ARM

2022 ANNUAL REPORT

ATMOSPHERIC RADIATION MEASUREMENT

U.S. DEPARTMENT OF ENERGY

From the Director

30 Years of ARM Data—and More to Come

The Atmospheric Radiation Measurement (ARM) user facility recognized a major milestone in fiscal year 2022 (FY2022): the 30th anniversary of ARM data collection. So much has happened in the past 30 years with data and field campaign management. We are reflecting on the science impacts of our data with a series of articles on the ARM website through May 2023. In this report, you will learn more about our 30 years of data through campaign retrospectives and highlights of recent user research results.

At the same time, we are working to ensure that ARM remains the world's premier ground-based observations facility advancing atmospheric and climate research, especially as we move forward from the COVID-19 pandemic.

In FY2022, many of us spent more time in the field than we had the previous two years.

From October 2021 through September 2022, ARM conducted the TRacking Aerosol Convection interactions ExpeRiment (TRACER) near Houston, Texas. Our staff worked hard to have sites and systems ready for the start of campaign operations after two COVID-induced delays. During intensive summertime operations, technicians kept instruments working through rain, heat, and dust.

In analyzing the TRACER data, researchers expect to learn more about how aerosols affect the severity of thunderstorms in a region where urban, rural, and coastal influences converge.

The U.S. Department of Energy (DOE) is now supporting more research related to urban environments and their interactions with the climate system. TRACER data could play a role in some of those projects.

The month before TRACER started, the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign kicked off near Crested Butte, Colorado. This 21-month campaign is among ARM's longest mobile deployments. Data from SAIL's first year are already helping scientists gain a better understanding of mountain hydrological processes, which can then be applied to improving earth system models.

Like many organizations, ARM dealt with supply chain and inflation impacts during FY2022. In addition, ARM worked through a nationwide helium shortage, which temporarily affected weather balloon launches at the Southern Great Plains atmospheric observatory.

We continued to make progress with our aerial efforts through tethered balloon and uncrewed aerial system missions. Both areas benefited from strong partnerships.

On the covers:

Front – On July 22, 2022, in La Porte, Texas, stormy conditions develop near the main site of the TRacking Aerosol Convection interactions ExpeRiment (TRACER).

Inside – Michelle Kiani prepares to launch a weather balloon from La Porte, Texas, on April 23, 2022, as part of the TRACER campaign.

The tethered balloon crew flew nine missions in FY2022, including many flights in collaboration with DOE's Environmental Molecular Sciences Laboratory (EMSL). The ARM Aerial Facility worked with Mississippi State University's Raspet Flight Research Laboratory to fine-tune the performance of uncrewed aerial systems used in atmospheric research. Later, ARM's uncrewed aerial system took to the skies above the Southern Great Plains observatory for a series of successful flights that both demonstrated operational capabilities and provided useful scientific measurements.

ARM staff also spent much of FY2022 working onsite and remotely to plan for future deployments. The Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) is a yearlong campaign scheduled to start in February 2023 in northern San Diego, California. Later in 2023, ARM is slated to begin a five-year deployment in northern Alabama.

The science and strategy underpinning some of ARM's future and recent fieldwork can be traced back to past campaigns, including extensive experience in polar regions.

ARM has collected more than 25 years of data in the Arctic and participated in several key research efforts in the region. One of them, the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition, brought hundreds of international scientists to the central Arctic in 2019 and 2020.

Data from MOSAiC and ARM's Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) are driving many new papers. COMBLE, which took place in northern Norway around the time of MOSAiC, is inspiring new modeling efforts. You will read much more about COMBLE and MOSAiC in the following pages.

While FY2022 represented a return to the field for many, as always, there was a great deal of activity preparing data for the science community. New and improved value-added products were developed to support wide-ranging science applications. In addition, the team leading ARM's high-resolution modeling activity took on a new challenge simulating deep convection associated with a past ARM campaign in Argentina. Preliminary data from those simulations became available in FY2022. The deep convection simulations and other computationally intensive data processing received a boost with a new Cumulus computing cluster at the ARM Data Center.

The future is exciting for ARM. We will keep pursuing in-person and virtual opportunities to engage with users and the broader scientific community as we move ahead with activities related to achieving our Decadal Vision. As part of new DOE initiatives, ARM will work with students and staff at institutions that are historically underrepresented in atmospheric science. We are continuing to foster research collaborations with EMSL. Also, we are eager to see the new ways in which researchers will engage with ARM data through machine learning, artificial intelligence, and open science.

Despite some lingering pandemic-related challenges in FY2022, ARM remained steadfast in delivering high-quality data to the scientific community. I hope you enjoy reading about ARM's accomplishments and future plans in this report.

Jim Mather
ARM Director

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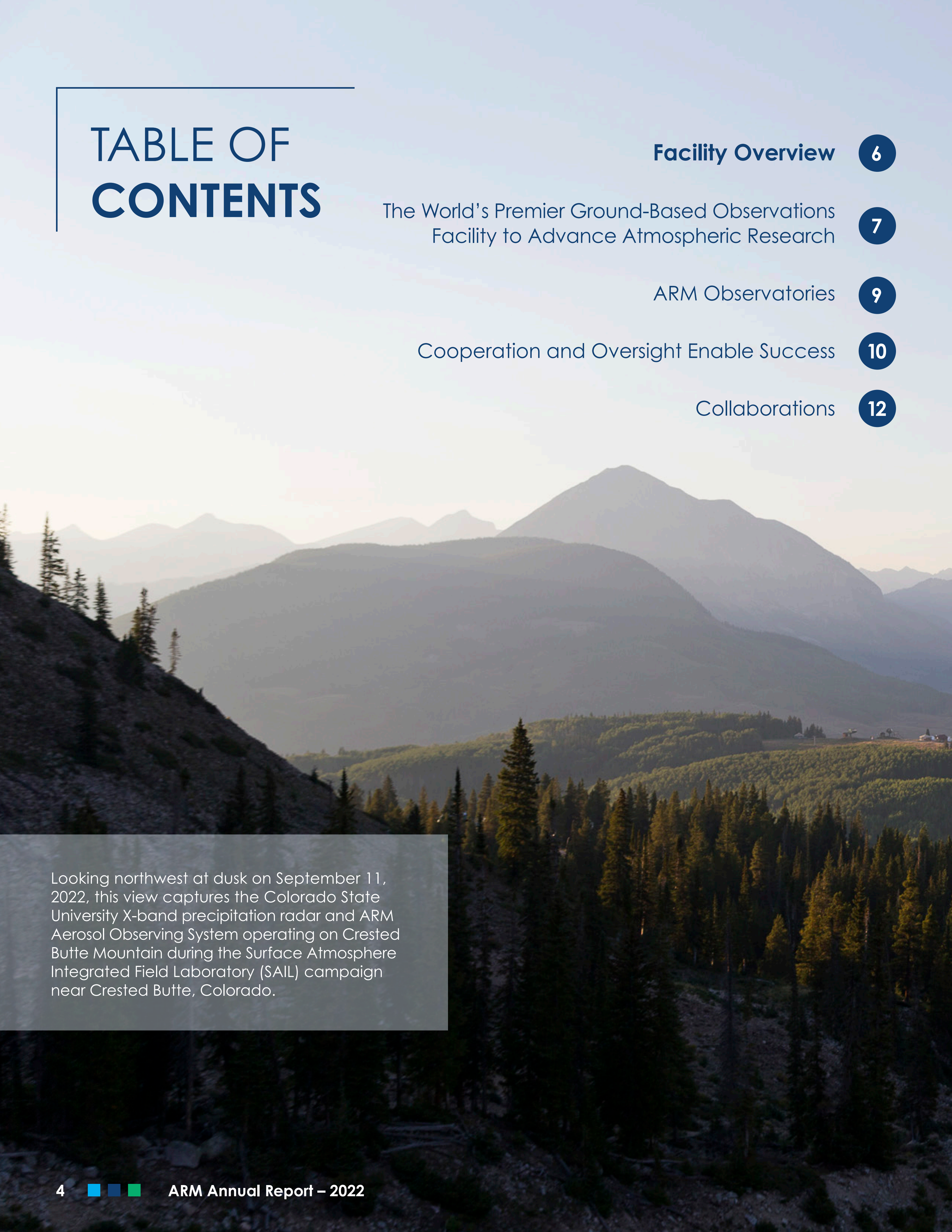


Looking northwest at dusk on September 11, 2022, this view captures the Colorado State University X-band precipitation radar and ARM Aerosol Observing System operating on Crested Butte Mountain during the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign near Crested Butte, Colorado.

FACILITY **OVERVIEW**

The World's Premier Ground-Based Observations Facility to Advance Atmospheric Research

This report provides an overview of the Atmospheric Radiation Measurement (ARM) user facility and a sample of achievements for fiscal year 2022 (FY2022).

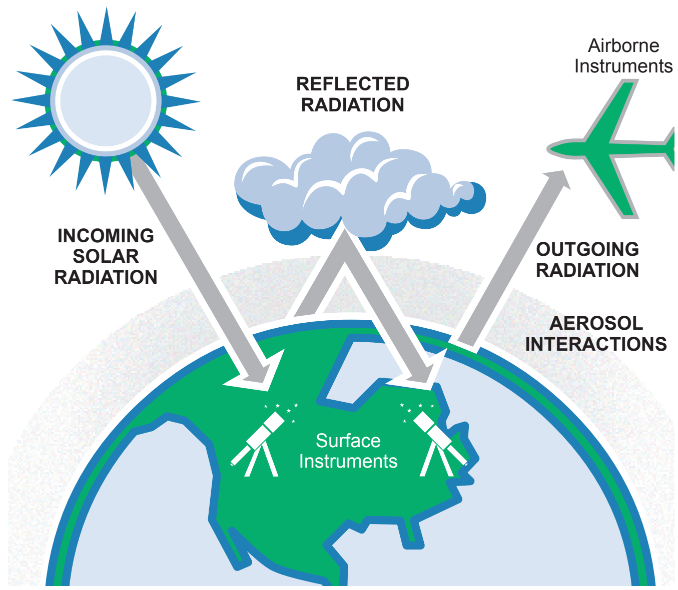
ARM is a multi-laboratory, U.S. Department of Energy (DOE) Office of Science user facility and a key contributor to national and international atmospheric and climate research efforts. ARM offers scientists cutting-edge, ground-based observatories, aerial observation capabilities, and high-performance computing. ARM's capabilities have enabled 30 years of continuous measurements of cloud and aerosol properties and their effects on Earth's energy balance.

Collected since 1992 in diverse climate regimes around the world, ARM data are helping researchers answer basic science questions about clouds, aerosols (small particles in the air), cloud formation, and Earth's energy balance.

ARM observations have yielded insights into a range of scientific issues, including measuring absorption of radiation (energy) from the sun by clouds, aerosols, and water vapor; identifying factors that trigger cloud formation; and detailing the characteristics of aerosol and cloud properties, such as ice crystal sizes. ARM data have led to greatly improved techniques for measuring cloud properties from the ground.

In addition to advancing scientists' understanding of how the atmosphere works, ARM observations contribute to improving the predictability of the earth system. ARM observations are used to improve and evaluate the representations of clouds, aerosols, precipitation, and their interactions with Earth's radiant energy in regional- and global-scale weather and earth system models. Better models help our nation develop sustainable solutions to energy and environmental challenges.

ARM was the first atmospheric research program to deploy a comprehensive suite of ground-based, cutting-edge instruments to continually measure cloud and aerosol properties and their effects on Earth's energy balance. This strategy revolutionized scientists' ability to collect long-term statistics of detailed cloud properties and now serves as a model for similar programs around the world.



Researchers use data collected from ARM ground-based and airborne instruments to study the natural phenomena that occur in clouds and how those cloud conditions affect incoming and outgoing radiative energy.

Strong collaborations between nine DOE national laboratories enable ARM to successfully operate in remote locations around the world. This unique partnership supports the DOE mission to provide for the energy security of the nation. Without the support of the following laboratories, ARM would not be the state-of-the-art facility that it is today.

Sandia National Laboratories | Pacific Northwest National Laboratory | Oak Ridge National Laboratory | NREL | Lawrence Livermore National Laboratory | Berkeley Lab | Los Alamos National Laboratory | Argonne National Laboratory | Brookhaven National Laboratory

ARM Marks 30 Years of Collecting Atmospheric Data

Connecting our past to our future

FREELY AVAILABLE DATA FOR THE RESEARCH COMMUNITY

In **May 1992,** the first ARM data were retrieved from a meteorological instrument array in an Oklahoma farm field. It was the start of something big.

As a U.S. Department of Energy Office of Science user facility, ARM today deploys more than **460 instruments** worldwide and has archived over **3.5 petabytes** of data.

ARM now operates **three fixed-location** and **three mobile observatories** and provides **aerial observation** capabilities.

Through **three decades of data collection,** ARM has also pioneered many concepts of **observation, data management, instrument development,** and **collaboration** that today are taken for granted around the world.

ARM BY THE NUMBERS

7 CONTINENTS, 5 OCEANS, 16 COUNTRIES

~700 FIELD CAMPAIGNS

38 AERIAL FACILITY CAMPAIGNS

23 MOBILE FACILITY DEPLOYMENTS

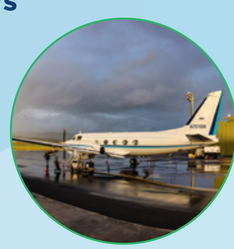
5 SHIP-BASED DEPLOYMENTS

Southern Great Plains
30 years

North Slope of Alaska
25 years

Tropical Western Pacific
18 years

Eastern North Atlantic
9 years



Aerial Facility
16 years

Mobile Facilities
17 years

LEARN MORE ABOUT ARM30: www.arm.gov/about/history/arm30

ARM Observatories

ARM operates three heavily instrumented fixed-location atmospheric observatories, three mobile facilities, and an aerial facility, and provides freely available data for use by scientists around the world. The sites of the fixed-location, long-term observatories were chosen to represent a broad range of atmospheric conditions and processes:

- **Southern Great Plains (SGP) –** Established in 1992, the first ARM observatory includes a heavily instrumented Central Facility near Lamont, Oklahoma, and smaller satellite facilities covering a 150-by-150-kilometer (93-by-93-mile) area in Oklahoma and Kansas.
- **North Slope of Alaska (NSA) –** Since 1997, ARM has operated a site at Utqiaġvik (formerly Barrow) near the edge of the Arctic Ocean.
- **Eastern North Atlantic (ENA) –** In operation since 2013, the youngest ARM observatory is located on Graciosa Island in the Azores, an area characterized by a wide variety of meteorological conditions and cloud types, including marine stratocumulus clouds.

