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# Desert-Urban System Integrated Atmospheric Monsoon (DUSTIEAIM) in the Southwestern United States Science Plan

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June 2025

ARM

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# Executive Summary

The Desert-Urban System Integrated Atmospheric Monsoon (DUSTIEAIM) campaign is a groundbreaking, high-impact scientific mission that will transform how we understand and respond to energy and water challenges in one of America's fastest-growing and most heat-stressed urban regions: Phoenix, Arizona. Starting in April 2026, this 18-month field campaign harnesses the full power of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility and an interdisciplinary science team including national laboratories, universities, and agencies with a broad range of subject-matter expertise. With cutting-edge instruments, active and passive ground-based sensors, radars, and integrated modeling, DUSTIEAIM will deliver the most comprehensive environmental data set ever collected for a desert-urban-agricultural interface.

DUSTIEAIM is a mission-critical investment in the future of U.S. cities and their interactions and dependence on energy systems. DUSTIEAIM will redefine how we model urban-land-atmosphere interactions, monsoon storms, and aerosol-cloud interactions. Observations to enhance model development can pinpoint vulnerabilities in Phoenix's energy grid and water systems, and provide decision-makers with science-backed insights to design resilient infrastructure for the Southwest U.S. The campaign will advance DOE's mission in energy innovation, grid reliability, and security, and enhance high-performance computing and artificial intelligence capabilities to keep the United States at the forefront of this technological revolution. The data and insights DUSTIEAIM generates will shape science and inform decision-making for the next generation.

# Abstract

DUSTIEAIM is planned to collect data from April 1, 2026, through September 30, 2027. The first ARM Mobile Facility (AMF1) will operate for 18 months at the Main Site, located within the Phoenix metropolitan area on the Arizona State University-West Campus. The focus of this project is to characterize interactions between the land surface and the atmosphere over a desert megalopolis (Phoenix) set in complex topography. We will interrogate the interaction between precipitation events, storms, and aerosol in the context of spatial contrasts at the urban interface with agricultural and drylands in the Sonoran Desert. The AMF1 will collect observations to understand the radiative properties, aerosol interactions, cloud formation, and precipitation in Arizona. In summer 2026, additional synergistic data collection will take place in the region by the U.S. Department of Energy Office of Science Southwest Urban Integrated Field Laboratory (SW-IFL) project that focuses on extreme heat and related hazards in urban environments. DUSTIEAIM's science focus is to quantify the bimodal water cycle during the winter and summer, and energy budgets at the urban/rural/agricultural interface of the southwestern U.S. as regional air masses and meteorological patterns change throughout the year in response to the seasonal cycle, including winter Pacific storms, atmospheric rivers (AR), and the North American Monsoon (NAM). We propose to do this with three science objectives and four testable hypotheses within each science objective.

Phoenix is the fifth-largest metropolitan statistical area (MSA) in the U.S. with ~5 million residents and is a leading hub for industrial growth and development where energy resilience is crucial. The spatial footprint is also very large, spanning approximately 50-80 km across depending on direction. Phoenix was the fastest-growing large city in the U.S. in 2024 (~2% growth rate), which has increased power demand and strain on the power grid, especially in the summer. It is America's hottest major city and set new records in 2024, one being 113 consecutive days with temperatures above 100 °F. The Phoenix metropolitan area depends on the Colorado River for 38% of its water, a source that has seen decreases in flow, partly due to rising demands and the sharing of which is currently under renegotiation to ensure stability for the system. Phoenix is surrounded by high terrain to the north and east that receives winter snow and monsoonal rain that are essential for replenishing the groundwater supply in and around Phoenix.

The hot summer months coincide with the NAM when the thermal low over the Southwest U.S. draws in moisture primarily from the Gulf of California, some of which is released in thunderstorms during late afternoon and evening. While most monsoonal precipitation falls over the mountains, Phoenix occasionally experiences heavy rain that can lead to flash floods, microbursts, and dust storms called haboobs. Lightning can spark intense fires in the higher-elevation forests where the storm's cold pool outflow creates erratic wind gusts and dangerous fire conditions. Smaller-scale processes remain understudied and lack in situ observations: for example, how aerosols from different sources interact with the boundary layer, convection, and surface energy balance. For all these reasons, now is the time to collect atmospheric observations to fill current data gaps and improve the understanding of atmospheric interactions with the land surface, the water cycle, and the power infrastructure in the southwestern United States.

# Acronyms and Abbreviations

| | |
|---|---|
| AAF | ARM Aerial Facility |
| ACSM | aerosol chemical speciation monitor |
| AERI | atmospheric emitted radiance interferometer |
| AI | artificial intelligence |
| AMF1 | first ARM Mobile Facility |
| AOS | Aerosol Observing System |
| AOSMET | meteorological measurements associated with AOS |
| APS | aerodynamic particle sizer |
| AR | atmospheric river |
| ARM | Atmospheric Radiation Measurement |
| ASCII | American Standard Code for Information Interchange |
| ASI | all-sky imager |
| a.s.l. | above sea level |
| ASOS | Automated Surface Observing System |
| ASR | Atmospheric System Research |
| ASU | Arizona State University |
| ASUW | Arizona State University-West Campus |
| AZMET | Arizona Meteorological Network |
| BAMS | *Bulletin of the American Meteorological Society* |
| BC | black carbon |
| BL | boundary layer |
| BNF | Bankhead National Forest |
| CACTI | Cloud, Aerosol, and Complex Terrain Interactions |
| CAP | Central Arizona Project |
| CBL | convective boundary layer |
| CCN | cloud condensation nuclei, cloud condensation nuclei counter |
| CMAS | Center for Multiscale Applied Sensing |
| CMAQ | Community Multiscale Air Quality Modeling System |
| CMIP6 | Coupled Model Intercomparison Project Phase 6 |
| Co-I | co-investigator |
| CONUS | continental United States |
| COURAGE | Coast-Urban-Rural Atmospheric Gradient Experiment |
| CSAPR2 | C-band Scanning ARM Precipitation Radar, 2$^{nd}$ generation |
| CuPIDO | Cumulus Photogrammetric, In Situ and Doppler Observations |
| DIAL | differential absorption water vapor lidar |

| | |
|---|---|
| DOD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DUSTIEAIM | Desert-Urban System Integrated Atmospheric Monsoon |
| E3SMv2 | Energy Exascale Earth System Model Version 2 |
| EC | eddy covariance |
| ECOR | eddy correlation flux measurement system |
| EESSD | Earth and Environmental Systems Sciences Division |
| EPA | Environmental Protection Agency |
| ESA | European Space Agency |
| ESCAPE | Experiment of Sea Breeze Convection, Aerosols, Precipitation and Environment |
| FAA | Federal Aviation Administration |
| GNDRD | round radiometer on stand for upwelling radiation |
| HPC | high-performance computing |
| HSRHI | hemispherical range height indicator |
| IMPROVE | Interagency Monitoring of Protected Visual Environments |
| INS | ice nucleating spectrometer |
| IOP | intensive operational period |
| IRT | infrared thermometer |
| LANL | Los Alamos National Laboratory |
| LD | laser disdrometer |
| LDIS | laser disdrometer |
| LT | local time |
| M1 | Main Site |
| MET | surface meteorological instrumentation |
| ML/AI | machine learning and artificial intelligence |
| MoM | Model-of-Models |
| MPAS | Model for Prediction Across Scales |
| MPL | micropulse lidar |
| MSA | metropolitan statistical area |
| NAM | North American Monsoon |
| NAME | North American Monsoon Experiment |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Center for Atmospheric Research |
| NEPH | nephelometer |
| NetCDF | Network Common Data Form |
| NEXRAD | Next-Generation Weather Radar |
| NOAA | National Oceanic and Atmospheric Administration |
| NSF | National Science Foundation |

| | |
|---|---|
| NWS | National Weather Service |
| PACE | Plankton, Aerosol, Cloud, ocean Ecosystem |
| PBL | planetary boundary layer |
| PI | principal investigator |
| POC | point of contact |
| PPI | plan position indicator |
| PSAP | particle soot absorption photometer |
| QA | quality assurance |
| QC | quality control |
| RHI | range-height indicator |
| RWP | radar wind profiler |
| S2 | Secondary Site |
| SAIL | Surface Atmosphere Integrated Field Laboratory |
| SEBS | surface energy balance system |
| SIRS | solar and infrared radiation station for downwelling and upwelling radiation |
| SKYRAD | sky radiometer on stand for downwelling radiation |
| SO | Science Objectives |
| SO2 | sulfur dioxide monitor |
| SP2 | single-particle soot photometer |
| SPLASH | Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology |
| STORMVEX | Storm Peak Lab Cloud Property Validation Experiment |
| SW-IFL | Southwest Urban Integrated Field Laboratory |
| TDR | tail Doppler radar |
| TEMPO | Tropospheric Emissions: Monitoring of Pollution |
| TRACER | Tracking Aerosol Convection Interactions Experiment |
| UAV | uncrewed aerial vehicle |
| UHSAS | ultra-high-sensitivity aerosol spectrometer |
| U.S. | United States |
| U.S. AID | United States Agency for International Development |
| UTC | Coordinated Universal Time |
| VAD | Velocity Azimuth Display |
| VAP | value-added product |
| VCP | volume coverage pattern |
| VDIS | video disdrometer |
| WB | weighing bucket precipitation gauge |
| WRF | Weather Research and Forecasting Model |
| WRF-Chem | Weather Research and Forecasting (WRF) model coupled with Chemistry |

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# 1.0 Background

The DUSTIEAIM campaign is designed to study how urban and desert regions influence Earth energy systems, specifically, convection and precipitation around Phoenix, especially in relation to the North American Monsoon (NAM). The Phoenix MSA is located in the Sonoran Desert, lowlands downstream of mountains that receive the brunt of the cold-season and monsoonal precipitation. This precipitation is essential for replenishing the groundwater supply in and around Phoenix (Phillips et al. 2004) and the reservoirs on the Salt and Verde Rivers (the main watersheds supplying water to Phoenix). The NAM can also deliver devastating flash floods (Saharia et al. 2017) when deluges fall on dry, impermeable soils and over steep terrain (e.g., Hong et al. 2012).

