, 2025, https://www.whitehouse.gov/presidential-actions/2025/04/strengthening-the-reliability-and-security-of-the-united-states-electric-grid/.

[2] “FY27-OMB-OSTP-RD-Priorites-Memo-FINALSIGNED.Pdf,” n.d., accessed October 27, 2025, https://www.whitehouse.gov/wp-content/uploads/2025/09/FY27-OMB-OSTP-RD-Priorites-Memo-FINALSIGNED.pdf.

[3] Vivian Do et al., “Spatiotemporal Distribution of Power Outages with Climate Events and Social Vulnerability in the USA,” *Nature Communications* 14, no. 1 (2023): 2470, https://doi.org/10.1038/s41467-023-38084-6.

The third recommended step to use ARM data for improving understanding of energy security would be to utilize LASSO actively over ARM sites, hindcasting meteorological events when power outages occurred. The benefit of using a high-resolution model such as LASSO is that differing modules and parameterizations can be tested for veracity against hail, icing, strong winds, and convective events. Model to model comparison and a hierarchy of model workflow would then need to be established as the fourth step to link the Single Column Model version of E3SM to then SCREAM and then E3SM.

Performing this work would give ARM the power of knowing what data collection might be missing to improve understanding around power outages, which then could be fed into ARM data products, LASSO, and then E3SM. For a seasonal to decadal time scale, understanding the risks to energy and security from atmospheric phenomena can be improved through global models, seeing teleconnection patterns, pre- and post- event patterns. This framework is shown in **Figure 2**. Cycling and frequently communication with liaisons would be needed between each of these elements to ensure success, building understanding with 3-5-10 year goals and milestones.

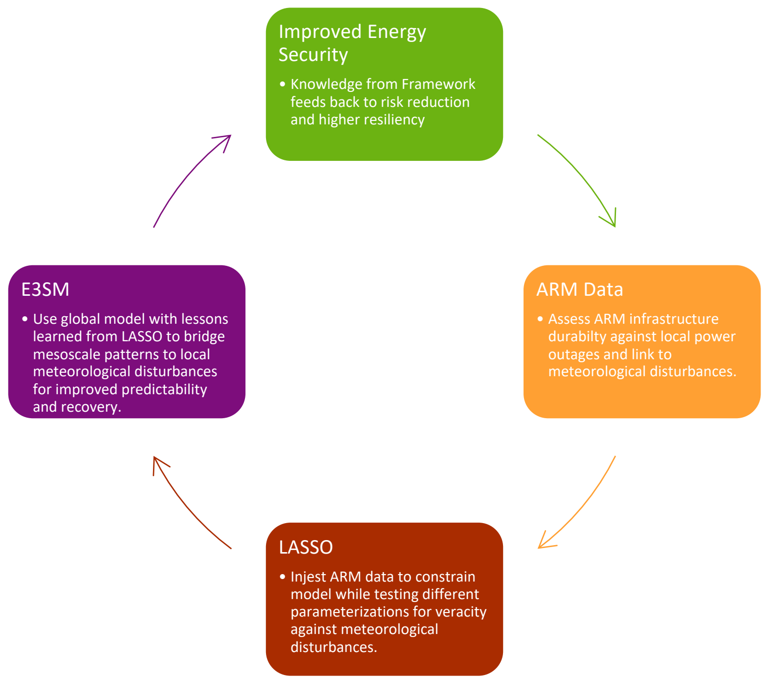

Figure 2: Proposed Framework to use ARM Data and a model hierarchy from LASSO to E3SM to improve predictability of power outages and increase energy security.

White paper for the ARM workshop on "Leveraging ARM Data to Improve Models for Predictive Understanding of Energy and Security Challenges"

David M. Romps, University of California, Berkeley

October 26, 2025

Since the request for white papers is relative to "energy *and* security challenges," I have chosen to focus on the latter since nuclear security represents one of DOE's most important missions, and it is one to which ARM could make key contributions.

DOE's one-sentence mission statement includes "strengthen[ing] the Nation's prosperity and security by addressing... nuclear challenges through transformative science." As part of DOE's Strategic Objective 14 ("Forge solutions that enable global security and stability"), DOE's NNSA is tasked with "respond[ing] to nuclear and radiological incidents and accidents worldwide." As I argue here, ARM is well-positioned to enable advances in two key areas within this mission: the forecasting of radioactive fallout from nuclear incidents and accidents, and quantifying the potential global dimming and food insecurity caused by nuclear firestorms.