Measurements obtained at the fixed atmospheric observatories are supplemented with data obtained from intensive field campaigns proposed by the scientific research community. Campaigns may use an ARM Mobile Facility (AMF), a collection of advanced measurement systems that can be deployed to locations around the world for six months to two years, or capabilities of the ARM Aerial Facility (AAF).

Each fixed or mobile observatory operates a broad suite of advanced measurement systems to provide high-quality research data sets. The current generation of instruments includes three-dimensional cloud and precipitation radars, advanced lidars that provide information such as profiles of aerosol extinction and vertical air motion, infrared interferometers that measure radiant energy from the atmosphere, in situ aerosol observing systems, microwave radiometers, and balloon-borne sounding systems, among others.

Once collected, the data from all ARM observatories are carefully reviewed for quality and stored in the ARM Data Center for use by the atmospheric science community.

As part of this effort, ARM personnel apply scientific methods developed in the research community to create enhanced value-added data products. All ARM data products are made available at no cost for the scientific community through the ARM Data Center to aid in further research.

ARM Eyes Northern Alabama for New Deployment

ARM is moving ahead with plans to begin a five-year deployment in the Southeastern United States in 2023.

During the December 2021 American Geophysical Union (AGU) Fall Meeting, Chongai Kuang, who leads the site science team for the new deployment, shared specifics about site planning.

Kuang announced that northern Alabama was the preferred location. This decision was based on science-driven siting criteria developed and applied by the site science team. DOE is funding the team's work through ARM and Atmospheric System Research (ASR).

The deployment's main site is expected to be near the U.S. Forest Service Black Warrior Work Center in the Bankhead National Forest, about 60 miles southwest of Huntsville. The "Black Warrior" name is commonly seen in Alabama to recognize a 16th-century Native American chief.

Kuang noted the area's proximity to existing radar, a lightning mapping array, air quality monitoring, and atmospheric profiling infrastructure. In addition, the area has relatively open land that could host ARM radars.

During AGU, the site science team also sought input on the planned science drivers of the deployment. The team is interested in processes tied to aerosols, convective clouds, and land-atmosphere interactions.

In FY2022, the site science and operations teams took additional trips to Alabama to evaluate possible instrument locations. They also met with potential local partners with an eye on pursuing what Kuang called "collaborative, interdisciplinary, transformational science."

ARM plans to install the new deployment in phases. The main site will be operational first, followed by aerial platforms and supplemental sites.

From left to right, Shawn Serbin, Scott Giangrande, and Nicki Hickmon observe an area near Alabama's Bankhead National Forest for potential ARM radar siting during a November 2021 site visit. Serbin and Giangrande are topical area leads on the site science team for ARM's upcoming Southeastern U.S. deployment. Hickmon is ARM's associate director for operations.

Cooperation and Oversight Enable Success

Nine DOE national laboratories and numerous government agencies, universities, private companies, and foreign organizations contribute to ARM. Each entity serves a vital role in managing and conducting the operation and administration of the user facility. These entities include:

- **DOE's Biological and Environmental Research program in the Office of Science –** Program managers provide oversight and accountability for ARM operations.
- **Infrastructure Management Board (IMB) –** DOE works with the IMB, whose members represent all areas of the facility, to coordinate and manage the scientific, operational, data, financial, and administrative functions of ARM.
- **ARM Science Board –** An independent review body that reviews proposals for the ARM Mobile Facility and ARM Aerial Facility to ensure appropriate scientific use. The DOE ARM program manager selects the board members.
- **Atmospheric System Research (ASR) –** A DOE-funded, observation-based atmospheric research program that represents the largest group of ARM users. ASR is an important source of scientific guidance for establishing ARM priorities.
- **ARM User Executive Committee –** An elected constituent group that provides feedback on the facility's activities and serves as the official voice of the user community in its interactions with ARM management.

ARM Solicits Community Feedback on Facility Capabilities

In FY2022, ARM management continued to engage with members of the scientific community to support activities related to its latest Decadal Vision and Triennial Review.

ARM created a new mechanism for people to request measurements, data products, or data services that could help advance their science.

During a community input webinar in November 2021, ARM Director Jim Mather introduced a new web form for providing input outside of regular science meetings and activities. People can use the form to ask for new ARM capabilities or expansion of existing capabilities. Periodically, requests will be evaluated on their potential impact and feasibility.

In its 2020 Triennial Review, ARM was asked to provide an updated strategy for operating its vertically pointing and scanning cloud radars. Also, ARM was asked to continue working on its process for reviewing assets and their scientific impact.

To that end, an ARM team developed a set of recommendations for the scanning cloud radars currently in the field. Also, ARM held a virtual series of four radar listening sessions in March and April 2022. Hosted by ARM Instrument Operations Manager Adam Theisen, these sessions collected input from users about ARM's radar operations.

Feedback from the sessions appears in the ARM FY2023 Radar Plan, released in September 2022. This plan lays out ARM's priorities to routinely manage select radar operations during FY2023.

Input from the radar listening sessions is also contributing to a roadmap that is being developed to better plan ARM's radar priorities and operations.

ARM is considering the future of its scanning cloud radars. Though ARM has operated these instruments with more success in recent years, they still present operational challenges because of their complexity and need for dedicated staff resources.

Revitalized Constituent Groups Work with ARM to Set Priorities

ARM is guided by several constituent groups that help steer the facility's overall direction. Combining scientific and technical expertise from within and outside ARM, these groups offer input on how ARM can best meet its science goals and those of the atmospheric research community.

In particular, the Aerosol Measurement Science Group (AMSG) and Cloud and Precipitation Measurements and Science Group (CPMSG) provide recommendations to help ARM increase the scientific impact of its data in mission-critical areas.

Both groups ramped up their efforts after announcing new chairs in FY2022. Gannet Hallar of the University of Utah and Timothy Onasch of Aerodyne Research Inc. took over as AMSG co-chairs, and Christine Chiu of Colorado State University became the CPMSG chair.

To help focus its activities, the AMSG formed four subgroups: Measurement Techniques, Measurement Quality, Measurement Modeling, and Measurement Sampling.

The AMSG is working with ARM management to explore the possibility of moving from continuous operations to intensive operational periods for some aerosol instrumentation starting with the Southern Great Plains atmospheric observatory. This is being done with an eye toward improving science outcomes and operational efficiency. The AMSG and ARM management are also considering the potential addition of aerosol instruments at the North Slope of Alaska observatory.

Meanwhile, the CPMSG identified eight key subtopics in cloud and precipitation science for ARM to address. Input and discussions related to these subtopics are documented in matrices that show pathways from roadblocks to improved understanding and modeling. This matrix mechanism will help ARM establish priorities and was rolled out to all ARM users during a community input webinar in November 2021.

The Aerosol Measurement Science Group and ARM management are discussing the possible addition of aerosol instruments at the North Slope of Alaska atmospheric observatory.

User Executive Committee Makes Recommendations to ARM

ARM's User Executive Committee (UEC) serves as the voice of the user community in interactions with facility management. In FY2022, much of the UEC's focus was on the four subgroups it created in early 2021 to continue previous UEC work and start new efforts to broaden community outreach. These subgroups are:

- Undergraduate Outreach and Increasing Diversity
- Measurement Uncertainty and Communicating Calibrations
- Enhancing Communication with the Satellite Community
- Enhancing Communication with the Modeling/ DOE Energy Exascale Earth System Model (E3SM) Community.

All four subgroup chairs wrote blogs for the ARM website to formally introduce their subgroups to the user community. Each chair then outlined their subgroup's recommendations to ARM. They asked users to share their thoughts on the recommendations or offer new ideas that the subgroup could bring back to the larger UEC and ARM management.

The subgroups' recommendations to ARM included:

- inviting a speaker to discuss diversity, equity, and inclusion at the annual Joint ARM User Facility/ Atmospheric System Research (ASR) Principal Investigators Meeting
- expanding ARM's science translator group to support calibration needs
- creating a page for the ARM website about satellite products by ARM
- exploring more opportunities to connect ARM and E3SM
- developing a user community survey to gauge ARM's effectiveness.

Most of these recommendations have been implemented or are in the process of being implemented by ARM.

Elections for UEC members occur every two years. In August and September 2022, ARM sought nominations for positions opening in January 2023.

Collaborations

By its very nature, ARM is a collaborative entity. As a national scientific user facility, ARM was designed to provide scientists with atmospheric observations needed to conduct their research. While ARM works closely with the Atmospheric System Research (ASR) program to meet the objectives of DOE's Earth and Environmental Systems Sciences Division, ARM also supports research by scientists with diverse programmatic and institutional affiliations around the United States—and the world.

In addition, ARM frequently leverages measurements obtained by other organizations to provide a more complete description of the environment around its observatories and regularly coordinates with other agencies on field campaigns. Though each agency has its own goals and priorities, the coordination of observational activities produces more comprehensive data and leads to broader science outcomes. These collaborations are key to ARM's success.

ARM/ASR Open Science Workshop Draws an Engaged Audience

With support from DOE, ARM and Atmospheric System Research (ASR) seek to make scientific research, data, and software more open and accessible.

The ARM/ASR Open Science Virtual Workshop 2022, held in May, provided a forum for discussion and discovery of open-science efforts within the atmospheric research community.

The workshop brought together people from DOE national laboratories, federal agencies, academia, and industry. During the four-day workshop, 128 people attended at least one day.

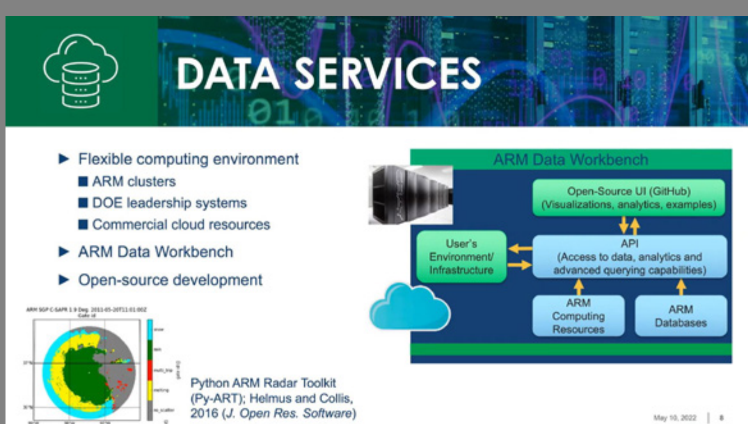
ARM provides tools for users to interact with its data, which are freely available online through Data Discovery. For example, ARM supports open-source toolkits for working with radar and atmospheric time-series data.

Users can access high-performance computing resources at the ARM Data Center, and ARM's JupyterHub system connects multiple users working on a single project.

On the GitHub software development platform, ARM hosts areas where staff and scientists can download and contribute code.

Other federal agencies are also highly interested in open science. NASA has declared 2023 as the Year of Open Science to increase global engagement in open science.

Throughout the workshop, participants shared how they are creating and using open-source software and hardware. Tutorials allowed attendees to try out open-science computing resources such as the Python programming language, GitHub, Data Discovery, and ARM-supported software packages.



During the ARM/ASR Open Science Virtual Workshop 2022, ARM Director Jim Mather discussed how open science connects to ARM's Decadal Vision, which describes ARM's plans to address scientific challenges over the next 10 years.

Through FICUS Program, Scientists Integrate User Facility Capabilities

ARM and DOE's Environmental Molecular Sciences Laboratory (EMSL) are continuing their research alliance as part of the Facilities Integrating Collaborations for User Science (FICUS) program.

In FY2022, the first two ARM/EMSL FICUS projects began, while four were chosen to start in FY2023.

Both sets of projects use ARM data to study aerosols. The projects are also helping EMSL refine its new automated aerosol sampler.

The sampler collects time-resolved aerosol samples of various sizes for offline analysis. Used on ARM's tethered balloon system, the sampler produces spatial chemical composition data sets for atmospheric studies.

In FY2022, the sampler operated during tethered balloon system flights at ARM's Southern Great Plains atmospheric observatory. The sampler also flew during the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign near Crested Butte, Colorado, and the TRacking Aerosol Convection interactions ExpeRiment (TRACER) near Houston, Texas.

FICUS support has enabled researchers to capture aerosols and analyze their properties using advanced techniques at EMSL.

Susannah Burrows led a study of how agricultural dust over the Southern Great Plains contributes to the development of particles that seed ice formation in clouds. Alexander Laskin focused on aerosol composition, properties, and deposition during SAIL.

For FY2023, the following FICUS awardees will integrate ARM and EMSL capabilities:

- Allison Aiken will study aerosols in the mountainous terrain of the Upper Colorado River.
- Allen Goldstein will research aerosol-cloud interactions and aerosol processes.
- Allison Steiner will investigate vertical gradients of biological aerosols during TRACER.
- Maria Zawadowicz will examine the vertical profile of biological aerosols during SAIL.

In FY2023, ARM will continue tethered balloon system flights during the SAIL campaign in Colorado.

Focus on Artificial Intelligence in Atmospheric Science

In recent years, the atmospheric science community has intensified its focus on applying artificial intelligence (AI) and machine learning to climate science. DOE has, in turn, become an essential driver in these conversations, launching the Artificial Intelligence for Earth System Predictability (AI4ESP) initiative in 2020.

AI4ESP is a multi-laboratory effort to develop a new approach to earth system predictability focused on enabling AI across field, lab, modeling, and analysis activities. Staff from ARM and DOE's Atmospheric System Research (ASR) hold key leadership roles in AI4ESP.

A call in 2020 drew 156 white papers that described new and innovative approaches to improving earth system predictability, particularly related to the integrated water cycle and associated extremes. Many of the papers included connections to ARM data and ASR priority research areas.

In late 2021, a five-week, 17-session workshop followed the white paper call. During the workshop, attendees discussed ideas and opportunities for incorporating AI as a component of earth system models and observations.

In September 2022, with input from 740 participants from 178 institutions, the AI4ESP Workshop Report was issued. It can be found at ai4esp.org. The report details grand challenges and research priorities that came from the workshop.