Given the rapid population growth and development plans for new data centers in the Phoenix MSA, the NAM impacts on the lives of American citizens, energy infrastructure, real estate, and industrial property and development are likely to increase with time. Since 2010, Arizona has suffered >$3 billion in damages from extreme weather, 96% of which was from thunderstorms and floods (Bakkensen and Johnson 2017). It is also America's hottest major city and set two new records in 2024 with 113 consecutive days with temperatures above 100 °F, and 70 days total with temperatures above 110 °F. In addition to the extreme summer heat, there are open questions about water availability. Last year the state proactively limited construction around Phoenix due to dwindling groundwater supplies that have little if any recent recharge, which is why the Central Arizona Project (CAP) transports Colorado River water to the region. Approximately two-thirds of Phoenix's water supply is derived from the mountains north and east of the city, watersheds that are mostly within Arizona, and one-third from the distant upper Colorado River basin.

Regional and global models to predict future impacts to energy resilience, increased energy demand, natural resources, and undue burdens on American energy do not fully capture the NAM and associated weather extremes including thunderstorm intensity, timing, and location (Adams and Comrie 1997, Castro et al. 2012, Luong et al. 2018). Global models also predict an increase in water vapor and precipitation over the past four decades that has not been observed (Simpson et al. 2024). This brings into question the validity of water and natural energy resource predictions for the Southwest and predicted impacts for energy security now and in the future.

DUSTIEAIM will start collecting data on April 1, 2026, continuing through September 30, 2027, to cover two summers and one winter. The duration of the campaign will enable investigation of the impacts of heat, flooding, and weather extremes on American family and business needs for future energy resilience, increased demand, and projected growth. The first ARM Mobile Facility (AMF1) will operate at the Main Site, located within the western Phoenix metropolitan area on the ASU-West Campus, one of the most anticipated areas for industrial growth in Phoenix. The radar site, north of the MSA (Figure 1), will enable detailed scanning profiles over the MSA, including the Main Site, to capture critical precipitation and boundary-layer circulations. An additional intensive site for studying airborne particulates will be sought to provide enhanced information on particle sources and impacts to regional energy systems.

The science team includes 20 experts in particle microphysics, analytical chemistry, high-performance computing, machine learning and artificial intelligence (ML/AI), model integration, atmospheric transport, particulate processes, water isotopes, land-atmosphere interactions, radiative impacts, and data analysis, visualization, integration, interpolation, and transformation. Affiliations of the science team include members from four DOE national laboratories (Argonne [ANL], Brookhaven, Los Alamos, Pacific Northwest [PNNL]) and nine universities (Arizona State University [ASU], Colorado State University, Embry Riddle Aeronautical University, University of California-Merced, University of California-San Diego, University of Miami, University of New Mexico, University of Wyoming). Each science objective and the modeling effort is led by a scientist from a different national laboratory and includes a team of three to four university scientists with subject-matter expertise and contributions in each: land-atmosphere is led by Katia Lamer at BNL, aerosol processes by Allison Aiken at LANL, precipitation processes by Adam Varble at PNNL, and process modeling by Yan Feng at ANL. Synergistic activities with the DOE-sponsored SW-IFL are coordinated by Jean Andino at ASU, who is on the DUSTIEAIM science team and is the SW-IFL Deputy Director. ASU's West Campus will coordinate with ARM Operations to support the AMF1 deployment. Collaborating agencies include the National Weather Service (NWS), the Air Force Weather Agency within the Department of Defense (DOD), the Federal Aviation Administration (FAA), and the National Oceanic and Atmospheric Administration (NOAA) for the Next-Generation Weather Radar (NEXRAD) data that will complement coverage from ARM scanning radars, and the U.S. Environmental Protection Agency (EPA) and DOD that operate monitoring stations in Arizona to enhance DUSTIEAIM data collection efforts. Additional DUSTIEAIM agency collaborations are being planned; interested collaborators and scientists are encouraged to reach out to ARM and the science team if they are interested in being involved in coordinating those efforts.

# 2.0 Scientific Objectives

DUSTIEAIM has three interrelated science objectives (SO#1-SO#3) that use ARM facilities, SW-IFL observations, and other long-standing collaborative resources, e.g., ground stations from the Flood Control District of Maricopa County and NEXRAD weather radars. Campaign data will improve process-level understanding by answering the overarching Science Objectives (SO) and four testable hypotheses (Section 5.3) within each SO:

- **SO#1: Land-Atmosphere Interactions and Impacts:** Determine how the urban-rural interface of the Phoenix MSA affects the surface energy balance, the boundary layer, energy demand, and related atmospheric processes within the Sonoran Desert.
- **SO#2: Aerosol Processes and Interactions with Clouds and Radiation:** Identify what aerosol sources and processes dominate seasonally in Phoenix and evaluate how well Earth system models capture their local and regional impacts on clouds, radiation, and American energy sources.
- **SO#3: Precipitation Processes:** Evaluate how orographic, surface, and aerosol processes intersect with larger-scale meteorological variability to affect spatial and temporal precipitation patterns in and around the Phoenix MSA and when energy distribution and infrastructure are affected.

Each SO remains unanswered without the detailed atmospheric observations we are proposing. By systematically scaling aerosol-cloud-precipitation data and sub-grid scale mechanisms, DUSTIEAIM will provide data to refine model parameterizations and predictive skill within this complex, aerosol-laden region, a water-stressed urban-agricultural-desert interface. Mesoscale convective systems and complexes will be a focus to monitor and model as their microphysical properties (e.g., lightning, hail, wind, microbursts, extreme precipitation) may impact existing and new plans for energy infrastructure and data centers.

# 3.0 Measurement Strategies

DUSTIEAIM will take place in Phoenix, Arizona, MSA, as shown in Figure 1. The 18-month deployment coincides with Water Year 2026-2027 (Oct. 1, 2026-Sept. 30, 2027) with three intensive operational periods (IOPs): (1) 2026 summer monsoons (June 22-September 30) overlapping with the SW-IFL IOP, (2) winter season precipitation and atmospheric rivers (November 1, 2026-March 31, 2027), (3) 2027 monsoons (July 1-September 30). The sampling period is designed to capture the bimodal precipitation regime in central Arizona (winter precipitation from Nov.-March and NAM from July-Sept.). The IOPs will capture the onset, evolution, and demise of the NAM with the opportunity to sample different convective regimes in central Arizona. Two consecutive summer IOPs are requested because of the large interannual variability of NAM intensity and the uncertain frequency of events that can dramatically modify atmospheric particles in the region, including ARs, haboobs, and wildfires. AMF observations will provide unprecedented opportunities to study monsoon convective processes in desert areas and their interaction with sources of heat, moisture, particles, and pollutants from urban sources. Complementary and coincident efforts will be coordinated to provide a more synoptic, regional view of monsoon convective processes and to characterize conditions at main and supplementary sites within the area surrounding the MSA (see Sections 3.8 and 3.9 for more detail.).

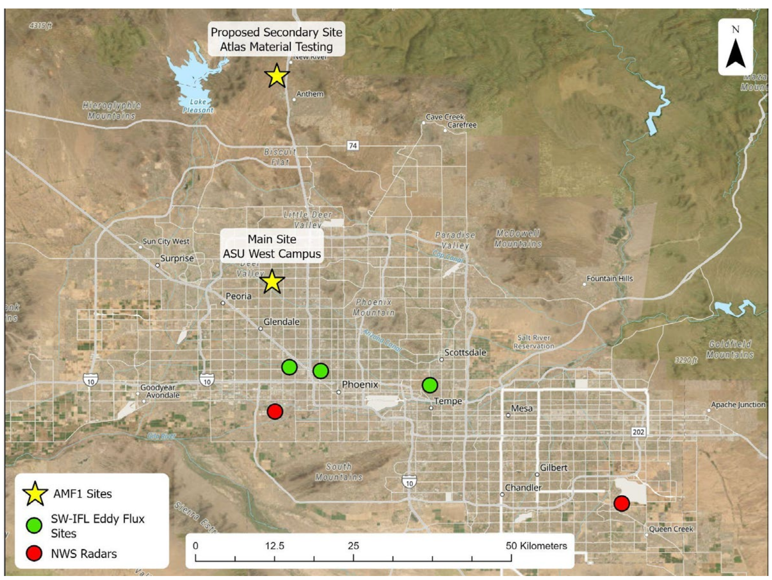


**Figure 1**. Map of the Phoenix metropolitan area with the AMF1 Main Site (M1) shown at ASU-West Campus in Glendale, Arizona and the Secondary Site (S2) for the C-band Scanning ARM Precipitation Radar, 2nd generation (CSAPR2) shown as yellow stars. Green dots indicate the SW-IFL eddy flux tower sites that are registered with AmeriFlux. Red dots indicate the NWS radars.

## 3.1 Main Site

Deployment of AMF1 at the Main Site will be on a secured location at ASU-West in Glendale, Arizona in the northwestern corner of Phoenix MSA (Figure 1). ASU-West is located at 388 m above sea level (a.s.l.) and is favorable for capturing the evolution of convective storms, which tend to travel from higher terrain to the north and east. It is also well suited to capture the impact of the Phoenix metro area on the convective boundary layer (CBL), since the prevailing flow is from the south in both seasons, especially during moist conditions. During cold season precipitation events, this site is also appropriate to sample aerosol profiles of CBL air advected into orographic clouds. Due to limited development at the proposed main site, a large parcel of vacant land, approximately 350 m by 500 m, is available for the deployment of AMF1 containers and field instrumentation. Figure 2 shows the proposed layout of the instruments at the main site, and Table 1 lists the instruments that will be deployed.