DOE's involvement in the science of radioactive fallout and remaining sources of uncertainty

DOE's National Nuclear Security Administration (NNSA) has, under its umbrella, several centers, programs, and groups related to the operational forecasting of radioactive fallout. The most public-facing of these is the National Atmospheric Release Advisory Center (NARAC) at LLNL, which is responsible for issuing real-time fallout forecasts. In addition, the Nuclear Security Modeling Group (NSMG) at ORNL develops science that informs the parameterizations within the NARAC models. The NNSA interfaces with DHS's Federal Radiological Monitoring and Assessment Center (FRMAC) and FEMA's Interagency Modeling and Atmospheric Assessment Center (IMAAC) to coordinate the response to nuclear incidents.

The key to an efficient and well-coordinated response is having accurate forecasts of the transport and fallout of radioactive material. For this purpose, NARAC runs two main models. The first is the Atmospheric Data Assimilation and Parameterization Technique (ADAPT), which generates a reanalysis of the meteorological state. The second is the Lagrangian Operational Dispersion Integrator (LODI), which is a dispersion model that calculates the transport of radioactive material. The LODI model relies on various parameterizations that inject a great deal of uncertainty and forecast error. For example, the LODI model uses Briggs-style parameterizations of the thermal rise of nuclear mushroom clouds and firestorm plumes (Leone Jr et al., 2001; Nasstrom et al., 2007), which perform poorly in evaluations (Raffuse et al., 2012). The LODI model also relies parameterizations of settling velocities and the interaction of particles with cloud microphysics, all of which remain highly uncertain. It is noteworthy that these are all relatively local meteorological processes that ARM, with its world-class fixed facilities and mobile facilities, is well-positioned to study.

DOE's involvement in the study of nuclear winter and remaining sources of uncertainty

DOE has long been engaged in the study of the potential for nuclear conflict to trigger a global dimming of sunlight, leading to lowered temperatures and multi-year crop failure, colloquially referred to as nuclear winter. In the 1980s, LLNL formed the Global Effects of Nuclear War Study Project, and LLNL and LANL scientists published studies on the phenomenon (e.g., MacCracken, 1983; Jones and Malone, 1985). This work within the NNSA laboratories continues to the current day (e.g., Reisner et al., 2018). In fact, for the recent 2025 report of the National Academies of Sciences, Engineering, and Medicine, titled “Potential Environmental Effects of Nuclear War” (NASEM, 2025), three of the fifteen main authors are scientists at DOE laboratories.

NASEM (2025) identifies research needs in several areas to which ARM is well-positioned to contribute: “fire and atmospheric chemistry and cloud–aerosol interactions; validation with observational data” and the “[i]nteractive effects of aerosol on UV, PAR, and diffuse vs. direct radiation.” And NASEM (2025) notes that “[t]he emissions from nuclear detonation fires depend critically on plume dynamics, where injection height—determined by factors such as fuel loading, fire area, and conditions—dictates the severity of any environmental impacts.” These major sources of uncertainties stem from relatively local processes, occurring on spatial scales amenable to study using ARM’s fixed and mobile assets.

ARM’s potential contributions to the forecasting of fallout and solar dimming

ARM has recently facilitated the study of plume-rise dynamics (Öktem et al., 2026) using data collected during the TRACER campaign (Jensen et al., 2025). Similarly, the CACTI campaign studied convection triggered by elevated heating of the Sierras de Córdoba mountain range (Varble et al., 2021). A collaboration between NNSA and the Office of Science on the study of plume-rise dynamics, direct aerosol effects of soot, and soot transport could involve the deployment of ARM assets to Sandia’s Lurance Canyon Burn Site (LCBS). Such a joint effort of NNSA and the Office of Science could move the forecasting of radioactive dispersal and soot lofting beyond the Briggs-style parameterizations currently in use.