The AI4ESP team will next chart a strategy that will, in the near term, include:

- open benchmark data sets
- AI-enabled observations and data products based on gaps
- seed efforts to demonstrate the potential of AI in existing programs and modeling frameworks
- cross-disciplinary collaborations to initiate activities.

ARM Data Services Manager Giri Prakash led a session on data acquisition to distribution as part of the AI4ESP workshop in late 2021.

KEY ACCOMPLISHMENTS

Featured Field Campaigns

In addition to providing continuous data collections from fixed observatories around the world, ARM sponsors field campaigns for scientists to obtain specific data sets or to test and validate instruments. The following pages highlight key campaigns in FY2022.

Study of Stormy Houston Moves from Observations to Analysis

Convection conveys heat and moisture upward through a turbulent atmosphere. This process creates clouds that are puffy and rain-free as well as clouds that are linked to thunderstorms.

Scientists want to know more about convection. How do convective clouds form, evolve, and dissipate? What role do aerosols play? How are cloud and aerosol processes different in coastal areas influenced by sea breezes, cityscapes, and rural land?

These questions and their social imperatives inspired a yearlong ARM field campaign called the TRacking Aerosol Convection interactions ExpeRiment (TRACER). Observations in the Houston, Texas, area ended in September 2022.

The campaign included a four-month period marked by an increased tempo of operations, more personnel in the field, and more instruments at work.

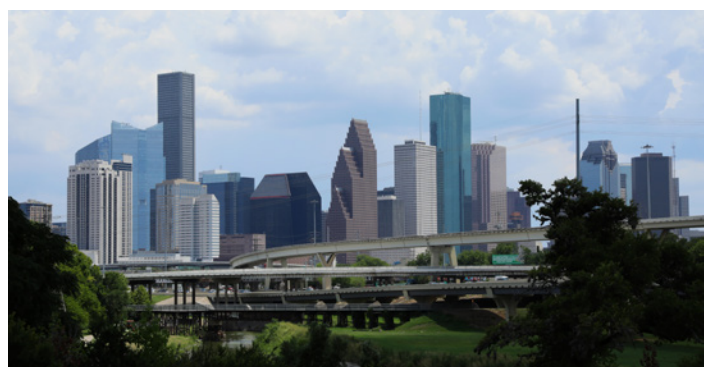
TRACER has now entered a phase of data analysis, model creation, and publications that could last a decade or more. Such durability is in the rich data.

"I don't think there has ever been another urban coastal study like this," said TRACER Principal Investigator Michael Jensen of Brookhaven National Laboratory in New York.

Jensen cited the number of other agencies with observational assets (five), related campaigns (more than 10), institutions (45), field participants (150), datastreams (188), and radiosonde launches (1,885).

TRACER and its related campaigns also relied on a wide variety of instrument platforms. There were satellites, crewed and uncrewed aircraft, truck- and trailer-mounted mobile sensors, tethered balloons, radiosondes, watercraft, and dozens of surface instruments.

Eventually, TRACER data will help inform models of cloud-aerosol interactions worldwide.



Houston, Texas, was the backdrop for ARM's TRACER campaign, which closed its yearlong observational phase in September 2022.

"I don't think there has ever been another urban coastal study like this."

—Michael Jensen, TRACER principal investigator from Brookhaven National Laboratory in New York

Campaign in the Rockies Completes Data-Rich First Year

Researchers are analyzing the first year of data from ARM's 21-month Surface Atmosphere Field Laboratory (SAIL) campaign, which aims to improve understanding and modeling of the processes that affect mountainous water cycles.

Since September 2021, multiple observation sites near Crested Butte, Colorado, have operated in a mountain valley feeding the Upper Colorado River—a fount of $1 trillion in downstream economic activity.

By the time the campaign ends in June 2023, SAIL data will provide key values for snow, aerosols, surface energy, and other factors that modelers require.

"Better models will arise from the data," said SAIL Principal Investigator Daniel Feldman of Lawrence Berkeley National Laboratory in California.

In SAIL's first year, instruments recorded data on one of the driest autumns and early winters on record. Then came the start of what Coloradans call "the Santa Slammer," when 100 inches of snow fell in just a few days.

During the rest of the winter, there were times with a lot of snowpack on the ground but little precipitation in the air.

SAIL witnessed a dusty, windy spring and an active summer. Monsoon rains were so heavy, said Feldman, "we're still trying to get our brains around it. Storm after storm, practically every single day."

At the end of SAIL operations, researchers will have detailed measurements of interannual variability across two autumns, two winters, two springs, and one summer.

"We have this long runway," said Feldman. "Mother Nature has told us many stories and will be telling us many more."

"Better models will arise from the data."

—Daniel Feldman, SAIL principal investigator from Lawrence Berkeley National Laboratory in California

In January 2022 during the SAIL campaign, ARM's Aerosol Observing System, right, operates alongside a precipitation radar from Colorado State University on Crested Butte Mountain.

Snow Campaign Resumes in Alaska after Pandemic Delay

A group of researchers waited longer than expected to watch snow melt in Utqiaġvik, Alaska.

ARM's Snow ALbedo eVOlution (SALVO) field campaign is an ongoing effort to track seasonal changes on tundra and sea ice from an entirely snowy landscape to complete melt.

Initially, SALVO was scheduled to capture the 2019, 2020, and 2021 melt seasons. Researchers completed their 2019 fieldwork, but the COVID-19 pandemic pushed the final two field seasons to 2022 and 2023.

Led by Jennifer Delamere at the University of Alaska Fairbanks, the SALVO group began its 2022 fieldwork in mid-April. Team members set up four sites to collect measurements before and during the melt.

The group returned to Utqiaġvik on May 15 and planned to leave June 15 based on when the snow melted in previous years. However, the melt started June 9 and finished around June 21—an anomaly related to a changing arctic climate.

From left to right, Hannah Chapman-Dutton, Anika Pinzner, and Serina Wesen take measurements in May 2022 on Elson Lagoon as part of the SALVO field campaign in northern Alaska.

New Southern Great Plains Facility Hosts First Campaign

Researchers visiting ARM's Southern Great Plains Central Facility have a new building for their instruments.

The new Guest Instrument Facility hosted its first field campaign in October 2021.

Eleanor Browne led the Characterizing New Particle Formation and Growth campaign. Browne is with the University of Colorado Boulder and the Cooperative Institute for Research in Environmental Sciences. Her campaign was supposed to start in May 2020, but it was delayed because of the COVID-19 pandemic.

Browne's team brought mass spectrometers to measure the concentration of gas-phase bases (e.g., ammonia and amines) and the chemical composition of ambient ions. These measurements, combined with ARM data, will help researchers study how different chemical processes affect particle growth.

The new Guest Instrument Facility is 2,800 square feet—almost double the size of the old facility. It can accommodate larger or vertically pointing instruments such as lidars. In 2022, a tornado shelter was added.

Bri Dobson, a member of Eleanor Browne's research team, works in the new Guest Instrument Facility at ARM's Southern Great Plains Central Facility.

Past Campaign Results

Studies Still Rain Down from 2011 Convective Cloud Campaign

In spring 2011, dozens of scientists and technicians fanned out into the Oklahoma countryside and the skies above it to execute an epic field campaign on the processes that distribute heat and moisture in the atmosphere and create thunderstorms.

The Midlatitude Continental Convective Clouds Experiment (MC3E), a joint effort between ARM and NASA, took place at ARM's Southern Great Plains atmospheric observatory. MC3E's basic objective was to monitor and record, in three dimensions, the primary realities behind convection: clouds, precipitation, moisture, and wind.

Within months of finishing, MC3E had created rich data sets and satellite intercomparisons that proved to be long-lived. The data have inspired close to 100 papers so far.

"We're still seeing publications come out of MC3E (even though) it was just six weeks long," said MC3E Principal Investigator Michael Jensen of Brookhaven National Laboratory in New York. The three most recent studies appeared in September and October 2022.

Jensen recently led another ARM campaign on convective processes—one for which MC3E helped him prepare. The yearlong TRacking Aerosol Convection interactions ExpeRiment (TRACER) took measurements at three main observation sites near Houston, Texas.

Some MC3E publications, said Jensen, point to an important legacy that scientists hope TRACER will repeat: improvements in models that describe convection, estimate precipitation, and simulate the behavior of convective clouds.

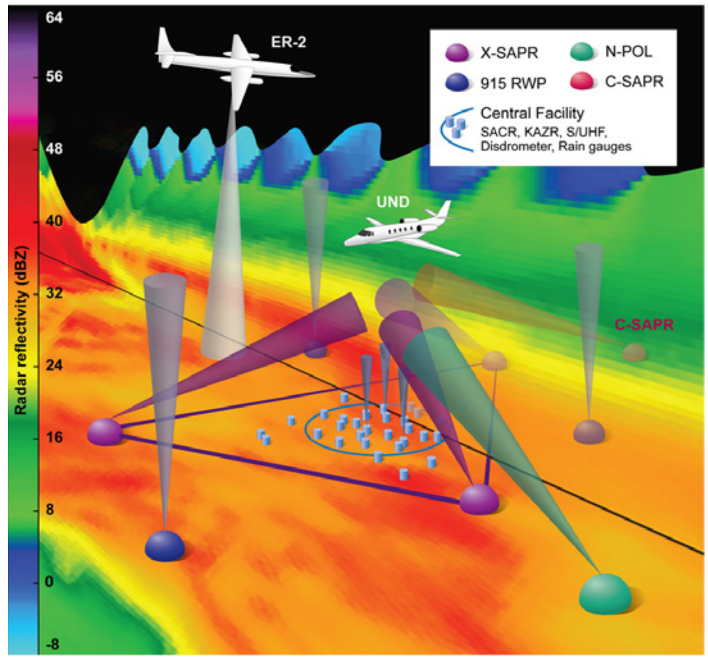
Jensen noted a 2017 paper led by Gregory Elsaesser at Columbia University. The paper used data from MC3E and three other campaigns to create an improved representation of cloud-borne convective ice in the NASA Goddard Institute for Space Studies' global climate model.

"It's a case where data we collected in the field directly improved a model representation of clouds," said Jensen, calling this case "something to be proud of."

MC3E also provided a training ground for a large cohort of early career scientists, including current ARM users Scott Collis, Brenda Dolan, Scott Giangrande, and Adam Varble. They learned to coordinate a then-new multiscale observational strategy that involved two aircraft, six networked radiosonde sites, and an array of multifrequency ground radars.

Jensen and the others also got a grounding in the kind of weather forecasting, coordination, and material logistics that later informed TRACER. Collis, Giangrande, and Varble were among the co-investigators for the Texas campaign.

TRACER addressed "very similar underlying science," said Jensen, but it was "10 times the scale" of its older, smaller, and influential cousin, MC3E.



The MC3E campaign employed radars, instrumented aircraft, and other sensors to measure the properties of storms over the central United States.

ARM radars captured convective cloud data during MC3E.

See all MC3E publications bit.ly/MC3E_publications

A Decade Later, Marine Cloud Campaign Continues to Inspire Research

On September 22, 2012, the Horizon Lines container ship *Spirit* left Los Angeles, California, and set course for Honolulu, Hawaii. This voyage marked the beginning of the yearlong Marine ARM GPCI Investigation of Clouds (MAGIC).

MAGIC researchers, led by Ernie Lewis of Brookhaven National Laboratory in New York, investigated how two climate-critical marine cloud regimes—stratocumulus and shallow cumulus—transition from one to the other. These clouds blanket 30% of global oceans, so it is important to understand their role in cloud-climate feedbacks.

Characterized by drizzle, stratocumulus clouds predominate above the cold waters of coastal California. The high reflectivity and vast horizontal extent of stratocumulus clouds strongly influence Earth's energy budget.

Shallow cumulus clouds occur over warmer subtropical waters near Hawaii. They are less reflective and create more rain than stratocumulus, and they significantly influence global surface evaporation.

The transition between stratocumulus and shallow cumulus is well documented, but its details are not. That means global weather and climate models do not accurately represent the transition between these cloud regimes. Key uncertainties are the location where stratocumulus clouds break up, the amounts of such clouds, and the frequency of both types of cloud coverage.

To address observational gaps, MAGIC was the first ship-based campaign to use an ARM Mobile Facility. *Spirit* hosted three 20-foot cargo containers packed with a suite of marine-capable ARM instruments. Radars, lidars, radiometers, a total sky imager, a meteorological station, and other instruments measured key atmospheric properties.

By the end of September 2013, *Spirit* had logged 20 transects during almost 200 days at sea.

Data from MAGIC have so far informed 60 publications, including journal articles, presentations, and technical reports.

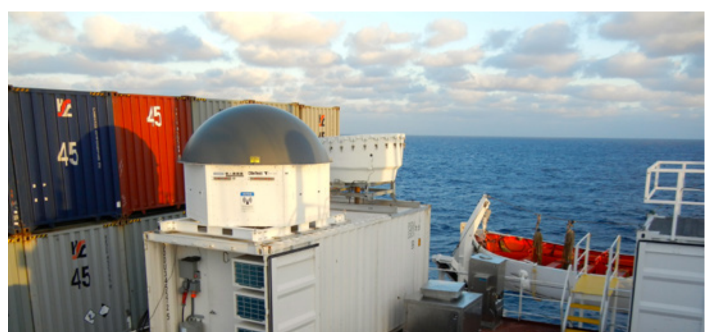
A May 2022 paper used data from MAGIC and five other campaigns to evaluate aerosol predictions in earth system models. Another 2022 paper examined the microphysical processes of drizzle by applying a machine-learning algorithm to MAGIC and other ARM data.

Other papers used MAGIC data to identify shortwave radiation errors (2018), investigate ship-following large-eddy simulations (2017), and study the link between ice-nucleating particles and sea-spray aerosols (2015).

A March 2015 paper by Lewis and two authors from McGill University outlined MAGIC's rationale, methods, and preliminary conclusions.

After *Spirit*'s final measurement voyage almost a decade ago, Lewis praised the "incredible ride" of MAGIC. "It has succeeded beyond my wildest expectations."

During a year of MAGIC transects, the container ship *Spirit* followed regular routes to measure cloud transitions.



Aboard *Spirit*, ARM's remote-sensing instruments measured the properties of clouds in transition.

See all MAGIC publications bit.ly/MAGIC_publications

The COMBLE Campaign: A Review

Cold-air outbreaks (CAOs) are high-latitude cloud regimes that signify the thermal instability of cold-air masses from frozen surfaces hitting adjoining warm water.