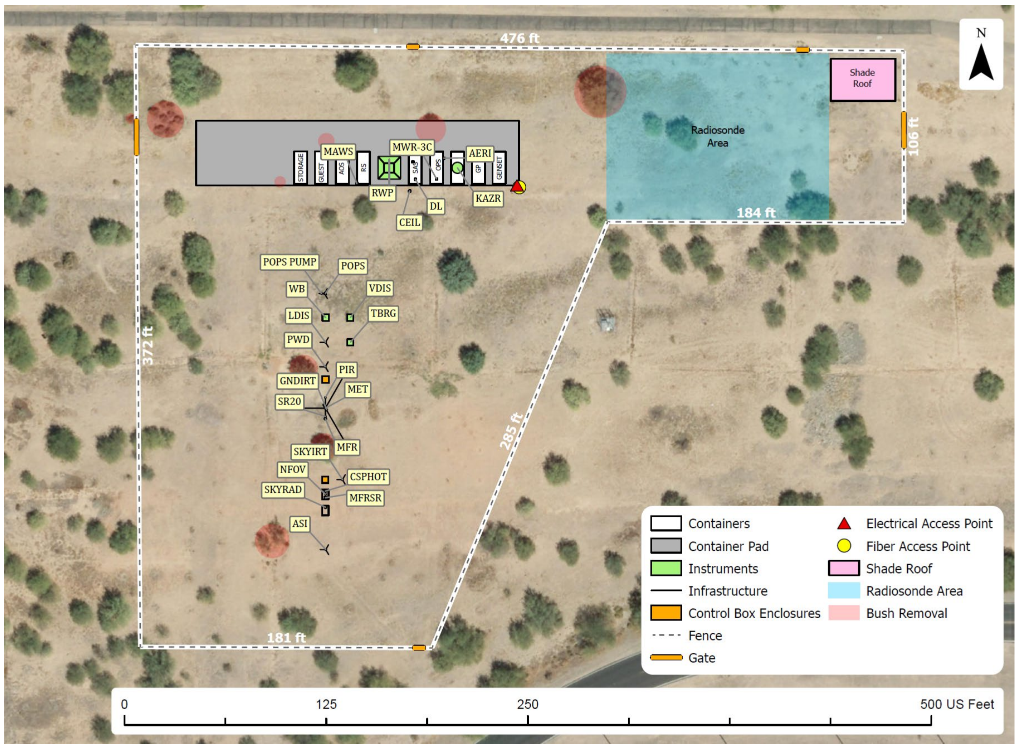


Figure 2. Proposed Main Site layout on ASU-West Campus in Glendale, Arizona at approximately 33°36' N 112°09' W. Containers shown along the top/north in white and field instruments running from north to south across the field.

**Table 1.** Main Site (M1) instrumentation.

| ARM Acronym | Short Description |
|---|---|
| AOS+ | Aerosol Observing Systems |
| AETH | aethelometer |
| APS | aerodynamic particle sizer |
| CCN-200 | cloud condensation nuclei counter |
| CO-Analyzer | carbon monoxide analyzer |
| CPCF | condensation particle counter-fine |
| CPCU | condensation particle counter-ultrafine |

| ARM Acronym | Short Description |
|---|---|
| IMPACTOR | impactor (1 um and 10 um) |
| AOSMET | Meteorological Measurements Assoc. with AOS |
| NEPH | nephelometer (dry) |
| O3 | ozone monitor |
| PSAP | particle soot absorption photometer |
| SMPS | scanning mobility particle sizer |
| SO2 | sulfur dioxide monitor |
| UHSAS | ultra-high-sensitivity aerosol spectrometer |
| AERI | atmospheric emitted radiance interferometer |
| ASI | all-sky imager |
| CAM | camera |
| CEIL | ceilometer |
| CSPHOT | Cimel sunphotometer |
| DIAL* | differential absorption water vapor lidar |
| DL | Doppler lidar |
| ECOR | eddy correlation flux measurement system |
| ExtLidar* | extinction lidar |
| GNDIRT | ground infrared thermometer |
| GNDRAD | ground radiometers on stand for upwelling radiation |
| INS | ice nucleation spectrometer |
| IRT | infrared thermometer |
| KAZR | Ka-Band ARM Zenith Radar |
| LD | laser disdrometer |
| MAWS | automatic weather station |
| MET | surface meteorological instrumentation |
| MFR | multifilter radiometer |
| MFRSR | multifilter rotating shadowband radiometer |
| MPL | micropulse lidar |

| ARM Acronym | Short Description |
|---|---|
| MWR3C | microwave radiometer – three-channel |
| NFOV | narrow field of view zenith radiometer |
| POPS* | portable optical particle spectrometer |
| RWP | radar wind profiler |
| SEBS | surface energy balance systems |
| SKYRAD | sky radiometers on stand for downwelling radiation |
| STEREOCAMs* | stereo camera technology |
| SONDE | balloon-borne sounding system |
| WB | weighing bucket precipitation gauge |
| VDIS | 2-dimensional video disdrometer |

*requested

## 3.2 Supplementary Sites

One Supplementary Site (S2) will be placed near New River, Arizona at Atlas Material Testing, approximately 33° 53' N 112° 09' W. This site is safe, operationally supportable, and approximately 40 km driving distance from the Main Site (see Figure 1). The New River site is 32 km north of the Main Site, enabling radar scans using the CSAPR2 at New River over the Main Site at ASU-West and towards the mountains to the northeast of the Phoenix MSA. The elevation of the site is 637 m a.s.l. Beam blockage analysis was done by ARM Operations and the DUSTIEAIM science team as a part of the site selection and to ensure data collection is optimized for the location.

Installation of the CSAPR2 is planned for September 2025 to include a six-month onsite testing period for the new radar before the official start of the campaign. Additional measurements at S2 include the ECOR, laser disdrometer, surface meteorological instrumentation, MFRSR, SEBS, and a solar and infrared radiation station for downwelling and upwelling radiation (SIRS). The addition of a Doppler lidar is requested to support land-atmosphere interaction science, specifically the impact of land use gradient on planetary boundary-layer (PBL) properties across the two ARM sites.

A second Supplementary Site will be evaluated for deployment of additional aerosol instrumentation since S2 is non-ideal for the aerosol process science goals related to understanding regional sources, processing, and growth across the Phoenix MSA.

**Table 2**. Supplementary Site (S2) Instrumentation.

| ARM Acronym | Short Description |
|---|---|
| CSAPR2 | C-Band Scanning ARM Precipitation Radar |

| ARM Acronym | Short Description |
|---|---|
| DL* | Doppler lidar |
| ECOR | eddy correlation flux measurement system |
| INS | ice nucleation spectrometer |
| LD | laser disdrometer |
| MET | surface meteorological instrumentation (includes tipping bucket and optical rain gauge, and a present weather detector) |
| MFRSR | 7-channel multifilter rotating shadowband radiometer (same channels as MFR) |
| POPS* | portable optical particle spectrometer |
| SEBS | surface energy balance system |
| SIRS | solar and infrared radiation station for downwelling and upwelling radiation |
| STEREOCAMs* | Stereo camera technology |

*requested

## 3.3 Measurements

The major resources for this campaign are included within AMF1 and are focused on standard meteorological instrumentation, broadband and spectral radiometers, remote-sensing measurements (lidars and radars), and the AOS. ARM instrumentation included are the AOS, Ka-band Scanning ARM Cloud Radar, ceilometer, MPL, AERI, surface meteorological instrumentation, rain gauge or precipitation instrumentation, Doppler lidar, video disdrometer, multifilter rotating shadowband radiometer, microwave radiometer, and radiosondes. The DIAL and extinction lidar are requested for water vapor and aerosol profiling. The AOS includes the SMPS, ACSM, CCN, APS, nephelometer, ozone monitor, UHSAS, sulfur dioxide monitor (SO2), single-particle soot photometer (SP2), aethalometer, PSAP, INS, and AOSMET to help with simulating radiative fluxes using aerosol data, including absorption.

**Critical**: The aerosol chemical speciation monitor (ACSM) details non-refractory aerosol chemistry and will be used to identify sources and atmospheric aging of particles. The INS will be used to study variations in ice nucleating particle abundance and activity that can affect development of ice in supercooled clouds. We request biweekly or weekly collections with the option for additional sampling during IOPs. The SP2 will provide black carbon measurements from urban and biomass burning aerosol sources. Doppler lidar (boundary-layer flow, aerosol and heat transport), ceilometer (cloud base height, PBL height, aerosol vertical distribution), disdrometer (for KAZR calibration for quantitative precipitation retrievals), and MWR (constraint for precipitation onset studies) measurements will also be made.

**Important**: The CSAPR is important for studies related to precipitation and convective cloud characterization. Two NEXRAD radars operate near the Phoenix Metro: the KIWA radar, located near Phoenix-Mesa Gateway Airport 60 km to the SE of the proposed AMF main site and the KFSX radar located in Flagstaff 139 km NE of the proposed AMF Main Site on the Mogollon Rim at 2290 m elevation. Given the topography of the region, the NEXRAD radars suffer from significant low-level blockage leaving gaps in their data sets. For this reason, the CSAPR will collect important data for studies related to precipitation and convective cloud characterization. The CSAPR2 at the Supplementary Site north of Phoenix serves not only as a low-level gap-filling radar, but also provides much better resolution and higher sensitivity compared to the NEXRAD network. The CSAPR2 volume coverage pattern and scan sequence is defined in support of DUSTIEAIM objectives, for example, RHIs in the direction of the AMF Main Site. The DIAL will provide boundary-layer water vapor profiles, which cannot be determined off the surface using other techniques with sufficient accuracy. The ExtLidar observations will be used to retrieve aerosol particle types within the boundary layer. The ExtLidar provides independent vertically resolved retrievals of aerosol extinction and backscattering at 532nm, depolarization at 532 and 1064 nm, and aerosol backscattering at 1064 nm. Unlike MPL, it measures backscattering and extinction without prior assumptions about the lidar ratio. This capability eliminates the main source of systematic errors of aerosol extinction from elastic backscatter lidars such as MPL and enables the identification of aerosol types in the column.

**Nice to Have**: Additional characterization of aerosol size distributions at the Main and Supplementary Site that cover the coarse mode, such as can be made with an APS, open-path sensor, POPS-net, etc., and that could be located with the field measurements and/or adjacent to the ARM AOS, e.g., on the roof, when collocated with the AOS, would be nice to have. Such measurements are also not available anywhere in existing networks. Collection and archiving of filter-based aerosol samples would be useful for single-particle analysis that could be completed during or after the campaign.

STEREOCAMs, if deployed, can characterize cloud top height and width of convective clouds through stereo photogrammetry from multiple (at least two) angles. Two stereo cameras would need to be deployed at each site pointing toward each other with 50 km as the maximum separation. A second option would be to use three focused over the Main and/or Supplementary Site to map cumulus over that site.