ARM already has a world-class coordinated effort in the study of aerosol-cloud interactions that could be harnessed to advance the study of those interactions involving gas-phase radionuclides and associated aerosols, larger radioactive fallout particles, and sunlight-blocking soot. With regards to the effects of soot on radiation, ARM has a rich history of studying the effect of clouds and aerosols on direct versus diffuse radiation, including, e.g., the recent Small-Scale Variability of Solar Radiation (S2VSR) campaign (Deneke et al., 2024), which deployed 60 pyranometers to the SGP site. And, with ARM’s recent diversification into Urban Integrated Field Laboratories, there is a strong case for ARM to be playing a leading role in the study and forecasting of atmospheric dispersal in urban environments. At major ARM sites, the atmospheric transport of radionuclides could be refined using the release of perflourocarbon tracers (PFTs), aiding the development of the next generation of NARAC’s models.

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Leveraging ARM to Support Understanding of Ice Storms

Paul Ullrich
Lead of Earth-Energy System Resilience
Lawrence Livermore National Laboratory

The 1998 January Ice Storm affected millions across the northeastern United States and eastern Canada. In total, the storm dropped up to 100 mm of frozen precipitation in some areas, clinging to energy infrastructure and downing over 1,000 transmission towers. Power was out for many for days to weeks, and 34 fatalities were directly attributable to the storm. Since 2000, high-impact ice storms in the United States have occurred regularly, sparing few regions east of the Rocky Mountains. Many regions remain vulnerable to these events – in March of 2025, a major ice storm that impacted Northern Michigan damaged 3 million acres of forest and left over one million residents without power.

Despite events like the 1998 January Ice Storm posing a significant risk to energy infrastructure throughout the United States, these events are poorly simulated in regional and global Earth system models because of deep sensitivities in the microphysics under the environmental conditions necessary for these storms. There is further a poor understanding of the broader environmental conditions responsible for ice storms. Atmospheric Radiation Measurement (ARM) observations in conjunction with high-resolution model simulations, could lead to better representation of freezing rain, hail and other types of winter storms. Vertical profiles of environmental conditions prior to, during and following frozen storms could provide important data to tune and validate model simulations of frozen precipitation.

ARM observations of frozen storm events could complement other efforts in the Office of Science. Recent work under the US DOE HyperFACETS project from Cornell University has sought to build a dataset of frozen precipitation events across the United States, leveraging Automated Surface Observing System (ASOS) measurements, primarily drawn from airports. Further, at Pennsylvania State University, machine learning methods have been developed to identify the risk of freezing rain events in model output using simulated environmental conditions.

One issue with an ARM deployment to meet this need is the relative rarity of such events and the large geographic area that is vulnerable to their occurrence. Unfortunately, the likelihood of an ARM deployment being directly hit by a frozen precipitation event is low, unless observations could be quickly repositioned to intercept storms prior to their arrival.

Whitepaper for the ARM workshop titled "Leveraging ARM Data to Improve Models for Predictive Understanding of Energy and Security Challenges"

Yunyan Zhang, Lawrence Livermore National Laboratory

1. *ARM's mission is to provide data to inform the improved understanding of atmospheric processes to support the representation of those processes in earth system models. What are examples of atmospheric processes which are relevant to energy system or security vulnerability that represent a source of uncertainty in earth system models, and which ARM can usefully inform, what is the associated impact to energy systems, and where is this most likely to occur in the United States?*

Mesoscale convective system (MCS) is one of the dominant contributors to extreme precipitation events. The emergent next generation of models, such as global storm-resolving models (GSRMs), explicitly simulate deep convective motions at kilometer scale resolution and showed great capability in representing MCS, which is missing in traditional coarse resolution models. However, recent studies showed GSRMs tend to underestimate the size of precipitation clusters, especially related to the lifecycle of MCS, the so-called "popcorn" convection issue.

In the past and recent observations of ARM, MCS was often measured with vertical pointing and scanning radars, even with retrievals of vertical velocities especially for heavy precipitating MCS, e.g., during GoAmazon. ARM's SGP and BNF facilities are already in very nice locations for observing MCS passages.

Other processes such as mixed-phase cloud liquid-ice partition during cold air outbreak (CAO) also showed large model biases of underestimate of supercooled liquid which leads to significant impacts on surface energy balance, especially the large scale cold air temperature extreme during autumn and winter seasons. ARM did have observations on these processes, such as COMBLE field campaign, NSA, and MOSAiC.