CAOs were the focus of the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE). ARM conducted the COMBLE campaign from December 2019 through May 2020 in northern Norway.

The May 2022 issue of the *Bulletin of the American Meteorological Society* included a review paper on COMBLE.

Led by the University of Wyoming's Bart Geerts, COMBLE took place at two ARM-instrumented island sites.

Scientists think that CAOs may influence several atmospheric processes, yet their properties remain little known.

Two years after COMBLE, researchers are using its unprecedented data set to test and improve the treatment of CAOs in climate models.

"The exciting thing about the COMBLE data is that they are being used not just to learn about CAO clouds," said Geerts.

Reference

Geerts B, S Giangrande, G McFarquhar, L Xue, S Abel, J Comstock, S Crewell, P DeMott, K Ebell, P Field, T Hill, A Hunzinger, M Jensen, K Johnson, T Juliano, P Kollias, B Kosovic, C Lackner, E Luke, C Lüpkes, A Matthews, R Neggers, M Ovchinnikov, H Powers, M Shupe, T Spengler, B Swanson, M Tjernström, A Theisen, N Wales, Y Wang, M Wendisch, and P Wu. 2022. "The COMBLE campaign: a study of marine boundary-layer clouds in Arctic cold-air outbreaks." *Bulletin of the American Meteorological Society* 103(5):E1371-E1389, https://doi.org/10.1175/BAMS-D-21-0044.1.

ARM collected data on the Norwegian island of Andøya during the 2019–2020 COMBLE campaign.

'Nova' Delivers Arctic Experience to Viewers

In October 2022, the PBS science series "Nova" first aired "Arctic Drift," the story of the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition.

The hourlong "Nova" episode is a version of a documentary film originally produced for a German broadcaster. Germany's Alfred Wegener Institute led MOSAiC from September 2019 to October 2020.

Researchers went to the central Arctic to study the atmosphere, sea ice, ocean, ecosystem, and biogeochemistry in a part of the world warming faster than the rest of the planet.

More than 50 ARM instruments collected measurements during MOSAiC. Expedition co-coordinator Matthew Shupe, who appeared in "Arctic Drift," was the principal investigator for ARM's MOSAiC deployment.

"Arctic Drift" documents the MOSAiC team's scientific and logistical successes, including the collection of 150 terabytes of data. The episode also explores challenges faced in the harsh, remote environment.

"Arctic Drift" is available to watch at www.pbs.org/wgbh/nova/video/arctic-drift.

MOSAiC personnel trudge through snow near the German icebreaker *R/V Polarstern*, which carried ARM instruments during the 13-month expedition.

Research Highlights

ARM Sites Build Accurate Picture of How Wind Changes Local Environment

The temperature and humidity of the atmosphere vary from place to place. These differences are caused by local influences, including interactions with the land surface, and advection, when wind blows in new and different air.

Observations generally measure atmospheric properties that include both local influences and advection effects. It can be challenging to identify how much advection specifically contributes to an area's temperature and humidity.

Mathematics shows that data from a network of observing sites should allow researchers to determine advection and other wind-based properties. Researchers applied a mathematical technique to data from ARM's Southern Great Plains (SGP) atmospheric observatory in a March 2022 study in the *Journal of Atmospheric and Oceanic Technology*. They found that SGP instruments are nearly ideally spaced for observing advection.

"By using this technique to subtract out the influence of advection, it is easier to measure how the land surface directly influences the atmosphere," said the paper's lead author, Tim Wagner of the University of Wisconsin–Madison.

The SGP has five profiling sites, which gather data on temperature, humidity, and wind. Combining these observations creates a rich picture of the bottom kilometer of the atmosphere.

Researchers compared real-world SGP observations with modeled data. They found that the advection calculated from observations and the model output were closely matched.

The team determined why the observation network produces such accurate advection.

At 70 kilometers (about 43 miles) apart, the distance between the profiling sites is nearly ideal spacing. If the sites are closer, uncertainties in the data are too large for the calculations. If the sites are farther apart, the advection effects become unobservable. The SGP sits in a so-called Goldilocks zone for measuring these key atmospheric properties.

Reference

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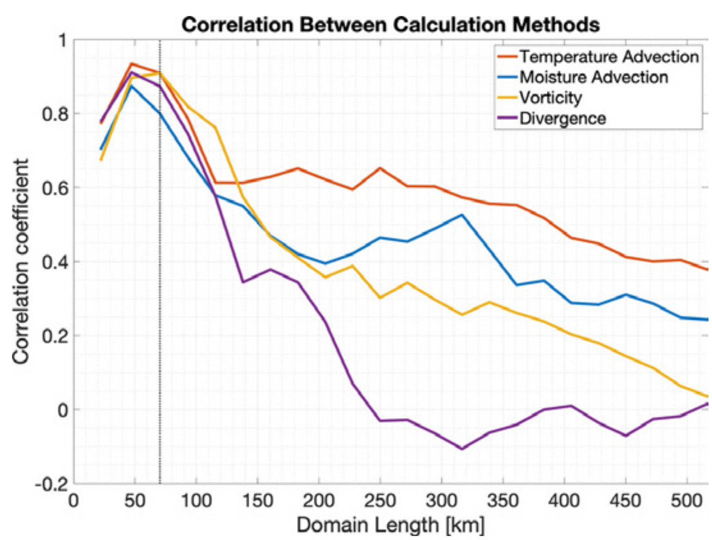
ARM's Southern Great Plains atmospheric observatory has five profiling sites, including one at its Central Facility.



At 70 kilometers (about 43 miles) apart, represented by the dashed line, the Southern Great Plains profiling sites are ideally spaced to collect advection data for models. (*Copyrighted image from the journal.***)**

ARM Data Add New Perspective on How Aerosols Affect Convective Depth

Atmospheric aerosols can change the size of droplets in clouds. Greater numbers of aerosol present increase the number of small cloud droplets. Some, but not all, studies have shown that greater numbers of small droplets can invigorate updrafts to produce taller clouds. Therefore, more investigation of aerosol effects on cloud behavior is needed.

A team from the University of Utah and Pacific Northwest National Laboratory in Washington state set out to explore how aerosols affect large, deep clouds. Such clouds are integral to the global atmospheric circulation and energy balance.

Researchers studied data from ARM's 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in Argentina. Their findings appeared in a paper published online in February 2022 by the *Journal of the Atmospheric Sciences*.

"The effect of aerosol concentration on the depth of storms is a difficult question to answer with observations," said the paper's lead author, Peter Veals of the University of Utah. "This study represents one of the most careful and rigorous efforts to date to control for meteorology, isolating the aerosol concentration signal."

The researchers used multiple statistical techniques, including machine learning, to analyze relationships between different aerosol concentration metrics and meteorological conditions. All aerosol metrics correlate with key meteorological factors that strongly affect cloud depth. The analysis showed that one commonly used metric, aerosol optical depth, is not a good proxy for the concentration of aerosol entering the cloud base.

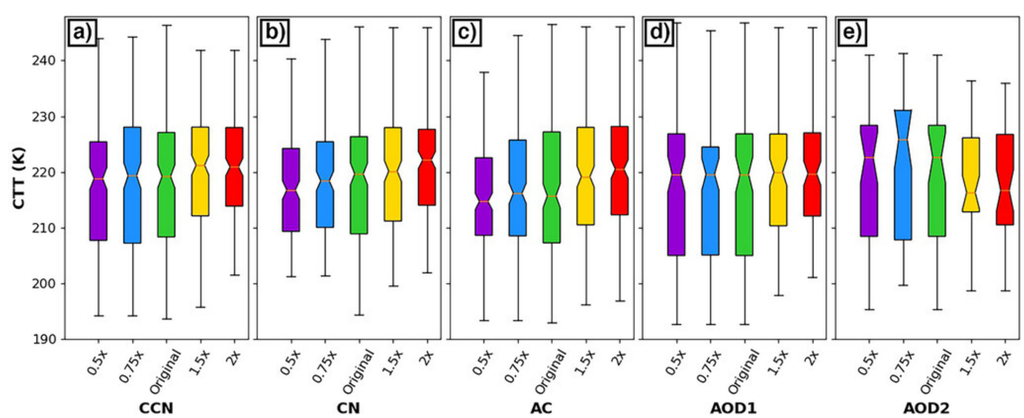
Critically, the team found no evidence that greater aerosol concentrations led to taller clouds. In fact, researchers noted that increases in aerosol concentration correlated with warmer cloud tops that had shallower depths.

While it is unclear how well these findings apply to other geographical regions, they add an important perspective to the ongoing debate over how aerosols affect deep clouds.

Reference

Veals P, A Varble, J Russell, J Hardin, and E Zipser. 2022. "Indications of a decrease in the depth of deep convective cores with increasing aerosol concentration during the CACTI campaign." *Journal of the Atmospheric Sciences* 79(3):705-722, https://doi.org/10.1175/JAS-D-21-0119.1.

The CACTI campaign gathered data from clouds like these in northern Argentina.



In these box-and-whisker distributions of machine learning-predicted cloud top temperature, multiplier changes (0.5, 0.75, 1.5, and 2) are applied to input values of (a) cloud condensation nuclei, (b) condensation nuclei, (c) aerosol concentration, and (d-e) two differently sampled aerosol optical depths with all non-aerosol inputs held constant. Non-overlapping notches indicate statistically significant differences in median values. (*Copyrighted image from the journal.***)**

Massive Arctic Expedition Generates Unprecedented Observations

The Arctic is undergoing dramatic changes, including rapid warming and diminished sea ice. Scientists need to observe and accurately model these changes to understand the Arctic and its impact on the rest of the global system.

For over a year, the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition collected coupled atmosphere, ice, and ocean measurements in the central Arctic. In February 2022, *Elementa: Science of the Anthropocene* presented a summary of MOSAiC and an overview of key research program elements related to the atmosphere and its interactions.

MOSAiC gathered atmospheric observations in four main categories: the atmospheric state, clouds and precipitation, gases and aerosols, and energy budgets. These measurements will enable researchers to gain a holistic perspective on the Arctic's atmosphere and the ways in which it interacts with the sea ice, snow, ocean, and ecosystem.

"The observations we've brought home from MOSAiC offer an unprecedented view of a system in rapid transition," said University of Colorado Boulder researcher Matthew Shupe, the paper's lead author and the expedition's co-coordinator. "They will enable major advances in representing key arctic processes in earth system models."

MOSAiC is the largest scientific expedition in the Arctic to date, requiring collaboration among 20 nations. An ARM portable observatory served as the centerpiece of MOSAiC's atmospheric program.

The research icebreaker *R/V Polarstern* is embedded in sea ice during the MOSAiC expedition in February 2020.

Though MOSAiC ended relatively recently, in October 2020, scientists are already using the data in impactful ways.

Shupe and collaborators analyzed MOSAiC data to understand snowfall accumulation on sea ice during the winter. They used radar data that are largely immune to errors induced by blowing snow. The team found that snow accumulated most in the spring, with about half of the total snow coming from weak precipitation events. These results are important for understanding the significant role that snow plays in insulating sea ice.

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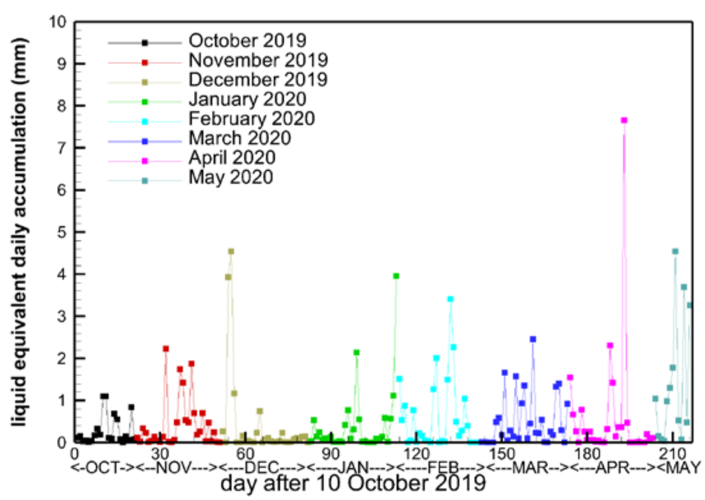

Radar data provide daily snowfall accumulation from part of the MOSAiC expedition. This represents just one of the measurement types obtained during MOSAiC. (*Copyrighted image from the journal.*)

Turbulence Influences Transport of Freshly Formed Particles

New particles can form in a complex atmospheric process commonly known as nucleation. Evidence shows that around half of nucleation events detected on the ground actually occur in the lower atmosphere. Understanding how these events occur has implications for climate science.

Researchers gathered data during a 2020 field campaign at ARM's Southern Great Plains atmospheric observatory to study aerosol nucleation. The team examined the movement of particles up and down within the atmosphere. These fluxes represent an important nuance to explain aerosol nucleation.

In September 2022, the *Journal of Geophysical Research: Atmospheres* published results from the campaign.

"The study revealed that the ground-level measurements of aerosol and precursor gases may not always represent conditions conducive to nucleation," said corresponding author Nicholas Meskhidze of North Carolina State University. "We hope that our measurements of the vertical movement of freshly nucleated particles will help improve scientific understanding of the fundamental mechanisms that regulate the occurrence and variability of particle nucleation."

Researchers were particularly interested in what happens in the residual layer. The residual layer forms overnight above a collapsing boundary layer. In the morning, the lower layer near the surface pushes through the residual layer to form the boundary layer again.

This up-and-down movement of air transports particles that form in the residual layer back down toward the ground. Measuring the fluxes allowed researchers to identify which particles formed near the ground and which formed in the residual layer. The results show that current methods do not accurately represent aerosol nucleation in models.