## 3.4 Intensive Operational Periods

DUSTIEAIM will have three seasonal coordinated intensive operational periods (IOPs): June 22-September 30, 2026 (Summer 1), November 1, 2026-March 31, 2027 (Winter), July 1-September 30, 2027 (Summer 2). During IOPs, two additional radiosondes will be launched in addition to the standard two radiosonde launches per day during the non-IOP periods, for a total of four per day. Standard launch times will be 12 and 00 UTC (5 AM and 5 PM LT) to coincide with operational radiosonde timing. The additional radiosondes will be offset by 3-6 hours from the standard launch times depending on the timing of forecasted events of interest such as monsoon storms moving into and initiating over Phoenix (often in the evening) and atmospheric rivers (variable timing and duration).

- IOP 1 (Summer Monsoons): June 22, 2026-September 30, 2026
- IOP 2 (Winter Precipitation): November 1, 2026-March 31, 2027
- IOP 3 (Summer Monsoons): July 1, 2027-September 30, 2027

IOP-mode additional launches are also requested during vertical profiling campaigns, e.g., during ARM tethered balloon sonde deployments. Event-based launching will be conducted during the IOPs when there are forecasted periods for convection and dust storms. During those periods, two additional launches a day at a time determined based on forecasting will be conducted.

**Science justification for additional sondes during IOPs**: Precipitation events in the Phoenix MSA are relatively short-lived. Additional radiosondes are needed to better characterize the environment in which these short-lived events develop.

While the annual mean total precipitation at Sky Harbor (near the AMF main site) is just 183 mm (7.2’’), the mean rainfall intensity (when raining) is comparable to that of several U.S. MSAs in wetter regions, such as Chicago. For example, modeling results from Brandi et al. (2024) show four wind regimes: 1) Morning transition 8:00 LT, 2) Peak anabatic 11:00 LT (SW winds), 3) Evening transition 19:00 LT (westerly winds), and 4) Peak katabatic 6:00LT. The modeling results also show that the impact of urbanization on wind speed is maximum along a W-E transect through downtown Phoenix, along a SW-NE transect. The DOE SW-IFL team also noted the frequent occurrence of a notable wind direction and speed shift at 23-24 LT in the urban center.

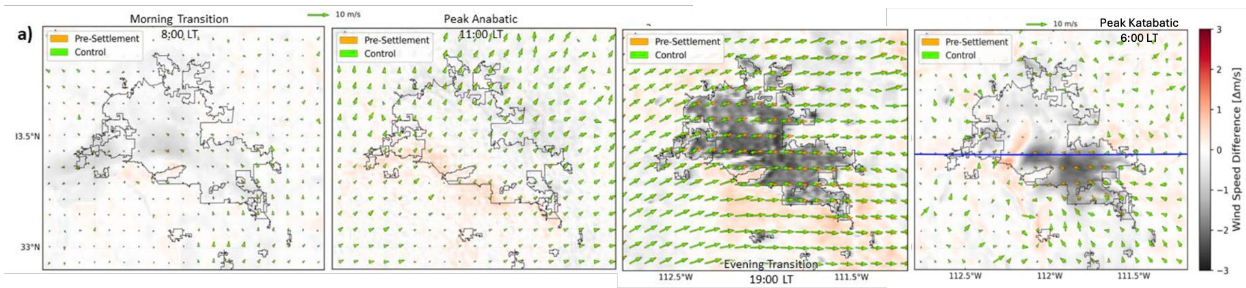


**Figure 3**. Simulation results from Brandi et al. (2024) showing wind patterns (green arrows) for Phoenix under modern land use and land cover conditions.

## 3.5 Radar and Lidar Scanning Strategies

Phoenix and surrounding areas are covered by  operational radars including one NEXRAD on the southeast side of the metro area, one NEXRAD on the Mogollon Rim, and a tail Doppler radar (TDR) just west of downtown Phoenix. The combination of these radars provides excellent surveillance of precipitation and gust fronts over Phoenix and upslope regions between Phoenix and the Mogollon Rim, where precipitation maximizes. Such coverage frees up the CSAPR2 to perform targeted research scans. The CSAPR2 will be located at S2, approximately 32 km north of the AMF1 location at M1. The science team will work with ARM staff to finalize optimal CSAPR2 scanning radar strategies. Listed here are the scanning priorities:

- -Range-height indicator (RHI, surface to zenith) scans in multiple directions between SW and SE directions that encompass the metro area, with one scan precisely over M1, is priority. Plus, two RHI scans in the up-valley (Black Canyon) direction, towards the north. Such scans would provide extremely detailed evolution of diurnal katabatic flow, as well as precipitation, sub-cloud-base evaporation, and cold pool outflows including haboobs affecting Phoenix and M1. The S2 site is also located so that it can observe diurnal Black Canyon flows interacting with the metro area when sufficient clear-air echoes exist. We also are considering balancing these RHI scans with hemispheric RHIs to give the northward canyon view integrated with southward views. It would be ideal if these were at consistent azimuths so the data is easier to use later and to integrate with modeling efforts. The radar science team will figure out how to balance the number of azimuths with sequence time length with input and advice from ARM radar engineers.

- Volume coverage pattern (VCP, 360 degrees azimuth) at multiple elevation angles, between 0.5 and at least 6.5 degrees (above the highest blocking terrain and encompassing the depth of the urban boundary layer) to examine the detailed structure of precipitation within the region of most interest (~70 km radius), including other near-metro upslope regions north and east of Phoenix. The uppermost elevation angle should be limited given the operational radars in the area that can help to fill that in with the RHIs, which will improve temporal resolution of CSAPR. The angles used will be determined based on testing done onsite once the radar is installed and running. For example, we should not operate below the lowest angle that can get useful data to the south. We do not want separation of angles more than approximately 1-degree given the ~1-degree CSAPR beam width. These parameters (and RHI or hemispherical range height indicator [HSRHI] azimuths and numbers) will be tested before the start of the campaign to optimize the strategy.
- The low-level plan position indicator (PPI) sweeps also will document clear-air echoes that can be merged with NEXRAD clear-air echoes to characterize urban, topographic, and cold pool boundary-layer circulations.

The VCP intermixed with specific RHI scan sequences focusing on along-valley and south-facing metro-encompassing sectors will be used to observe these phenomena in a level of detail that operational radars cannot due to being located further away and scanning to maximize areal coverage rather than details in specific locations.

The team will also discuss the Doppler lidar scanning options proposed here with ARM technical staff:

- The default DL scan strategy at the S2 site intermixes (a) zenith dwells to characterize boundary-layer and cloud-base vertical motion in detail with (b) RHI scans along-valley (north-south), to characterize the spatiotemporal structure of slope and cold pool flows passing over the S2 site, with (c) high-elevation conical scans to derive horizontal wind profiles using the Velocity Azimuth Display (VAD) technique. All three are important to DUSTIEAIM science objectives.
- The default DL scan strategy at the M1 site combines the same three patterns (zenith, RHI, and VAD), but the RHIs will point not just meridionally (N-S), but also zonally.

## 3.6 Value-Added Products (VAPs)

**Table 3**. Requested ARM VAPs.

| ARM VAP |
|---|
| ACSMCDCE |
| AERINF |
| AOD-MFRSR |
| AOP |
| ARMBE |
| KAZRARSCL |
| CMAC |
| CCNSMPSKappa |
| DLPROF |
| INTERPSONDE |
| LDQUANTS/VDISQUANTS |
| MICROBASEKaPlus |
| MPLCMASK |
| MWRRET |
| PBLHT |
| QCECOR |
| QCRAD/RADFLUX |
| SPHOTCOD |
| MERGEDSMPSAPS |
| VISST, external GOES |
| TROPOE, external |

## 3.7 Vertical Profiling

Organic aerosol formation and growth processes are largely understudied and have unique sources within the desert Southwest U.S. that differ from the southeast U.S. (e.g., ARM's Bankhead National Forest [BNF] deployment in Alabama), warranting in-depth study and in situ observations. Vertical profiling at the Main Site may be challenging due to congested airspace but would benefit SO#2 and should still be pursued for options using tethered balloons and/or uncrewed aerial vehicles (UAVs) north and northeast of the Main Site. Aircraft measurements that could provide spirals over the sites/s and/or crosswise flight paths to follow plume trajectories would also be highly advantageous, but it is uncertain what options exist during DUSTIEAIM that might be available to fill this gap.

## 3.8 Collaborations

### 3.8.1 Partnerships

The SW-IFL was designed to engage stakeholders and provide scientists and decision makers with high-quality, relevant knowledge capable of spurring and guiding responses to environmental concerns, with a focus on extreme heat and mitigating those impacts since the region's urban areas routinely experiencing 30+ days of temperatures above 110 °F (43 °C) each summer. The SW-IFL is a partnership involving the three public universities in Arizona, two national laboratories, and industry. Our stakeholder network includes city governments, county-level agencies, community groups, and local non-profits throughout the region and has just completed its first annual report. SW-IFL is comprised of three thematic groups — Observations, Modeling, and Resilient Solutions — that engage in activities that include data collection on land-atmosphere exchange processes, atmospheric composition, and emissions while leveraging existing networks that collect weather, air quality, and hydrological data to address extreme heat and its associated environmental and societal stressors. SW-IFL is building a "Model-of-Models (MoM)" using global Model for Prediction Across Scales (MPAS) simulations to drive 2-km Weather Research and Forecasting Model (WRF) simulations that will then inform building energy model simulations and human exposure simulations. SW-IFL will identify data sources and prepare initialization and boundary-layer conditions for these various models as well as build bridges between these models. These methodologies can be leveraged by the AMF team. It is worth noting that the SW-IFL simulations will focus on June-July-August, which complements rather than overlaps with the proposed AMF plan.

SW-IFL performs annual IOPs in the summer when temperatures are at their highest. During 2024 and 2026 IOPs, the two Center for Multiscale Applied Sensing (CMAS) mobile observatories will be deployed to measure boundary-layer processes and land surface properties. Focused neighborhood-scale heavily instrumented testbed experiments will also elucidate drivers of micro-variations and evaluate the efficacy of proposed resilience solutions.