In addition, frequent occurrence of Pacific Northwest extreme events, such as atmospheric river induced strong precipitation/flood and wildfire induced aerosol, clouds and radiative feedback, would have strong implications on infrastructure and power grid planning. Urban heat island and urban-rural differences especially during heat/cold wave events, could also be very interesting topics along this line, and hopefully CouRage field campaign could lead to process studies in this area.

2. *For relevant atmospheric processes (such as those listed in the introduction), what additional measurements are needed? These could include specific instruments or deployment strategies for instruments (could include specific ground-based instruments, networks of instruments, or aerial measurements).*

As global models are approaching kilometer or its regionally refined modes into sub-kilometer resolution, ARM's high-resolution data become even more relevant in model assessment and diagnosis. For example, statistics of cloud morphology or precipitation features based on individual clouds or convective cells and their ensemble behaviors. Coupled with EMC^2 radar/lidar simulators may even make such comparisons in a more consistent way. If model physics keeps improving towards solving the "popcorn" problem, can ARM data provide such statistics to help quickly diagnose model performance?

To constrain specific parameterized processes, e.g., the turbulence scheme, continuous w'^2, w'theta', w'q', the turbulent variances and fluxes are needed. For microphysics, vertical profiles of liquid water content, ice water content, CCN and IN are needed, especially for mixed-phase boundary layer clouds.

For land-atmosphere interaction, a network would be great for different land cover/use or topographies, including surface fluxes and PBL/cloud profiling. This network should be focusing on a scale of heterogeneity around 1 to 25 km range with near surface measurements of fluxes and turbulence (maybe using UAVs) in the lowest 100 meters.

3. *What data products and/or analysis frameworks or methodologies would allow ARM data to more efficiently support earth system model development to address these phenomena?*

Here is a strategy THREAD project adopted, hopefully may serve as a starting point for discussion.

1) Enrich and update ARM case library with prototypes of convective regimes, especially those with "mesoscale" variabilities that GSRM can resolve or partially resolve now. Main purpose is to quickly diagnose model biases for improvement of SCREAM using DP-SCREAM.
The E3SM SCM/DP-SCREAM case library is at link to the SCM/DPxx library

   - Bogenschutz, P.A., Y. Zhang, X. Zheng, Y. Tian, M. Zhang, L. Lin, P. Wu, S. Xie, C. Tao, 2025: Exposing Process-Level Biases in a Global Cloud Permitting Model with ARM Observations, Journal of Geophysical Research – Atmospheres, 130, e2024JD043059. https://doi.org/10.1029/2024JD043059
   - Tian, Y. and Y. Zhang, 2025: Factors controlling precipitation onset and maintenance: inferences from large eddy simulation of two contrasting deep convective cases observed during the GoAmazon field campaign. Geophysical Research Letters, 52, e2024GL113920. https://doi.org/10.1029/2024GL113920

2) Global or Regionally refined validations against ARM observations or LASSO simulations with fully coupled E3SM land model to diagnose SCREAM performance. We have completed RRM simulations for CACTI, GoAmazon, EPCAPE, TRACER; we have completed validations of RRM at COMBLE, BNF, SGP, MAGIC, more detailed simulations are ongoing. In addition, we created RRM meshes and are planning on CouRage RRM runs.
All these are included into the library of RRM cases of E3SM.

   - Su, T., Y. Zhang, H.-Y. Ma, A. Varble, P. Bogenschutz, 2025: Convective Biases in the US DOE Global Storm-Resolving Model: Insights from Regionally Refined Simulations During the CACTI Campaign. Journal of Geophysical Research – Atmospheres, submitted.

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3) Use ARM Data or LES to help with model calibration

- Zhang, Y., T. Su, H. Tang, P. Bogenschutz, S. A. Klein, C. Jackson, P. Caldwell, 2025: Process-oriented calibration of a turbulence scheme in the DOE's global storm-resolving model using machine learning. Geophysical Research Letters, submitted.