Reference

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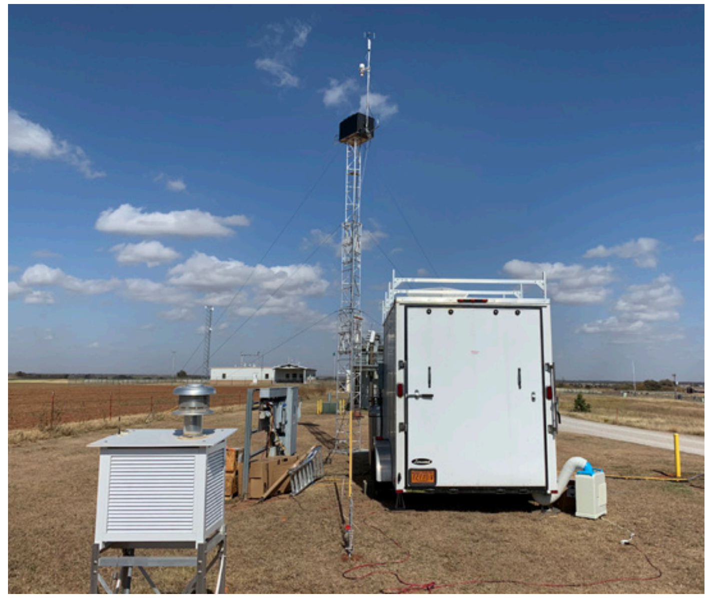
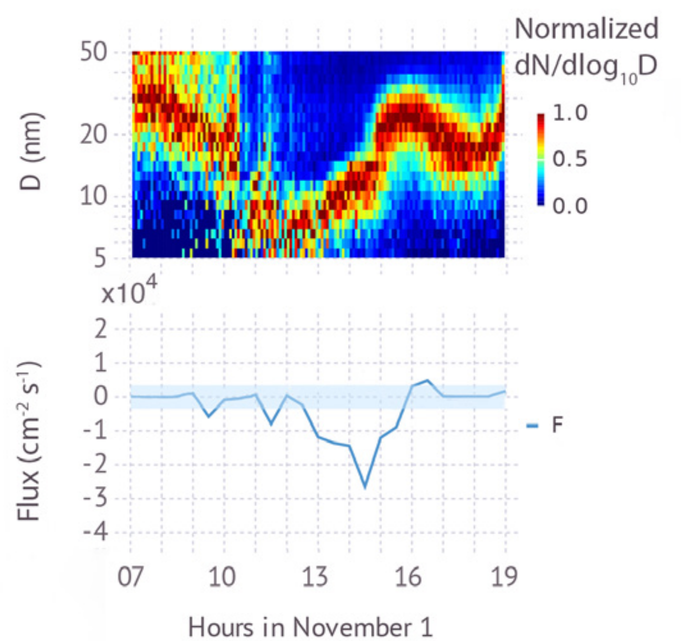


During a fall 2020 campaign at ARM's Southern Great Plains atmospheric observatory, researchers collected measurements to determine where particles formed in the atmosphere. This photo shows the team's trailer and equipment.



Plots show a normalized particle number size distribution from the ARM Aerosol Observing System, top, and the measured flux term, bottom, on November 1, 2020, during a new particle formation event at ARM's Southern Great Plains atmospheric observatory. (*Image adapted from the journal.***)**

Small Island Has Big Effect on Eastern North Atlantic Turbulence

Low-level clouds and the rain they carry over the eastern North Atlantic are deeply connected to turbulence in the lowest level of the atmosphere. Understanding what factors lead to this chaotic movement of air can help researchers better predict and model the atmosphere.

An international team of researchers used six years of data from ARM's Eastern North Atlantic (ENA) atmospheric observatory to explore boundary-layer turbulence. Research published in October 2021 in the *Journal of Applied Meteorology and Climatology* looks at timescales ranging from hourly to monthly, creating a detailed picture of turbulence over the ENA.

Scientists found that low-level clouds and rain play a dominant role in affecting turbulence at an hourly scale. On a monthly scale, winds, surface fluxes, and clouds all meaningfully affect turbulence.

The ENA observatory is located on a small island in the North Atlantic Ocean. This analysis showed that the island affected a large percentage of the collected cloud and turbulence observations. The island effect caused a significant increase in turbulence across over half of potential wind directions.

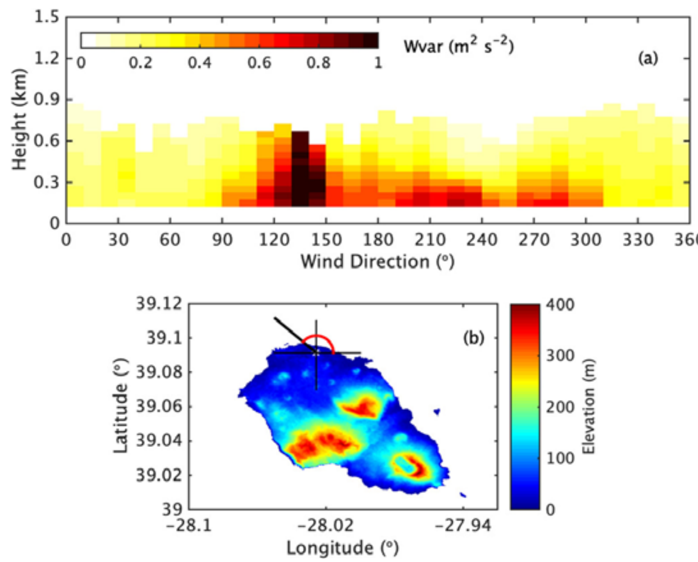
"The island is much smaller than the spatial resolution of modern earth system models (ESMs)," said lead author Virendra Ghate of Argonne National Laboratory in Illinois. "ESMs thus do not represent the island's influence on the lower atmosphere. Researchers must use caution when evaluating ESM simulations with ENA observations."

The study also reported that heavy drizzle primarily falls within downdrafts. Weak drizzle falls in both updrafts and downdrafts. Many ESMs poorly represent this important drizzle-turbulence correlation, potentially leading to errors.

Reference

Ghate V, M Cadeddu, X Zheng, and E O'Connor. 2021. "Turbulence in the marine boundary layer and air motions below stratocumulus clouds at the ARM Eastern North Atlantic site." *Journal of Applied Meteorology and Climatology* 60(10):1495-1510, https://doi.org/10.1175/JAMC-D-21-0087.1.

This June 2017 aerial photo captures Graciosa Island, the home of ARM's Eastern North Atlantic atmospheric observatory in the Azores. As a result of low wind conditions, land-influenced clouds formed over the island.



The top plot contains profiles of vertical air motion binned by surface wind direction, with the island effect visible from 90–310 degrees. Underneath, a topographical map of Graciosa Island shows where observations are unaffected by the island. (*Copyrighted images from the journal.***)**

> **"The island is much smaller than the spatial resolution of modern earth system models (ESMs)."**
>
> *—Virendra Ghate, Argonne National Laboratory in Illinois*

New Diagnostics Package Incorporates ARM Data to Evaluate Modeled Aerosols

Earth system models are important tools for understanding the planet's behavior in the past, present, and future. They play a critical role in climate science, allowing researchers to explore multiple possible futures. A major uncertainty in these models comes from how they represent aerosols.

Aerosols interact with clouds and light, affecting energy flows and weather across the globe. Model simulations need to be compared with real-world observations to test their accuracy. This requires an evaluation toolkit targeted to aerosol data.

Led by Shuaiqi Tang from Pacific Northwest National Laboratory in Washington state, researchers developed a new diagnostics package focused on evaluating aerosol properties with aircraft, ship, and surface measurements.

In *Geoscientific Model Development* in May 2022, the team presented its Earth System Model Aerosol-Cloud Diagnostics (ESMAC Diags) package, which provides a wide range of aerosol-specific diagnostics and metrics.

"There are still uncertainties in aerosol properties and aerosol-cloud interactions predicted by earth system models," said Tang. "This tool provides a robust way to quantify those uncertainties, helping identify and understand processes that need improvement."

ESMAC Diags incorporates data from six field campaigns, including four from ARM. These campaigns cover the northeastern Atlantic, continental United States, northeastern Pacific, and Southern Ocean.

The data are a combination of aircraft, ship, and surface measurements focused on aerosols. This provides a rich mixture of data types for model comparison.

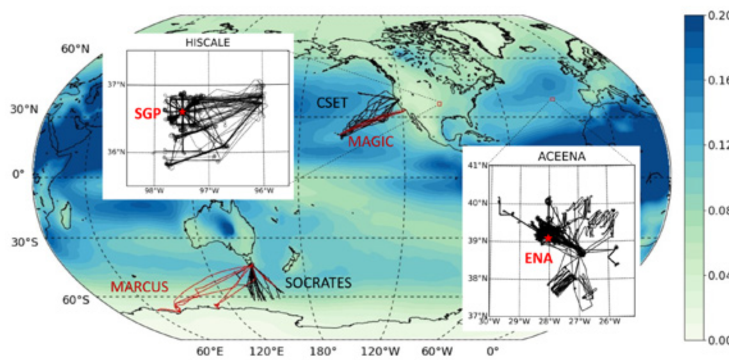
The team developed the open-source package to evaluate new and existing components of DOE's Energy Exascale Earth System Model. Researchers designed the package with flexible code that allows them to incorporate additional data sets, including from new field campaigns.

A soon-to-be-released update of the package will extend the evaluation to include clouds and aerosol-cloud interactions.

Reference

Tang S, J Fast, K Zhang, J Hardin, A Varble, J Shilling, F Mei, M Zawadowicz, and P Ma. 2022. "Earth System Model Aerosol-Cloud Diagnostics (ESMAC Diags) package, version 1: assessing E3SM aerosol predictions using aircraft, ship, and surface measurements." *Geoscientific Model Development* 15(10):4055-4076, https://doi.org/10.5194/gmd-15-4055-2022.

The ESMAC Diags package incorporates data from ARM's now-retired Gulfstream-159 (G-1) research aircraft.



The red and black tracks, including those in the insets, show where data incorporated into ESMAC Diags were collected. (*Copyrighted image from the journal***.)**

ARM Observations for Machine Learning

More scientists are turning to machine learning (ML) to help them glean new insights into the atmosphere. ML uses data to train software to better predict and model different phenomena.

Across fields that generate substantial quantities of data, researchers are developing ML approaches to help solve complex problems.

In FY2022, several studies combined ARM data with ML techniques. They represent an exciting direction and use for ARM observations.

Detecting growing drizzle particles is important for understanding the transition from cloud water to rainwater. Scientists used data from three ARM marine field campaigns to test an ML algorithm that detects small drizzle particles. They found that drizzle is far more common than previously thought and varies by location.

Other ML work leaned heavily on data from ARM's Southern Great Plains (SGP) atmospheric observatory.

Researchers are using SGP data to study the planetary boundary layer, the lowest part of the atmosphere. One team applied a new ML algorithm to temperature, humidity, and radiation data. The new method produced planetary boundary-layer height estimates that are more stable than traditional measurements.

Using SGP lidar data, another team developed an ML method to determine boundary-layer height under complex atmospheric conditions. The new algorithm shows promise for estimating boundary-layer height under complex cloud or residual-layer conditions.

Scientists compared SGP aerosol data with ML-determined numbers of cloud condensation nuclei, the small particles that form cloud seeds. Using aircraft measurements from a range of atmospheric environments, the team showed that the ML model accurately predicts loud condensation nuclei data. The model makes decisions based on realistic physical and chemical principles, leading to its accuracy.

Researchers used data from the 2016 Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) campaign at the SGP as an example set for analyzing aerosol mass spectrometer measurements. A new supervised ML approach determines and attributes the source of organic aerosols. This method works for both aircraft- and ground-based aerosol mass spectrometer measurements.

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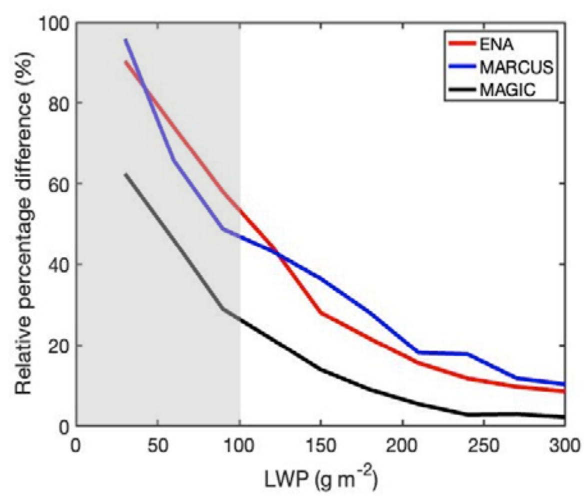


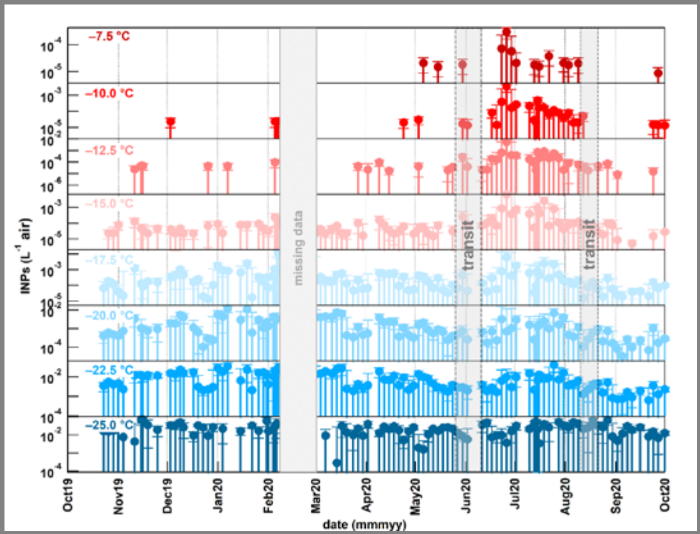
The figure shows the relative percentage difference in drizzle occurrence between traditional and new detection methods as a function of liquid water path (LWP) for three ARM campaigns: ACE-ENA (ENA), MARCUS, and MAGIC. These results indicate that drizzle is far more common in stratocumulus clouds than previously thought and that the drizzle formation is regime dependent. Spaceborne radar observations used to generate precipitation climatologies have low sensitivity in the light precipitation region, which is indicated by the shaded area. (*Copyrighted image from the journal.***)**

Data Reveal Seasonal Atmospheric Processes in the Central Arctic

Ice-nucleating particles (INPs), which seed the formation of ice in clouds, are key players in climate change. But little is known about the effects of INPs in the Arctic, the world's fastest-warming region.

As part of the 2019–2020 Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition, scientists aimed to report never-before-seen observations of INPs in the central Arctic. They collected the data necessary to determine where INPs in the region come from and how they might affect the clouds that form during different seasons. A June 2022 paper in *Nature Communications*, led by ARM INP co-mentor Jessie Creamean, describes the observations.