The SW-IFL project has established long-term facilities including three flux towers in distinct land surface regions. Additional portable eddy covariance systems mounted on a trailer with a telescoping tower will be deployed during the summer IOPs. Templeton et al. (2018) and Perez-Ruiz et al. (2020) piloted this activity in Phoenix by placing the setup at three sites (parking lot, suburban neighborhood, gravel site), with each deployment lasting 2-6 months. These studies identified significant differences in water, energy, and carbon dioxide exchanges that were clearly linked to urban land cover type. For instance, where irrigated vegetation had a strong control, the land-atmosphere exchanges were decoupled from precipitation events. Sensors on the trailer-tower setup are already available through a loan by the AmeriFlux Rapid Response System and include observations of radiation, energy, momentum, and trace gas fluxes ($H_2O$, $CO_2$ and $CH_4$). Of particular interest for the trailer-tower setup will be placement in agricultural and natural regions along the urban-rural boundary that are farther away from the core areas that are sampled by the existing or planned eddy covariance (EC) systems.

The three EC sites have been registered as part of the DOE AmeriFlux network and consist of: (1) Maryvale Neighborhood Site (US-Px1) – a low-rise residential area in west Phoenix at 26 m measurement height, (2) Encanto Golf Course (US-Px2) – an irrigated turf grass (agricultural) site in central Phoenix at 3 m measurement height, and (3) Desert Botanical Gardens (US-Px3) – a remnant natural site in east

Phoenix at 10 m measurement height. Thus, an east-west transect through the Phoenix MSA is currently managed by the DOE SW-IFL project and data sets from February 2024 will be available prior to and during the proposed deployment. Key measurements at these sites for the deployment activities include: (1) four components of the radiation budget and net radiation, (2) surface latent, sensible, and ground heat and momentum fluxes, (3) sub-hourly precipitation, (4) soil moisture and temperature at five sampling depths into the soil, (5) surface skin temperature, and standard meteorological variables (e.g., barometric pressure, wind speed and direction, air temperature, and relative humidity). Furthermore, the sites can serve as hosting locations for ancillary instruments deployed by other scientific teams.

### 3.8.2 Existing Infrastructure

NEXRAD existing radar data in the region are located in Flagstaff (KFSX), Phoenix (KIWA), and Tucson (KEMX). These data will be used as background coverage so that ARM scanning radars can target specific locations and processes.

The EPA operates monitoring stations in Arizona, e.g., Interagency Monitoring of Protected Visual Environments (IMPROVE). Stations collect 24-hr fine PM2.5 and coarse PM10 every three days and can augment the more-detailed AMF AOS data.

The Automated Surface Observing System (ASOS) and the Arizona Meteorological Network (AZMET) maintain many weather stations that report a variety of weather and meteorological parameters throughout the Phoenix metro area and surrounding regions. The ASOS program is a joint effort of the NWS, the FAA, and DOD. AZMET is a Cooperative Extension of ASU that publicly shares meteorological data and weather-based information to agricultural and horticultural interested parties in southern and central Arizona.

The IOP data sets may serve as a useful resource for the calibration and validation of newly launched orbiting instruments on satellites. Given the unique observations collected during IOPs, these data could be used as validation data sets and reference points for comparison with open data sets from newer Earth-observing satellite platforms such as Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) and Tropospheric Emissions: Monitoring of Pollution (TEMPO) by National Aeronautics and Space Administration (NASA), and EarthCARE launched by the European Space Agency (ESA).

### 3.8.3 Evolving Partnerships

While the science goals of DUSTIEAIM can be accomplished using the ARM assets requested with the existing infrastructure as outlined in this science plan, a number of complementary instrument suites are also being pursued that would further enhance the scientific impact of the campaign.

The science team is also engaging in discussions with NASA, the National Center for Atmospheric Research (NCAR), and Climavision for synergies and proposals for vertical profiling using aircraft measurement of aerosols, cloud properties and trace gases, additional radar coverage, and ground-based surface energy balance sensors as well as atmospheric and soil profiling. When possible, funded proposals for vertical profiling will coordinate deployments and IOPs with DUSTIEAIM to include flights over the ARM sites. One such proposal is already planned for submission to the National Science Foundation (NSF). The science team welcomes interested parties to contact us for coordination.

Outreach and student engagement in the form of workshops, summer schools such as ARM hosts, and summer student internships are supported to inform local, regional, and the larger scientific community in terms of training and engaging early career scientists.

## 3.9 Guest Instrumentation

Measurements of the stable isotopic composition of water vapor are anticipated to be conducted for DUSTIEAIM at the Main and Supplementary Sites using water vapor isotope analyzers. The goal is to better understand the processes that govern the regional transport of water vapor as well as the distribution, phase, amount, and intensity of precipitation in the Phoenix MSA. The stable isotopic composition of atmospheric water vapor is expected to reflect the balance between long-range transport, orographic circulations, precipitation processes, and surface fluxes. Measuring the atmospheric water vapor isotopes at two sites will enable us to advance our understanding of how convective processes within an urban interface with agricultural and natural lands in the Sonoran Desert influence water vapor abundance and distribution. We expect that the isotopic measurements will provide new insights into the more conventional meteorological measurements that will be made during the project and could be used in the Energy Exascale Earth System Model (E3SM) modeling efforts (as mentioned in Section 5.3.4).

A mobile aerosol container using the same inlet design as the new AMF AOSs will be deployed for aerosol science. The container is customized for IOP deployments based on science objectives that can include additional guest collaborator instrumentation.

**Table 4**. Example of expected guest instrument data products.

| Data Product | Instrument | Measurement |
|---|---|---|
| ams | aerosol mass spectrometer (AMS) - soot particle, high-resolution time-of-flight | Particle mass loading and chemical composition in real time for refractory and non-refractory aerosol |
| aps | aerosol particle sizer (APS) | Aerosol size distributions from 500 nm to 20 microns |
| caps-ssa | humidified cavity attenuated phase shift particulate mass single scatter albedo monitor (HCAPS-PMssa) | Optical scattering and extinction of particles at 450 nm; ambient and humidified modes |
| ccn | cloud condensation nuclei counter (CCNc-100) | Aerosol cloud droplet activation counts |
| cpc | condensation particle counter (CPC, 2) | Submicron particulate concentration |
| pass | photoacoustic soot spectrometer (PASS) | Submicron aerosol absorption and scattering at 405 nm and 532 nm |
| pax | photoacoustic extinctiometer (PAX) | Optical scattering and extinction of particles at 870 nm |
| pm | PM Modulair (2) | $PM_{10}$, $PM_{2.5}$ and $PM_1$ mass concentrations |

| Data Product | Instrument | Measurement |
|---|---|---|
| ptrms | pProton-transfer reaction time-of-flight mass spectrometer (PTR-TOFMS 4000) | Gas-phase organic compounds |
| smps | scanning mobility particle sizer (SMPS) | Aerosol size distributions from ~10 nm to ~600 nm diameter |
| sp2 | single-particle soot photometer (SP2) | Black carbon (BC) number and mass concentrations |
| tracegas | $CO/CH_4/CO_2/H_2O$ analyzer | Trace gas concentrations, cavity ringdown spectrometer, Picarro-G2401 |
| wibs | wideband integrated bioaerosol sensor (WIBS-5/NEO) | Single-particle fluorescence to infer biological material with data on size, shape, and fluorescent properties to classify pollen, bacteria and fungi |
| wviso | water vapor isotope analyzer | Stable isotopic composition of water vapor |

# 4.0 Project Management and Execution

AMF1 instrumentation will operate in default modes as defined by ARM instrument mentors and the AMF1 site operations team. Notable exceptions requested are presented in Section 3.

The DUSTIEAIM science team will work with the ARM radar engineers to define the baseline scanning operation of the CSAPR2. These groups will work together to define the criteria for choosing which convective cells to track, and for how long, to accomplish the science goals of DUSTIEAIM.

## 4.1 Communication Strategy

The DUSTIEAIM proposal team is committed to communicating with the ARM points of contact (POCs) throughout the planning, deployment, and operational periods. Active communication between ARM and collaborative resources includes planning with SW-IFL and ASU for which the principal investigator (PI) will ensure communication with co-investigators (Co-Is) Andino, Lamer, and Vivoni, who are POCs leading SW-IFL operations, management, and science. Co-I Morris will be the main point of contact for operations at M1. We will also work with ARM IOP and guest instrument proposers to maximize scientific benefit.

## 4.2 Review Process

Real-time data quality and data reviews will be conducted during the campaign to ensure the right measurements are being made for DUSTIEAIM science goals. We will also conduct IOP project reviews to ensure operations are being executed as planned and to assess any changes needed to procedures.

Starting in October 2025, six months before the start of the campaign, quarterly virtual meetings will be held to review instrument status, logistical and data issues, and preparations for upcoming IOPs and guest instruments. These meetings will be attended by the ARM responsible parties and at least one person from the PI team.

During the first few days of the campaign, all data will be examined by the ARM responsible parties (technical staff in the field, instrument mentors, translators, etc.) and the PI team, to ascertain that data collection methods (such as radar and lidar scan strategies) are as desired, the data QA/QC process and VAP development process are accurate, and the data are displayed correctly on ARM Data Discovery and the Campaign Dashboard.

Throughout the full duration of DUSTIEIAIM, the PI team will have a designated representative that regularly checks on data quality, missing/suspect data, etc., and reports anything unusual to the lead PI. The lead PI will then contact the designated ARM translator and/or assigned technical staff member for data collection and ingest regarding the datastream, VAP, and/or instrument of concern. Forecasting of convection and dust events will also be performed and coordinated by the science team during the IOPs.

## 4.3 Reporting Schedule

The DUSTIEAIM team will coordinate with AMF observations and project management to produce status reports during the planning and execution stages of the project. The goal of the reports will be to ensure DUSTIAIM is on course to meet our Science Objectives. We will produce a final campaign report at the end of DUSTIEAIM and participate in project reviews during the Joint ARM User Facility and Atmospheric System Research (ASR) PI Meetings.