4) Use ARM Data to build machine learning models targeting on PBL development and PBL-coupled clouds, which will serve as model diagnosis or maybe push for machine-learning based diagnostic modules for models

- Su, T. and Zhang, Y., 2024: Deep-learning-driven simulations of boundary layer clouds over the Southern Great Plains, Geosci. Model Dev., 17, 6319–6336, https://doi.org/10.5194/gmd-17-6319-2024
- Su, T. and Zhang, Y., 2024: Deep-learning-derived planetary boundary layer height from conventional meteorological measurements, Atmos. Chem. Phys., 24, 6477–6493, https://doi.org/10.5194/acp-24-6477-2024

Automated Event-Triggered Intensive Observations at ARM Permanent Sites for Blocking Systems and Mesoscale Convective Systems (MCSs)

Xue Zheng, LLNL (zheng7@llnl.gov)

ARM Sites of Emphasis: Southern Great Plains (SGP) and Bankhead National Forest (BNF) — **no additional field-campaign planning required**

Core idea. Leverage ARM's permanent sites, harden key instruments for extreme conditions, and implement an **automated event-triggered intensive observation protocol (Auto-IOP)** so blocking and MCS events are captured repeatedly over multi-year periods. The resulting, consistent datasets help reduce **near-surface model biases** in **E3SM/SCREAM** toward a digital testbed for S2D planning.

Motivation & energy-security relevance

Persistent blocking systems and organized MCSs cause prolonged heat/cold, icing, flooding, and large swings in energy load and generation. These regimes remain difficult for models—even at km scale—especially for near-surface temperature/humidity, radiation, boundary-layer structure, and convective organization. An always-ready, **automated** capability at SGP and BNF systematically captures more events with consistent instrumentation and protocols, improving constraints without ad-hoc campaigns.

Target phenomena & modeling gaps

- **Blocking systems (SGP/BNF frequently affected):** Quasi-stationary highs or wave patterns yield heat domes, extreme cold, drought, and icing. *Model gaps:* PBL entrainment/mixing, radiative and cloud feedbacks, and soil-moisture/vegetation coupling. *Outcome:* reduced warm/cold and radiation biases over the central U.S., especially during blocks.
- **Mesoscale convective systems (warm-season Plains; cool-season Southeast):** Models struggle with initiation, nocturnal maintenance/propagation, cold-pool dynamics, and coupling with the low-level jet and land surface. *Outcome:* improved timing, track speed, stratiform fraction, and precipitation efficiency.

Auto-IOP at permanent sites

- **Automated triggers (no manual planning):** Forecast- and observation-based thresholds (blocking indices; LLJ/shear/CAPE proxies; radar/lidar signatures) switch sites from baseline to **intensive** mode for the event duration.
- **Intensive sampling mode:** Radiosonde **autolaunchers** (hourly–3-hourly as warranted); storm-mode dual-pol radar schedules; expanded 0–2 km profiling via Doppler lidar, radar wind profilers, microwave radiometers, and frequent soundings; tethered balloons/UAS as standing capabilities subject to safety rules.
- **Extreme-ready continuity:** Ruggedized enclosures for heat/cold/icing/high winds; resilient power/comms; automated QC/recovery to preserve uptime during extremes.
- **Heterogeneity & microphysics/radiation constraints:** Densify flux towers and soil networks near SGP/BNF; add **disdrometers** and hydrometeor imagers; deploy **Raman/DIAL** water-vapor profiling for CAPE/CIN and moisture convergence; maintain

continuous surface/column radiation. **Value-added products (VAPs)** co-locate fluxes, radiation, PBL height, profiles, and precipitation on common time–height grids.

Linking observations to models

- **Event libraries & hindcasts:** Curated multi-year Auto-IOP cases for blocks and MCSs paired with **E3SM** hindcasts and short-range ensembles for systematic evaluation.
- **Bias diagnostics tied to energy metrics:** Object-based verification for MCS initiation/propagation/stratiform structure and blocked-regime duration/intensity; scorecards for 2-m temperature/RH, surface radiation, PBL height, and precipitation relevant to S2D planning.

Impact

Shifting from episodic campaigns to automated, site-based intensive observations lets ARM maximize existing infrastructure and build statistically robust, event-centric datasets for blocking and MCSs. This directly helps reduce near-surface and PBL biases, improves representation of convective organization and land–atmosphere coupling, and advances **E3SM** toward a dependable **digital testbed for S2D energy-resilience planning**.

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