Researchers found that INPs are strongly seasonal, with lower concentrations in the winter, spring, and fall coming from lower latitudes. The biology associated with melt leads to greater INP concentrations in the summer.



Analyzing data from the MOSAiC expedition, scientists noted a difference in ice-nucleating particle concentration scales between different temperatures. Error bars represent standard deviation. (*Copyrighted image from the journal.***)**

Reference

Creamean J, K Barry, T Hill, C Hume, P DeMott, M Shupe, S Dahlke, S Willmes, J Schmale, I Beck, C Hoppe, A Fong, E Chamberlain, J Bowman, R Scharien, and O Persson. 2022. "Annual cycle observations of aerosols capable of ice formation in central Arctic clouds." *Nature Communications* 13:3537, https://doi.org/10.1038/s41467-022-31182-x.

Cloud-Land Coupling Examined at Southern Great Plains Observatory

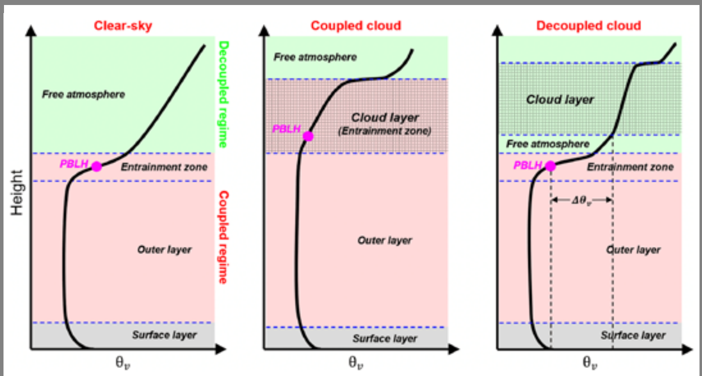
Connections between the surface and clouds are important for understanding how clouds develop. Most previous work on these connections has centered on oceans rather than land. Data from ARM's Southern Great Plains atmospheric observatory allowed researchers to study the coupling between clouds and land.

In research published by *Atmospheric Chemistry and Physics* in January 2022, scientists simultaneously measured the planetary boundary-layer height and coupled states under cloudy conditions. A lidar-based method developed by the researchers relies on the planetary boundary-layer height, lifted condensation level (the altitude at which a moist but unsaturated air parcel becomes saturated), and cloud base height to identify cloud coupling.

As coupled and decoupled clouds have distinct features, the new method offers an advanced tool to separately investigate them. Researchers generated a 20-year climatology by using the method.

Reference

Su T, Y Zheng, and Z Li. 2022. "Methodology to determine the coupling of continental clouds with surface and boundary layer height under cloudy conditions from lidar and meteorological data." *Atmospheric Chemistry and Physics* 22(2):1453-1466, https://doi.org/10.5194/acp-22-1453-2022.



Analyzing data from the MOSAiC expedition, scientists noted a difference in ice-nucleating particle concentration scales between different temperatures. Error bars represent standard deviation. (*Copyrighted image from the journal.***)**

ADVANCING **CAPABILITIES**

Infrastructure Achievements

Maintaining multiple instrumented observatories around the world is no easy feat. ARM uses a team of science, engineering, and technical personnel to ensure effective operations, keep up with technology developments, deliver high-quality data, and provide scientific outreach to a global audience.

ARM Team Overcomes Oklahoma Heat to Fly Uncrewed Aerial System

As summer temperatures soared in north-central Oklahoma, so too did ARM's ArcticShark uncrewed aerial system.

Over 12 days in July 2022, the ARM Aerial Facility (AAF) conducted seven flights to ARM's Southern Great Plains (SGP) atmospheric observatory. There, the ArcticShark flew precise flight patterns between 2,000 and 4,000 feet, collecting atmospheric data before returning to the Blackwell-Tonkawa Municipal Airport.

"The entire flight series was a great success for the ArcticShark program," said Jason Tomlinson, who leads the AAF's engineering efforts. "We are excited about the data we collected over the SGP; it was very high quality, and importantly, it was consistent with measurements taken from the ground."

The 110-degree-plus temperatures were even higher in the ArcticShark's small payload bays for instruments.

"The high heat helped make this one of the tougher deployments we've ever had," said Tomlinson. "But we adjusted by shifting operations to early morning hours and were able to get flights in safely. And our people, the ArcticShark, and the payload all performed well."

The July deployment was a follow-up to flights over the SGP in November 2021 to evaluate the implementation of customized instrumentation and demonstrate safe operations. The November flights took place with the Mississippi State University TigerShark.

Fan Mei, who oversees AAF science activities, led a paper that used the TigerShark data to show how uncrewed systems can help address important questions in earth system science.

ARM Aerial Facility staff pose with the ArcticShark uncrewed aerial system in July 2022 after almost two weeks of flights over ARM's Southern Great Plains atmospheric observatory.

"The entire flight series was a great success for the ArcticShark program. We are excited about the data we collected over the SGP (Southern Great Plains); it was very high quality, and importantly, it was consistent with measurements taken from the ground."

—Jason Tomlinson, ARM Aerial Facility operations manager from Pacific Northwest National Laboratory

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New ARM High-Performance Computing Cluster Enters Operations

ARM has a new high-performance computing cluster available for users' big-data needs.

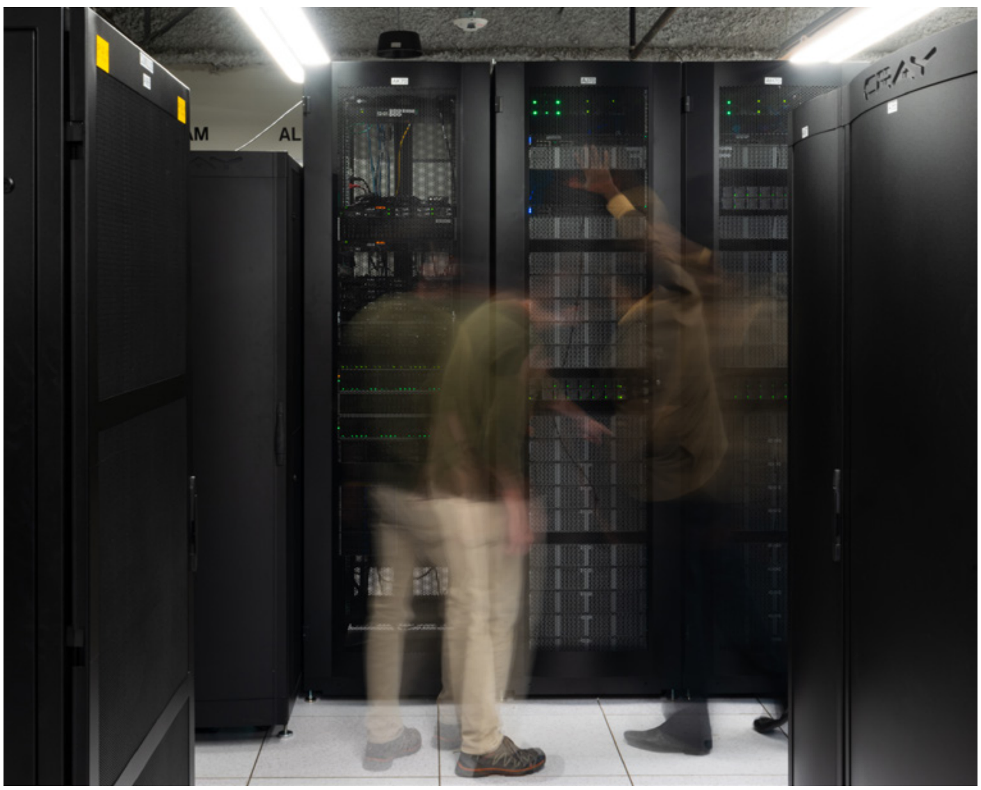
Based at the ARM Data Center, the new Cumulus cluster replaces the Stratus cluster and the original Cumulus. The new cluster can do the work of Stratus and the original Cumulus.

Researchers can use the new cluster for ARM-approved projects by submitting a request for access. Any request for ARM computational resources must include a clear use of ARM observational data. Requests will be reviewed quarterly.

Another use of Cumulus is for the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity. LASSO brings together LES simulations, ARM observations, skill scores, and diagnostics for researchers and modelers.

In FY2022, the LASSO team announced a beta release of deep convection data from a 2018–2019 ARM field campaign in Argentina.

The cluster will also support other computationally intensive ARM activities, including radar data processing and data quality analysis.



ARM's new high-performance computing cluster is available for user projects.

ARM Carries Out Development Work with Users Top of Mind

Each year, ARM prioritizes development activities for maximum benefit and impact to the scientific community. Examples include adding new instruments, sites, and capabilities.

In FY2022, ARM installed a scanning mobility particle sizer at the Eastern North Atlantic (ENA) atmospheric observatory to measure aerosol size distribution. For tethered balloon system flights, ARM added a new instrument to collect time- and altitude-resolved samples of particles that seed ice formation in clouds.

ARM also moved ahead with plans to replace aging instruments across its sites. The facility bought new broadband visible radiometers for its fixed-location observatories and mobile facilities. In addition, ARM purchased new eddy correlation flux measurement systems for the ENA, the North Slope of Alaska (NSA) observatory, and all three mobile facilities.

Meanwhile, ARM replaced its NSA autosonde launcher, which uses hydrogen instead of helium as a lifting gas for weather balloons.

A few miles south of the main NSA instruments, ARM set up a new inland site to collect additional measurements of frozen precipitation.

During the TRacking Aerosol Convection interactions ExpeRiment (TRACER) near Houston, Texas, ARM implemented an innovative framework for tracking convective cloud cells with one of its scanning precipitation radars.

The ARM Data Center added a new high-performance computing cluster for ARM-approved science projects and computationally intensive facility activities. The data center also assisted with developing tools that report ARM user metrics and link the facility's property tracking with data processing.

While developing and releasing new data products in FY2022, ARM's translator group published a plan detailing its priorities over the next three years.

This ARM radar in Pearland, Texas, tracked convective cloud cells as part of the TRACER campaign.

First Deep Convection Data Available from ARM Modeling Activity

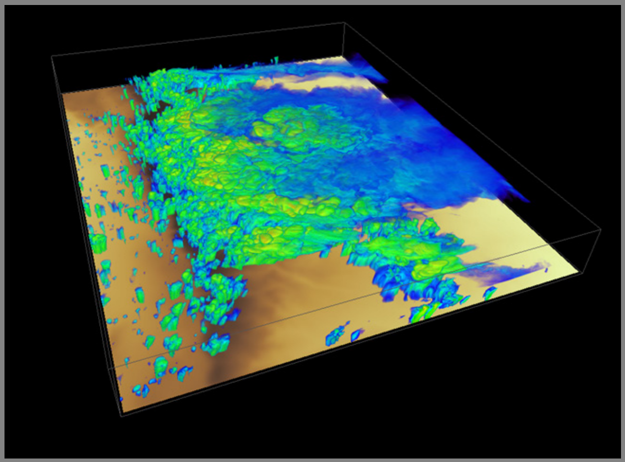
The Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity ties together ARM data and high-resolution simulations to support model development and process studies.

After five years of focusing on shallow convection, the LASSO team is producing a new scenario with high-resolution simulations of deep convection. This scenario is based on ARM's Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign.

A beta release of the LASSO-CACTI scenario became available to users in FY2022, with data accessible on ARM's high-performance computing cluster.

The CACTI campaign occurred along the Sierras de Córdoba mountain range in northern Argentina. This region experiences some of the most intense thunderstorms in the world, making for an opportune ARM deployment from October 2018 through April 2019.

The full formal LASSO-CACTI release is expected in early 2023. The final data set will result in roughly 660 mesoscale simulations and 30 LES simulations from selected case dates.



This is a rendering of simulated radar reflectivity over the ARM Mobile Facility site during the CACTI campaign. Brown colors indicate terrain height, with darker colors representing higher terrain. Blue, green, and yellow colors represent reflectivity, with warmer colors indicating higher reflectivity.

New Data Products

Assortment of ARM Aerosol Data Grows

ARM expanded its data offerings in FY2022 to help advance aerosol science.

For observational and modeling studies of ice formation in clouds, ARM now provides routine data on ice-nucleating particles.

ARM released a value-added product (VAP) that merges size distributions of aerosols measured by two different particle size spectrometers. This VAP is useful for scientists who need a representation of the aerosol size distribution from approximately 10–20,000 nanometers in diameter.

Also available is a new version of a VAP that provides the vertical distribution of cloud condensation nuclei number concentrations for better representation of aerosol indirect effects in climate models. This VAP and the merged size distribution VAP are available for ARM's Southern Great Plains atmospheric observatory.

A new VAP provides 60-second averaged black carbon mass and number concentrations from single-particle soot photometers. This VAP was first released for ARM's North Slope of Alaska observatory and for a 2019–2020 expedition in the central Arctic.

New data became available from a VAP that calculates moisture-absorbing properties of measured particles.

For its most recent mobile facility campaigns in Texas and Colorado, ARM produced a VAP that combines light absorption and scattering data to calculate aerosol optical properties at three wavelengths.

This instrument, used at ARM's Southern Great Plains atmospheric observatory, measures the number concentration of ice-nucleating particles.

ARM Ramps Up Releases from Cold-Air Outbreak Campaign

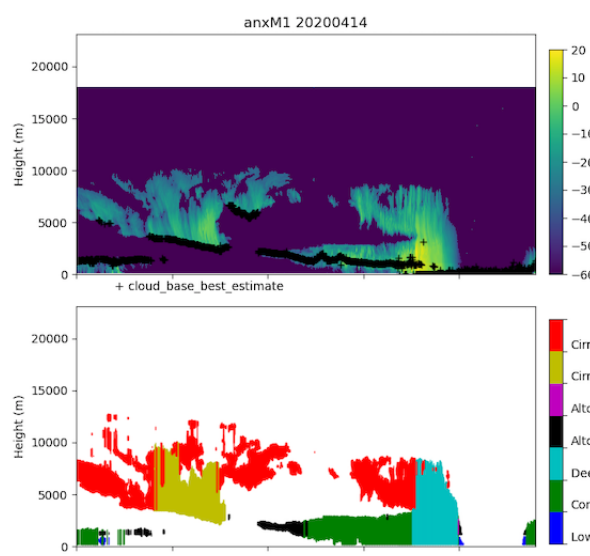
In FY2022, ARM rolled out additional data products from the 2019–2020 Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) in Norway. COMBLE data are helping researchers better understand what happens when air masses from the Arctic sweep across open, relatively warm water.