## 4.4 Data Management

Data from the PI/guest instrument deployments will be submitted to the ARM Data Center no later than six months after the end of the campaign using standard formats following established guidelines set by ARM. All data will be quality-assured, documented, and released with proper uncertainty and error quantification to the ARM Data Center through the External Data Center. Data products expected from LANL and UNM are listed in Table 4/Guest instrument data products. An ARM report including a summary of the deployment will be submitted for online publication also within six months after the end of the campaign that may be of interest for potential users of the data. All published data that includes any additional VAPs will be made freely available to the public at the time of publication.

SW-IFL data could also be linked and/or integrated with ARM Data Discovery. Data is planned to be shared via open access with current platforms under evaluation. The flux tower data is already available via open access on the AmeriFlux website and could be linked with ARM data for DUSTIEAIM.

All the DUSTIEAIM data files, including observational data products and output from atmospheric model simulations, will be preserved and shared in appropriate standard data formats (e.g., CF-compliant NetCDF, ASCII). Relevant descriptive metadata will be included, e.g., the date/time of collection or processing, location (latitude, longitude, elevation) and description (e.g., instrument status), PI contact information, data provenance, and keywords following community standards.

## 4.5 Website

DUSTIEAIM will work with LANL Communications and the Partnerships & Pipeline Office to set up and manage a website for the campaign for deployment planning and scientific collaboration.

# 5.0 Science

## 5.1 Objectives

There have been two DOE campaigns in urban-agricultural/rural interfaces studying land-atmosphere interactions and three in areas with complex topography that could be compared to this deployment's scientific focus and location: two within the Northern Hemisphere and continental United States (Coast-Urban-Rural Atmospheric Gradient Experiment: COURAGE; Tracking Aerosol Convection Interactions Experiment: TRACER), one in the Southern Hemisphere (Cloud, Aerosol, and Complex Terrain Interactions: CACTI), and two at high altitude in the mountain west U.S. (Surface Atmosphere Integrated Field Laboratory: SAIL; Storm Peak Lab Cloud Property Validation Experiment: STORMVEX). See Table 5 for more information on these previous campaigns. However, none of these previous campaigns have connected the Earth energy systems with goals to prioritize American energy innovation and reliably meet growing resource demands for energy grid reliability and security.

**Table 5.** List of relevant large-scale field campaigns using atmospheric observations for science within the Americas including those funded by DOE ARM.

| Campaign | Location and Dates | Objectives | References |
|---|---|---|---|
| *Urban-rural/agriculture* | | | |
| COURAGE – Coast-Urban-Rural Atmospheric Gradient Experiment | Baltimore, Maryland, U.S.<br>AMF (DOE)<br>Dec 2024-Nov 2025 | Integrated coast-urban-rural system | Backgrounder |
| TRACER and ESCAPE | Houston, Texas, U.S.<br>AMF (DOE)<br>NCAR C-130 (NSF)<br>Oct 2021-Sept 2022 | Convection in an urban-coastal system | Field Campaign Report<br>Science Plan |
| *Convection* | | | |
| CACTI – Cloud, Aerosol, and Complex Terrain Interactions | Argentina<br>AMF and AAF (DOE)<br>Oct 2018-Apr 2019 | Orographic clouds and deep convective precipitation in an urban-coastal system | BAMS |
| NAME – North American Monsoon Experiment | Mexico<br>(U.S. AID)<br>2004 | Monsoon precipitation in the mountains | BAMS |

| Campaign | Location and Dates | Objectives | References |
|---|---|---|---|
| CuPIDO – Cumulus, Photogrammetric, In Situ, and Doppler Observations Experiment | Tucson, Arizona (NSF)<br>July-Aug 2006 | Boundary-layer evolution and orographic convection over Santa Catalina Mountains | BAMS |
| *Mountainous Terrain* | | | |
| SAIL/SPLASH | Crested Butte, Colorado<br>AMF (DOE)<br>Sept 2021-Jun 2023 | High-elevation snowpack, surface layer, BL interactions and precipitation | SAIL , SPLASH |
| STORMVEX | Storm Peak, Colorado<br>AMF (DOE)<br>Nov 2010-Apr 2011 | Improve cloud representation in models | Field Campaign Report<br>Science Plan |

## 5.2 Using ARM Instrumentation to Address Objectives

Remote sensing and in situ observations from the AMF1 and the requested supplemental equipment will provide important quantification of the time-varying boundary-layer thermodynamic structure (AERI, SONDE), the sub-cloud vertical velocity (DL), the horizontal wind profile (RWP, SONDE) and the boundary-layer depth (SONDE, MPL, RWP, and others). They will additionally be essential to estimate the properties of shallow clouds including cloud boundaries (KAZR, MPL, CEIL), macrophysical properties (KAZR), and liquid water path (MWR). For deeper convective clouds, the requested instrumentation will allow for the characterization of deep convective vertical velocities (RWP) and deep convective macrophysical and microphysical properties (CSAPR). The ARM observations will complement existing radar data in the region from the NEXRAD radars in Flagstaff (KFSX), Phoenix (KIWA), and Tucson (KEMX). To maximize this complementarity, we propose to deploy the scanning precipitation radar (CSAPR) at the Main Site to enable dual-Doppler retrievals with the Phoenix NEXRAD to examine circulations in the CBL and precipitation. There is no real blind zone between the two NEXRAD radars (KFSX and KIWA), but they are both long range to the area north of Phoenix, and therefore broad-beam and poor vertical resolution in our area of interest. We would like to explore the possibility of controlling the ARM radar using the Multisensor Agile Adaptive Sampling (MAAS) framework, which steers the ARM radar towards convective cells of interest, following them and collecting observations of them across their life cycle. However, if the MAAS framework is not operationally feasible, we will still be able to meet our three SOs. This mode of operation was previously successfully implemented during TRACER and early studies show the added value of running radars using MAAS for the study of short-lived isolated convective cells.

The full set of instruments (see Table 1) in the AOS is requested to provide a comprehensive characterization of the aerosol microphysical properties and processes that drive atmospheric radiative and cloud microphysical processes across the urban-agricultural atmospheric gradients. The AOS will provide (1) in situ measurements of aerosol size distributions from nucleation to coarse mode (SMPS, UHSAS, APS) to provide a critical constraint on aerosol dynamics and sources including dust, (2) total number concentration (CPCU, CPCF) to provide number closure on the size distribution measurements,

(3) non-refractory chemical composition (ACSM) and black carbon (BC) to characterize submicron atmospheric aerosol-phase composition including organic-to-BC ratios and air mass history, (4) aerosol supersaturated water uptake (CCN) to estimate CCN spectra, (5) aerosol optical properties (PSAP, DRY NEPH, IMPACTOR, SP2) to assess radiative impacts of aerosol absorption and scattering, and (6) trace gasses (CO, $O_3$, $SO_2$) to understand aerosol precursors and drivers of atmospheric chemistry in the region. The ARM ExtLidar provides independent vertically resolved retrievals of aerosol extinction profiles at 532 nm and depolarization at 532 and 1064 nm, which can be used to identify non-spherical particles such as dust in the column. The abundance of INPs, as functions of their freezing temperature, will be obtained through filter collections and processed in the ARM ice nucleation spectrometer (INS).

Ground-based observations from the AMF1 will provide key observations to enhance the spatial representation and coverage of surface state and flux conditions. In situ measurements of rain drop size distribution (LDIS, VDIS) and rain rate (WB) at the AMF will complement a network of rain gauges in Phoenix and two mobile truck-mounted radars during IOPs. Surface weather variables (MET), thermal, radiation, and energy balance components (SEBS, GNDRAD, SKYRAD, IRT), and turbulent fluxes of sensible heat and latent heat (ECOR) will help fully characterize local conditions. Existing sensors in Arizona will be useful to depict the spatiotemporal variation of precipitation and surface weather variables (e.g., >500 tipping bucket rain gauges, >60 weather stations, >50 ASOS sites). There are also three permanent ECOR sites registered with AmeriFlux (Figure 5), as well as a mobile EC available during IOPs to determine variation in soil moisture/temperature and turbulent fluxes over different land cover types.

## 5.3 Scientific Hypotheses

### 5.3.1 Science Objective 1: Land-Atmosphere Interactions and Impacts

(H1) Do urban surface conditions alter the diurnal cycle of turbulent fluxes and surface and air temperatures with distinct variations observable across seasons?

(H2) Does outdoor water use associated with urban and agricultural irrigation significantly affect surface fluxes, heat and moisture transport, and aerosol properties?

(H3) Does the warm-season surface energy budget suppress daytime sensible heat flux in the built environment (urban, agricultural), resulting in cooler daytime temperatures and a stronger nocturnal heat island effect?

(H4) Do the observed differences among urban, rural, and agricultural sites help to explain differences in boundary-layer processes and convective cloud conditions?

Urban areas, like Phoenix, exhibit high spatial and temporal heterogeneity due to varied land cover and built environments and local steep terrain, affecting surface temperature, greenhouse gas and aerosol emissions, and energy balance. These complexities make direct atmospheric and surface flux measurements both challenging and essential.

To address this, the SW-IFL operates three eddy covariance towers across an east-west transect in Phoenix that cover residential, agricultural, and natural sites and has been collecting data since February

2024. These towers (Figure 4), which are part of the AmeriFlux network, measure turbulent fluxes and components of the energy, water, and radiation budgets. The sites can also serve as host locations for ancillary guest instruments deployed by other scientific teams. SW-IFL will also deploy an additional portable EC system mounted on a trailer. The DUSTIEAIM ECOR measurements at M1 and S2 will further expand coverage.