A new set of COMBLE radar data underwent calibration, correction, and quality control processes beyond ARM's standard quality checks and corrections. ARM also announced a new COMBLE release from a family of products providing radar moments and quantities on a Cartesian grid.

There are now COMBLE products that classify clouds by thermodynamic phase (e.g., whether a cloud is composed of liquid, ice, or both) and by cloud type based on quantities derived from lidar and radar. In addition, ARM released continuous, high-time-resolution profiles of cloud microphysical properties from COMBLE.

Hygroscopicity describes the ability of particles to absorb moisture from the environment. An ARM product calculates the hygroscopic properties of aerosols measured during COMBLE. Scientists can use the data to evaluate aerosol properties simulated in global earth system models.

Meanwhile, researchers can now access continuous large-scale forcing data from COMBLE. These data can drive single-column models, cloud-resolving models, and large-eddy simulations for different cloud and convective systems.



Time-height displays show reflectivity, top, and cloud types, bottom, on April 14, 2020, near Andenes, Norway, during the COMBLE campaign.

ARM Data Products Aid Arctic Research

To study how the Arctic is changing, researchers can access 25 years of ARM data from this region. Higher-order products, which are analyzed and processed by ARM staff, make these data even more useful.

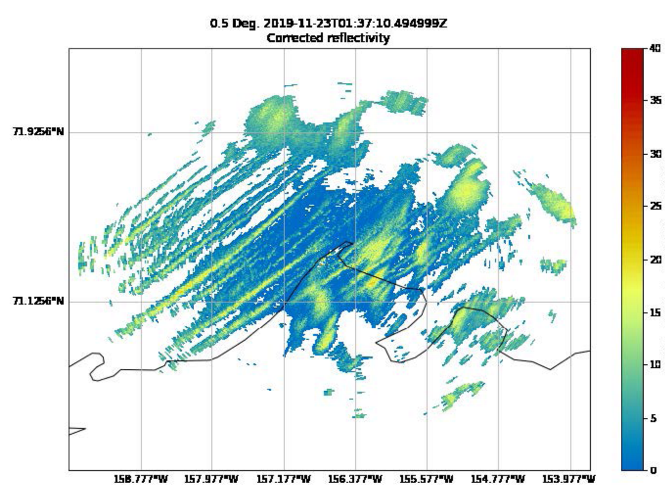
ARM produces best estimates of cloud, radiation, and basic atmospheric quantities that are often used in model evaluation. In FY2022, ARM Best Estimate (ARMBE) products became available from Oliktok Point, Alaska. Meanwhile, ARMBE data sets for the North Slope of Alaska (NSA) atmospheric observatory at Utqiaġvik were extended to cover 2019 and 2020.

A new ARM value-added product (VAP) applies a machine learning model to micropulse lidar data to produce cloud masks for various ARM sites, including Oliktok and the NSA. In addition, Oliktok data are now available from a VAP that provides height- and time-resolved estimates of cloud and aerosol optical properties from ARM Raman lidars.

ARM also continues to generate data products from the 2019–2020 Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. In FY2022, ARM released motion-corrected Doppler lidar data from the research icebreaker *R/V Polarstern*.

A new VAP for MOSAiC and the NSA provides 60-second averaged black carbon mass and number concentrations from single-particle soot photometers.

Improved MOSAiC and NSA data became available from a VAP that retrieves column precipitable water vapor and liquid water path from ARM's 2-channel microwave radiometers. Also, ARM released an NSA precipitation radar product that can be used to supplement MOSAiC observations.



On November 23, 2019, an ARM radar captured mesoscale convective snow bands with unusual movement at the North Slope of Alaska atmospheric observatory.

ARM Adds Products for Estimating Boundary-Layer Height

The structure and depth of the planetary boundary layer (PBL) are important to a wide range of atmospheric processes. Such processes include cloud formation and aerosol and chemical mixing, transport, and transformation.

Errors in the determination of PBL height can significantly affect the formation and maintenance of low-level clouds and the initiation of convective clouds in models. Numerous instruments and algorithms have been used for PBL height estimation, each with its own strengths and weaknesses.

To that end, ARM now offers value-added products (VAPs) that provide PBL height estimates from lidar measurements. Planetary Boundary Layer Height (PBLHT) products derived from micropulse and Doppler lidar data are now available. These VAPs complement previously released products that estimate PBL height from ARM radiosonde profiles and ceilometer data. Scientists can evaluate and compare estimates from ARM's various PBLHT products.

Currently, the Doppler lidar version of PBLHT covers nine years at ARM's Southern Great Plains atmospheric observatory. The micropulse lidar version is available for the Southern Great Plains observatory and for a 2018–2019 ARM field campaign in Argentina.

A PBLHT VAP derived from Raman lidar data is under development.

An ARM value-added product provides estimates of planetary boundary-layer height from Doppler lidar measurements at the Southern Great Plains atmospheric observatory.

New Products Help Improve Confidence in Cloud Retrievals

ARM now offers a satellite-aligned version of its widely used Ka-Band ARM Zenith Radar Active Remote Sensing of CLouds value-added product (KAZRARSCL VAP).

The new KAZRARSCL-CLOUDSAT VAP aligns radar reflectivities from KAZRARSCL with those from the well-characterized Cloud Profiling Radar operating on NASA's CloudSat satellite.

Because reliable external calibration sources are not readily available for the KAZRs, the alignment with CloudSat-based measurements provides an additional measure of confidence in the KAZRARSCL reflectivities.

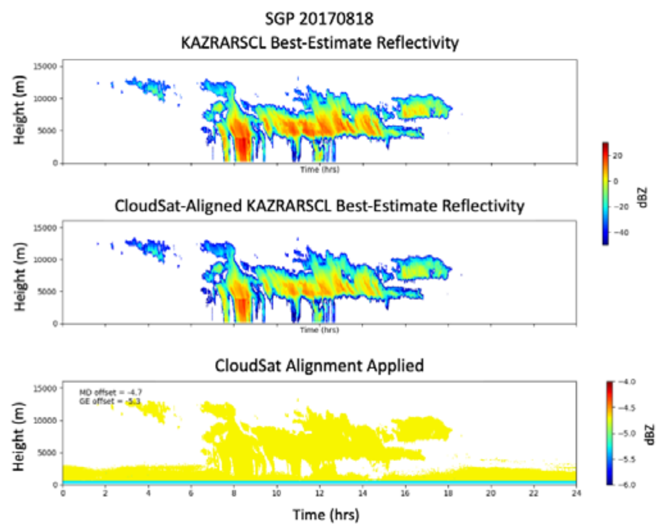
KAZRARSCL-CLOUDSAT applies a statistical CloudSat-derived offset to the KAZRARSCL reflectivity and best-estimate reflectivity fields. Other KAZRARSCL product fields are unmodified.

Users can access KAZRARSCL-CLOUDSAT for ARM's North Slope of Alaska and Southern Great Plains atmospheric observatories. Data are also available from past ARM deployments at Oliktok Point, Alaska, and in Antarctica.

KAZRARSCL and a similar ARSCL product for the W-Band ARM Cloud Radar (WACR), called WACRARSCL, feed into VAPs that improve upon ARM's historical MICROBASE product for baseline cloud microphysical retrievals.

The MICROBASEKAPLUS product, which uses KAZRARSCL, delivers continuous, high-time-resolution profiles of cloud microphysical properties such as liquid/ice water content and liquid/ice effective radius. The similar MICROBASEW product uses WACRARSCL.

In FY2022, ARM released new MICROBASEKAPLUS data and the first MICROBASEW data.



The top image shows best-estimate reflectivity from the KAZRARSCL product for a sample day at the Southern Great Plains atmospheric observatory. The middle image provides the KAZRARSCL best-estimate reflectivity after statistical alignment with CloudSat. The bottom image shows the CloudSat reflectivity offset that was applied at specific time-height points based on the radar's operational mode.

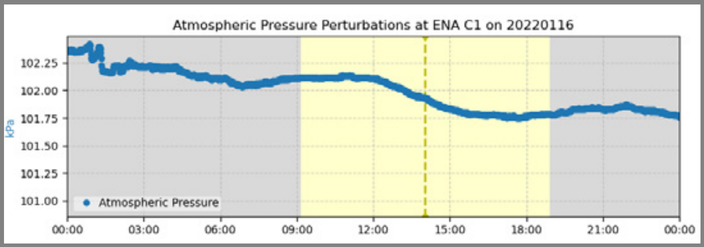
ARM Instruments Detect Pressure Wave from Tongan Volcano Eruption

The massive Hunga Tonga-Hunga Ha'apai volcanic eruption in January 2022 caused atmospheric pressure changes that registered at ARM sites around the world.

ARM's surface meteorology systems at its Southern Great Plains (SGP), North Slope of Alaska (NSA), and Eastern North Atlantic (ENA) atmospheric observatories caught the reflected pressure wave. So did the surface meteorology systems deployed for the TRacking Aerosol Convection interactions ExpeRiment (TRACER) near Houston, Texas, and the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign near Crested Butte, Colorado.

ARM collected the evidence of the atmospheric pressure perturbation from the Tongan volcano eruption as a data epoch. ARM data epochs identify high-quality data over a specific time range of scientific interest.

The new epoch comprises SGP, NSA, ENA, SAIL, and TRACER surface meteorological system data and SGP precipitation meteorological instrument data from January 16. The epoch is freely available to download from ARM's Data Discovery.



Around 1:00 Coordinated Universal Time (UTC) on January 16, 2022, the Eastern North Atlantic atmospheric observatory was the first ARM site to experience the reflected pressure wave from a volcano eruption in Tonga. The yellow shading indicates daylight hours, and the dashed line is solar noon.

Science Outreach

AMS Short Course Highlights Usability of ARM Data

The 2022 American Meteorological Society (AMS) Annual Meeting included a four-hour short course based on fresh observations from ARM's TRacking Aerosol Convection interactions ExpeRiment (TRACER).

The yearlong TRACER campaign began near Houston, Texas, in October 2021. AMS was supposed to be in Houston in January 2022, but it moved fully online because of COVID. This did not affect the short course, which was planned as remote before AMS went all virtual.

ARM Director Jim Mather opened the course with an overview of ARM. TRACER Principal Investigator Michael Jensen presented a campaign overview, and ARM Data Services Manager Giri Prakash introduced the ARM Data Center.

Interactive sessions demonstrated how to use TRACER measurements for research and how to engage with other ARM resources, such as large-scale computing capabilities. ARM staff members Maggie Davis, Karen Johnson, Cory Stuart, Zach Price, and Dié Wang led those sessions.

The course drew about 40 attendees. A post-course survey showed that the content met their expectations and provided good value.

ARM is supporting a short course at the 2023 AMS Annual Meeting in Denver, Colorado. The course will be based on measurements from the ongoing Surface Atmosphere Integrated Field Laboratory (SAIL) campaign in the Colorado Rockies.

ARM collected atmospheric data in the Houston, Texas, suburb of La Porte as part of the yearlong TRACER campaign.

Pan-GASS Meeting Strengthens Ties between ARM and Modelers

ARM maintains relationships with scientific communities that have informed its mission to improve climate and earth system models.

One is the Global Energy and Water Exchanges/Global Atmospheric System Studies (GEWEX/GASS) community. Periodically, the GEWEX/GASS panel holds a Pan-GASS meeting of international scientists who discuss improving the representation of atmospheric processes in models.

The 3rd Pan-GASS Meeting took place in July 2022 in Monterey, California. As with past Pan-GASS meetings, ARM staff and users played key roles in the 2022 event.

ARM science translator Shaocheng Xie, a co-chair of the Pan-GASS organizing committee, led a discussion on a GASS project that used ARM data to study precipitation.

ARM Associate Director for Research Jennifer Comstock presented updates on ARM data products and capabilities that are useful for model development and evaluation.

As part of a new program, ARM provided travel grants for early career scientists Kelly Balmes and August Mikkelsen to present at Pan-GASS.

Balmes and colleagues at NOAA and the Cooperative Institute for Research in Environmental Sciences used data from ARM sites to study cloud vertical overlap.

Mikkelsen, from the University of Wyoming, and his collaborators analyzed ARM Eastern North Atlantic data to learn how cyclones can affect aerosols.

Early career scientists Kelly Balmes, left, and August Mikkelsen received travel grants from ARM to present at the Pan-GASS meeting in July 2022.

ARM Webinars Hit Sweet Spot with Users

In FY2022, ARM continued to present a series of webinars on topics requested by the user community. ARM also held webinars to engage with users on their science needs.

ARM Director Jim Mather led a community input webinar in November 2021 and introduced a new online form for requesting measurements, data products, or data services.