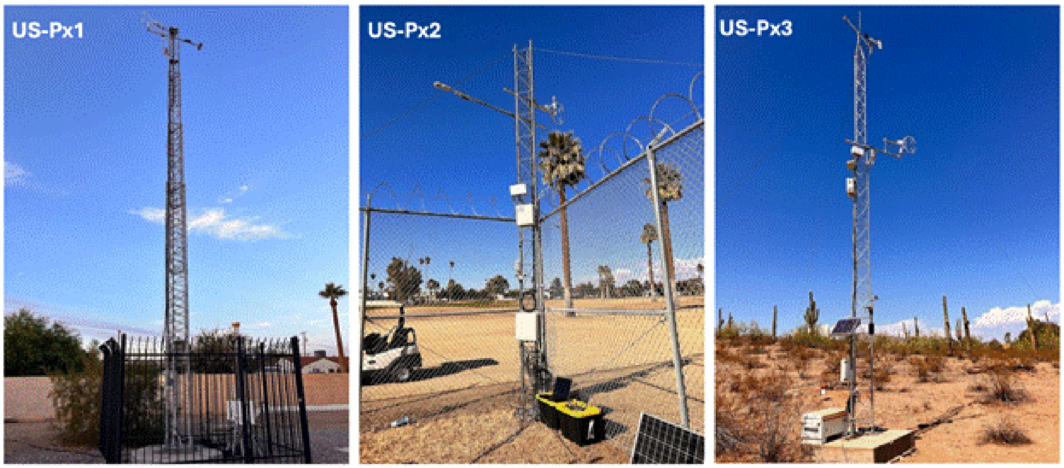


**Figure 4**. DOE SW-IFL eddy covariance tower sites in the Phoenix MSA labeled with their site names from the AmeriFlux Network. (US-Px1) a low-rise residential area, (US-Px2) an irrigated turf grass (agricultural) site, and (US-Px3) a natural site.

DUSTIEAIM will deploy an ECOR and ancillary instrumentation (MET, WB, LD, IRT) at the Main (ASUW) and an ECOR, LD, and MET at the Supplementary Site S2 to augment the SW-IFL network. The main observation site in northwestern Phoenix will form a north-south transect with US-Px1, while a Supplementary Site northeast of the city will monitor natural foothill conditions above the Sonoran Desert. Together with other eddy covariance sites, these locations will measure diurnal cycles of surface fluxes and temperatures across seasons at five distinct sites in the Phoenix MSA. Variability in observed conditions is expected due to differences in irrigation, land cover (urban versus vegetated), and proximity to dust and aerosol sources. These comparisons will help address hypotheses H1 and H4.

### 5.3.2 Science Objective 2: Aerosol Processes and Interactions

(H1) How are regional aerosol sources, sinks, and growth processes affected by the hydrological cycle in the Phoenix MSA?

(H2) How do the sources, frequency, and seasonality of low-visibility events near/in an urban site impact the desert southwest? (E.g., do dust and supermicron aerosol dominate the cloud-activating aerosol in the summer whereas other CCN and INP types, e.g., anthropogenic carbon and organics, dominate in the winter?)

(H3) Does urban air pollution build up under quiescent cold-season conditions, what role do biogenic emissions play, and do cold-season precipitation events (ARs) alter aerosols?

(H4) Do aerosols affect mixing-layer depth and cloud conditions enough to create measurable surface cooling that could counteract the urban heat island effects?

Aerosols in the Phoenix MSA influence both shortwave and longwave radiation, potentially affecting surface temperatures. While many aerosols scatter radiation and cool the atmosphere, Phoenix's abundant mineral dust can absorb radiation and cause atmospheric warming. Uncertainties in aerosol distribution and properties complicate accurate assessments of their impact on temperature, cloud formation, and boundary-layer processes.

Historical aerosol data, such as from the IMPROVE network and studies like Sorooshian et al. (2011), offer insight into aerosol composition and trends. These show Phoenix's aerosols are mainly composed of dust, sulfates, and organics, with data spanning over two decades. However, limitations in filter-based data necessitate more detailed observations. Considering limitations in filter data, detailed aerosol observations provided by AMF1 are critical in addressing the aerosol-cloud interaction questions in H2.

Advanced instruments (e.g., SMPS, UHSAS, APS, AOS nephelometer, ACSM) deployed by AMF1 will allow high-resolution analysis of aerosol size, composition, and cloud condensation nuclei (CCN). These data will improve understanding of seasonal aerosol behavior, especially during events like monsoons and dust storms.

Integrating DUSTIEAIM AMF1 observations into models will help address current deficiencies, enhance aerosol representation, and improve simulations of their radiative impacts on urban areas and regional hydrology. Observations will be used to identify model deficiencies, understand the contributing factors, and further guide the development and advancement of the model representation of aerosol properties in this urban-dusty-rural region. These advancements will in turn improve the model simulations of aerosol direct and indirect radiative impacts on the urban boundary-layer dynamics, the regional hydrological cycle, and energy infrastructure.

### 5.3.3 Science Objective 3: Precipitation Processes

(H1) [warm season] How do local atmospheric thermodynamic and kinematic conditions, including water vapor content and land surface conditions, affect storm propagation off the mountains, cold pool strength, local deep convection initiation and precipitation, and dust concentrations in and near the Phoenix MSA?

(H2) [warm season] Do boundary-layer properties, including aerosol variability, impact afternoon surface-coupled cumulus clouds and precipitation formation and fallout like virga, and how does evaporating precipitation in turn alter the boundary layer?

(H3) [cold season] Do local aerosol properties change with regional cloud and precipitation processes over the duration of an atmospheric river (AR) event?

(H4) [cold season] How does precipitation evaporation vary as a function of boundary-layer conditions and elevation in events of varying precipitation types and intensities?

The Phoenix area has several operational measurements that will be critical for providing spatial context for the comprehensive ARM measurements that aid in addressing the above science questions to characterize precipitation, cloud evolution, and aerosol impacts across urban and surrounding natural terrain. Two NEXRAD radars offer broad precipitation coverage but lack detailed boundary-layer resolution, particularly in areas with complex terrain. While NEXRAD radars provide excellent background coverage, they do not provide detailed measurements required to characterize the complex multi-scale flow from the Phoenix metro valley to higher terrain and its effects on precipitation formation and evolution, including evaporation that will be done with the AMF1 CSAPR2 at S2 for DUSTIEAIM. Supplemental ground-based networks, like Maricopa County's dense rain gauge and weather station systems, will help fill in spatial gaps for DUSTIEAIM science and validate radar data. GOES-W satellite retrievals will provide additional high-frequency cloud evolution data that can be linked to AMF1 data.

To enhance spatial and vertical detail, ARM's scanning radar (CSAPR2) and instruments (e.g., Doppler lidar, AERI, microwave radiometer) will be deployed at the Main AMF Site (ASU-West) and a Supplemental Site northeast of Phoenix. These systems will capture low-level circulations, boundary-layer structure, and precipitation evolution, especially important for understanding urban-terrain interactions, sub-cloud evaporation, and cold pool formation.

Monsoon and convective systems (H1) often form over higher terrain and propagate into Phoenix. Radiosondes, profilers, and surface networks will monitor atmospheric conditions enabling these processes that require sufficient shear and mesoscale organization of deep convection such that strong cold pools and mesoscale convection systems form. If available, the DIAL would provide detailed evolution of the water vapor vertical structure at low-mid levels. For events that pass overhead, the RWP, disdrometers, and rain gauges will provide characterization of precipitation structure within the context of the scanning radars, while the met station and vertical profilers will characterize cold pool structure. Blowing dust associated with haboob dust storms will be characterized by the APS.

For aerosol-cloud interactions (H2), advanced instrumentation (CCN counters, size distribution [SMPS, UHSAS, APS], ice nucleation spectrometers) will quantify aerosol characteristics and their effects on cloud properties and precipitation processes. Scanning radars will monitor precipitation evolution while Doppler lidar, AERI, and the DIAL monitor boundary-layer thermodynamic and kinematic structure, as for Q1, and coupling of clouds with the surface. Cloud macrophysical properties overhead will be quantified with the ceilometer and MPL (cloud base), all-sky imager (ASI; cloud coverage), KAZR (cloud depth, when detectable), and, if available, stereo cameras (cloud shape evolution). Cloud structure and radiative effects will be observed with tools like ceilometers, lidars, and radiation sensors. Potential interactions of aerosols with clouds aloft can be monitored with the extinction lidar. Radiative properties of clouds, as modulated by microwave radiometer-retrieved cloud liquid water path and aerosol-mediated cloud droplet number and size, will be measured with SKYRAD downwelling radiation and albedo as well as MFRSR-retrieved optical depth. Surface interactions with the boundary-layer growth and clouds will be further monitored with the SEBS and ECOR. When precipitation forms, the KAZR will allow characterization of sub-cloud evaporation, a critical process for modulating surface precipitation in the desert.

Winter precipitation and atmospheric rivers (ARs) (H3–H4) will be studied to understand the interaction between aerosols, moisture transport, and stability in cold-season precipitation. Elevation and surface characteristics influence how much precipitation evaporates before reaching the ground. Such events have been previously studied from large-scale perspectives, but the intersection of aerosols, moisture transport, stability, and precipitation will be studied in unprecedented detail for DUSTIEAIM. ARM's detailed vertical and surface observations will help assess precipitation efficiency, phase shifts, and the impact of urban-sourced modifications.

### 5.3.4 Improving Process Modeling

Understanding monsoon-driven dust storms in the desert-urban environment of southwest Arizona requires accurate numerical modeling capabilities. Past studies using regional models like WRF-Chem (Weather Research and Forecasting model coupled with Chemistry) and WRF/CMAQ (Community Multiscale Air Quality Modeling System), or Earth system models like E3SMv2 (Energy Exascale Earth System Model Version 2; Golaz et al. 2022) have underestimated $PM_{10}$ and $PM_{2.5}$ concentrations in Phoenix and Maricopa County and over the Southwest U.S. region, highlighting model limitations in dust source and transport characterization, and representation of subgrid wind variability. Recent model improvements incorporating subgrid wind distribution and lightning data in WRF-Chem have shown better results, but significant uncertainties remain, particularly around particle size distributions and the timing of dust emissions. As the metro area continues to grow, energy demand will require the grid to identify vulnerabilities related to natural hazards — such as dust storms and severe weather events — changes in natural resources, and the interdependencies among water, wind, and solar radiation distribution. Earth system modeling could be improved by integrating DUSTIEAIM observations to assess tipping points to mitigate when demand is predicted to crash the grid and to design a resilient grid evolution for increased demand.

High-resolution observations from upcoming campaigns like DUSTIEAIM will help reduce these uncertainties in modeling dust by refining model parameterizations and improving dust source inventories. These data will support model validation, data assimilation, and parameterization development, particularly for extreme $PM_{10}$ impacted by desert and agricultural regions. With the proposed new observations for DUSTIEAIM, we will first assess current limitations associated with the existing WRF-Chem modeling system and then perform data denial experiments to evaluate the sensitivity of the aerosol model physics to initial conditions, which will suggest further research to improve model fidelity. Planned WRF-Chem modeling experiments will assess current model limitations and guide enhancements in simulating dust storm dynamics, visibility, air quality, impacts on existing energy infrastructure, and predicting the best locations to develop new infrastructure, energy distribution, and data centers to reliably meet growing energy demands. Running WRF-Chem with urbanized processes would be a larger effort but could also be done if resources are available.

A key goal of the integrated modeling with DUSTIEAIM observations is to evaluate and improve E3SM's ability to simulate aerosol impacts, including dust, on radiation and cloud microphysics in the desert-urban environment. Aerosol data from AMF AOS instruments, along with IMPROVE and AERONET networks, will help identify missing or underrepresented aerosol sources (e.g., urban and agricultural), types (e.g., biological particles), and coarse particles as has been done in California for agricultural lands (Adebiyi et al. 2024). These observations will support better parameterizations of urban, biogenic, and agricultural dust emissions. Additionally, optical measurements (PSAP, MFRSR, CSPHOT) and vertical profiles (ExtLidar and MPL) will assess and reduce uncertainties in E3SM's simulation of aerosol optical properties and direct radiative effects.

DUSTIEAIM also provides a unique opportunity to evaluate the model's ability to simulate aerosol-CBL interactions, including the dust heating effect on thermodynamic stability and CBL development, as well as the frequent dust events and storms (haboobs) triggered by convection. Comparison with the observations for selected dusty events will inform the improvement of CBL parameterizations in E3SM. Cloud microphysical measurements and size-resolved aerosol chemical composition will constrain and improve CCN and INP activation parameterizations to address critical questions regarding the uncertainty associated with classic ice nucleation theory in E3SM, which does not treat the biological and organic influences. The high-resolution E3SM model configuration (e.g., North America Regionally Refined Mesh at ~25 km; Tang et al. 2023) will be employed for these process studies related to aerosol direct and indirect radiative effects on the development of cloud and precipitation during the NAM.

Water isotope measurements will be used to validate urban-scale hydrologic processes in simulations using the next version of E3SM, which will feature high-resolution (~3 km) convection-permitting capabilities. A DOE-funded project is currently incorporating water isotope tracers into E3SM to better understand the NAM and the impact of urban environments on hydrology. This work is especially important due to a major mismatch between model simulations (e.g., Coupled Model Intercomparison Project Phase 6 [CMIP6]) and observations: while models show long-term atmospheric moistening over arid regions like the U.S. Southwest, observations indicate a drying trend. Water isotopologue data from DUSTIEAIM will help resolve this mismatch by offering insight into atmospheric water transport, surface-atmosphere interactions, and precipitation mechanisms. This discrepancy limits our ability to optimize water and natural resources and energy production needs for rapidly growing urban areas in the southwestern U.S. such as Phoenix.

Another significant knowledge gap remains in understanding how the built environment directly influences summertime precipitation in metro Phoenix. While past studies show urban impacts on rainfall, high-resolution models reveal mismatches between urban-rural boundary-layer dynamics and the observed timing of peak precipitation (Georgescu et al. 2009). Incorporating realistic urban features, such as building morphology, through the DOE SW-IFL initiative offers a critical opportunity to improve understanding of convective processes driving intense summer storms and flooding. This is increasingly urgent given projected changes in precipitation patterns (Georgescu et al. 2021), highlighting the need for more accurate projections at local and urban scales based on improved urban-rural-PBL dynamical and thermodynamical understanding.

# 6.0 Relevancy to the DOE Mission

DUSTIEAIM supports discovery science within the DOE Office of Science, using one of the world's best facilities, the ARM user facility, to keep America at the forefront of discovery. The continuous observations collected can and will be used to improve Earth system modeling, extreme weather resiliency, and energy security, all of which are focus areas within the current missions for DOE Office of Science. Furthermore, the information gathered will facilitate the next generation of scientific inquiry using advanced and evolving high-performance computing (HPC) and artificial intelligence (AI) for energy systems in the southwestern United States.

The NAM system cloud, aerosol, dust, and precipitation dynamics remain a significant challenge for numerical models. The gap in observations is also a large concern in terms of the transport of regional aerosol, namely, dust and biomass burning aerosol as related surface changes impact Earth's energy systems, including hydrological cycles and natural resources, energy technologies, and increasing energy demand and reliance on America's electricity grid for electric utilities and within the energy systems. For these reasons, DUSTIEAIM will investigate the influence of urban and desert regions on convection and precipitation by studying aerosol-cloud-precipitation interactions and what the impacts are for energy security and reliability for current and anticipated load growth for the President's Executive Order, "Declaring a National Energy Emergency" and restoring energy dominance.

DUSTIEAIM will be the first coordinated set of ARM observations in the monsoon region and will also leverage DOE investments in the SW-IFL. Direct observations of large-scale and localized high-wind events, extreme heat, and mesoscale convective systems and their microphysical properties within the growing megalopolis of Phoenix can be used to determine how to best develop new energy infrastructure and distribution for growing energy demand and new data centers to support HPC and AI efforts. DUSTIEAIM will directly advance understanding of the NAM in the United States, where convective clouds play a significant role in energy security, grid stability and resilience, natural hazards, extreme weather, and water resources.

DUSTIEAIM observations will provide the scientific research community with strategically located atmospheric observations within the continental United States (CONUS), specifically of the desert/urban/agriculture interface in the Southwest. The data collected during this campaign will support the research community to improve the representation of land-atmosphere coupled processes and aerosol-cloud interactions in Earth energy system models such as DOE's E3SM. This campaign contributes key data and capabilities toward several of DOE Earth and Environmental Systems Sciences Division (EESSD)'s current grand challenges: Integrated Water Cycle, Drivers and Responses in the Earth System, and Data-Model Integration.

In conclusion, this project supports the science mission stated by Secretary of Energy Chris Wright in his Memorandum for heads of departmental elements to "accelerate American science, … and strengthen the reliability and security of our nation's energy system." Specifically, this project supports the actions listed in that document for DOE to advance energy addition, unleash American energy innovation, and strengthen grid reliability and security. Moreover, DUSTIEAIM supports the proposed priority areas to maintain U.S. competitiveness for DOE in the President's FY2026 Budget in HPC and AI, which are essential components to meet DUSTIEAIM science goals.

# 7.0 References

Adams, DK, and AC Comrie. 1997. "The North American Monsoon." *Bulletin of the American Meteorological Society* 78(10): 2197–2214, https://doi.org/10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2

Adebiyi, AA, MM Kibria, JT Abatzoglou, P Ginoux, S Pandey, A Heaney, S-H Chen, and AA Akinsanola. 2025. "Fallowed agricultural lands dominate anthropogenic dust sources in California." *Communications Earth & Environment* 6: 324, https://doi.org/10.1038/s43247-025-02306-0

Brandi, A, A Martilli, F Salamanca, and M. Georgescu. 2024. "Urban boundary-layer flows in complex terrain: Dynamic interactions during a hot and dry summer season in Phoenix, Arizona." *Quarterly Journal of the Royal Meteorological Society* 150(762): 3099–3116, https://doi.org/10.1002/qj.4752

Bakkensen, LA, and RD Johnson. 2017. The economic impacts of extreme weather: Tucson and Southern Arizona's current risks and future opportunities. Making Action Possible for Southern Arizona (MAP Dashboard) White Paper #4.

Castro, CL, HI Chang, F Dominguez, C Carrillo, JK Schemm, and HMH Juang. 2012. "Can a regional climate model improve the ability to forecast the North American monsoon?" *Journal of Climate* 25(23): 8212–8237, https://doi.org/10.1175/JCLI-D-11-00441.1

Hong, Y, P Adhikari, and JJ Gourley. 2012. "Flash flood." *Encyclopedia of Natural Hazards*, P Bobrowsky, Ed., Encyclopedia of Earth Science Series, Springer, 324–325, https://doi.org/10.1007/978-1-4020-4399-4_136

Georgescu, M, G Miguez-Macho, LT Steyaert, and CP Weaver. 2009. "Climatic effects of 30 years of landscape change over the Greater Phoenix, Arizona, region: 2. Dynamical and thermodynamical response." *Journal of Geophysical Research – Atmospheres* 114(D5): D05111, https://doi.org/10.1029/2008JD010762

Georgescu, M, AM Broadbent, M Wang, ES Krayenhoff, and M Moustaoui. 2021. "Precipitation response to climate change and urban development over the continental United States." *Environmental Research Letters* 16(4): 044001, https://doi.org/10.1088/1748-9326/abd8ac

Luong, TM, CL Castro, TM Nguyen, WW Cassell, and H-I Chang. 2018. "Improvement in the Modeled Representation of North American Monsoon Precipitation Using a Modified Kain–Fritsch Convective Parameterization Scheme." *Atmosphere* 9: 31, https://doi.org/10.3390/atmos9010031

Phillips, FM, MA Walvoord, and EE Small. 2004. "Effects of environmental change on groundwater recharge in the desert Southwest." In JF Hogan, FM Phillips, and BR Scanlon, Eds., *Groundwater Recharge in a Desert Environment: The Southwestern United States*. Water Science and Application Series 1(9): 273–94, https://doi.org/10.1029/.009WSA15

Saharia, M, P-E Kirstetter, H Vergara, JJ Gourley, Y Hong, and M Giroud. 2017. "Mapping flash flood severity in the United States." *Journal of Hydrometeorology* 18(2): 397–411, https://doi.org/10.1175/JHM-D-16-0082.1

Simpson, IR, KA McKinnon, D Kennedy, and R Seager. 2024. "Observed humidity trends in dry regions contradict climate models." *Proceedings of the National Academy of Sciences of the United States of America* 121(1): e2302480120, https://doi.org/10.1073/pnas.2302480120

Sorooshian, A, A Wonaschütz, EG Jarjour, BI Hashimoto, BA Schichtel, and EA Betterton. 2011. "An aerosol climatology for a rapidly growing arid region (southern Arizona): Major aerosol species and remotely sensed aerosol properties." *Journal of Geophysical Research – Atmospheres* 116(D19): D19205, https://doi.org/10.1029/2011JD016197

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