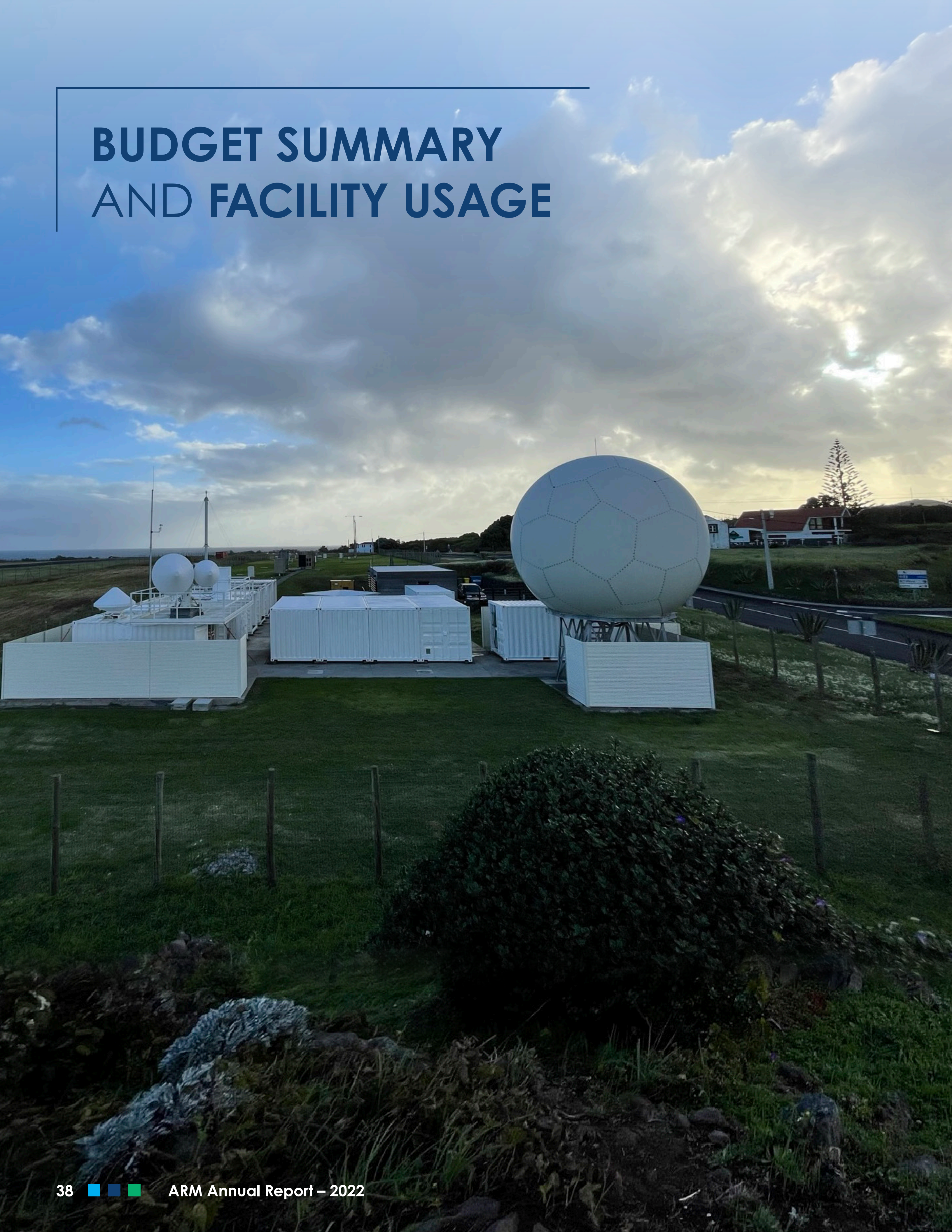
In February 2022, ARM management hosted a field campaign processes webinar to align with ARM's annual facility call for campaign proposals. The webinar outlined ARM Mobile Facility capabilities, ARM's proposal process, and responsibilities of principal investigators during deployments.

ARM held a series of listening sessions in March and April 2022 to gather feedback from users about its radar operations.

There is a growing effort in ARM, Atmospheric System Research (ASR), and other organizations to make scientific research, data, and software more accessible. An ARM/ASR workshop in May 2022 included tutorials and discussions on open-science topics.

ARM Instrument Operations Manager Adam Theisen leads the ARM/ASR Open Science Virtual Workshop 2022.

BUDGET SUMMARY AND FACILITY USAGE



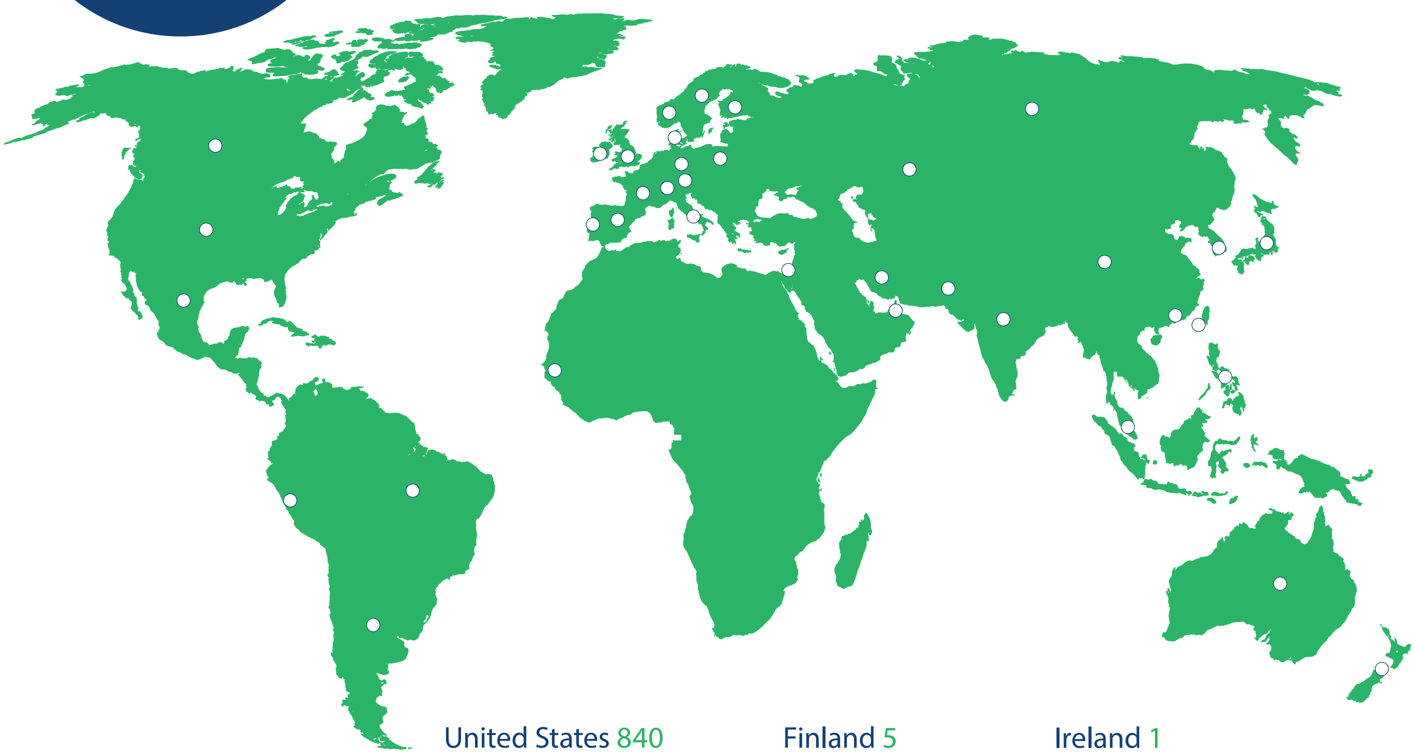
Fiscal Year 2022 Statistical Overview

INFRASTRUCTURE BUDGET

$86,988K

1,113
TOTAL SCIENTIFIC USERS

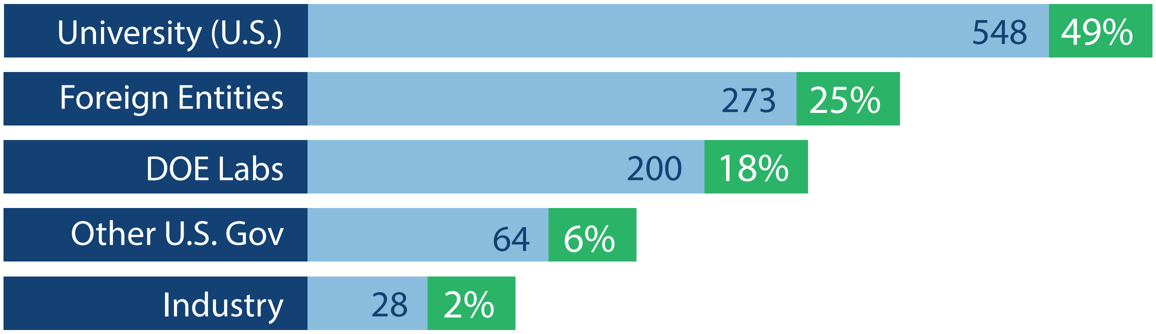
USERS BY COUNTRY



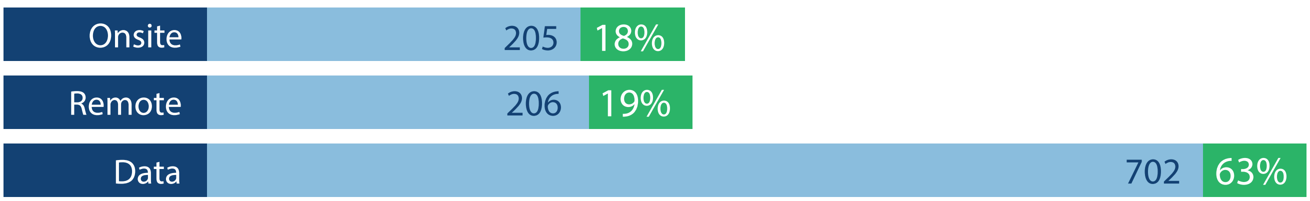
United States	840
China	55
Germany	38
Brazil	32
United Kingdom	21
India	16
Canada	15
Sweden	12
France	9
Japan	8
Switzerland	8
Australia	6
Italy	6
Finland	5
Portugal	5
Argentina	3
New Zealand	3
Norway	3
Peru	3
South Korea	3
Taiwan	3
Austria	2
Iran	2
Israel	2
Denmark	1
Hong Kong	1
Ireland	1
Kazakhstan	1
Malaysia	1
Mexico	1
Pakistan	1
Philippines	1
Poland	1
Russia	1
Senegal	1
Spain	1
United Arab Emirates	1

37
Countries

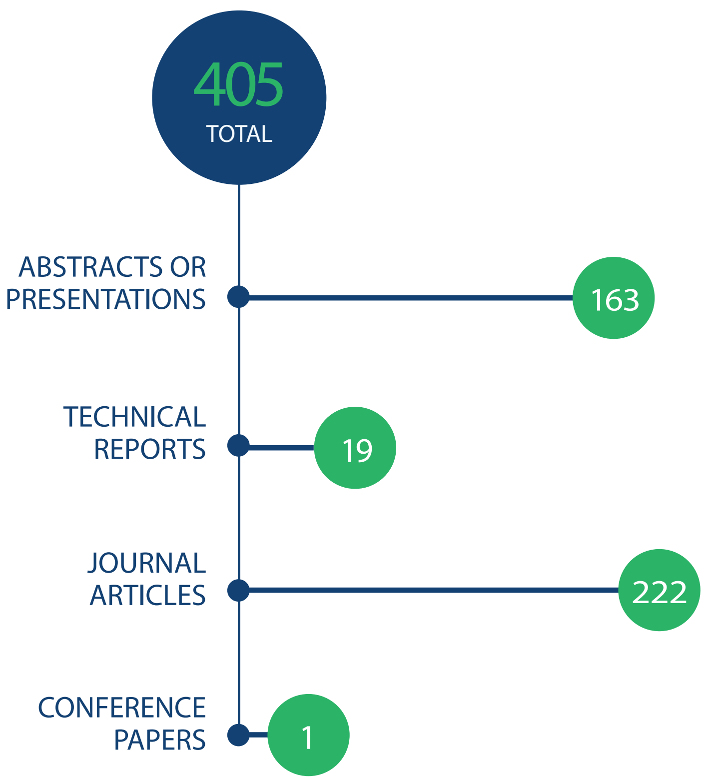
USER STATISTICS



FACILITY USAGE



PUBLICATIONS USING ARM*



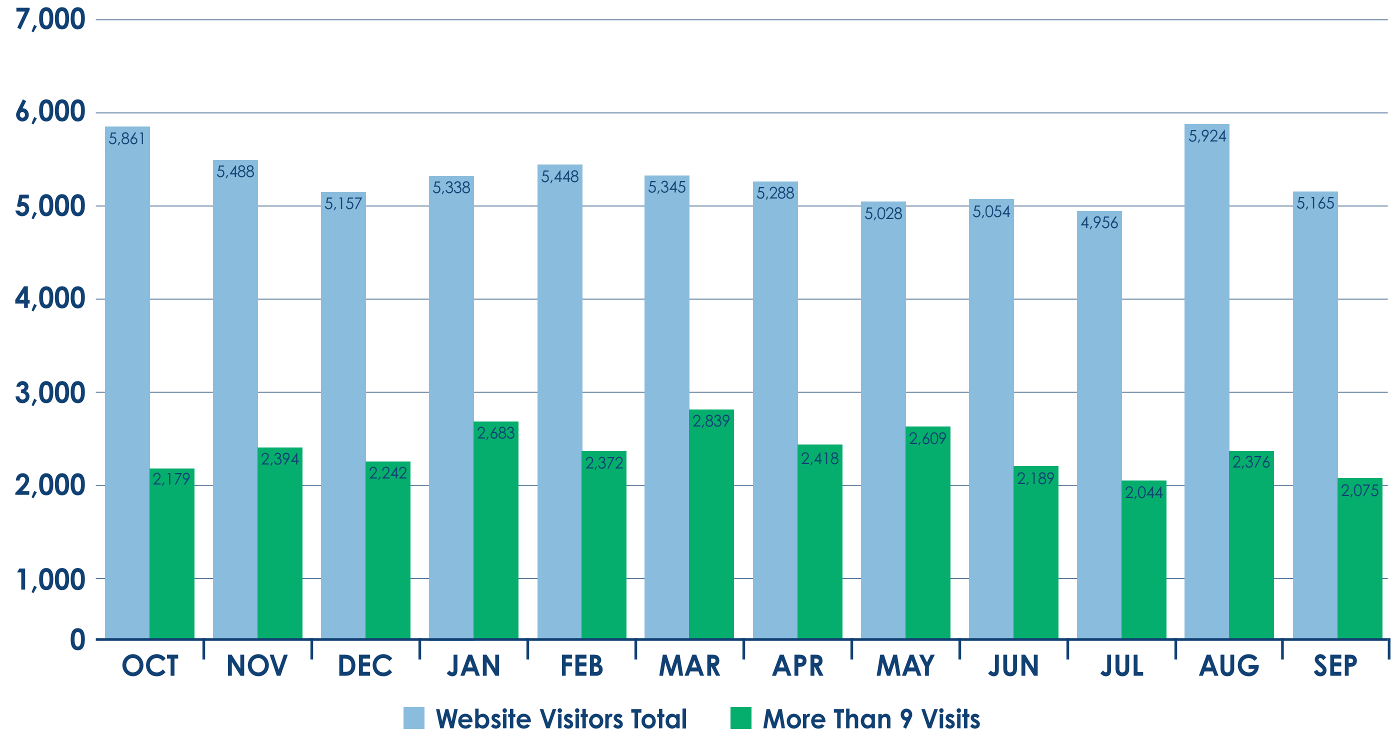
460+
Instruments Collect Atmospheric Data

~7,000+
Publicly Available Datastreams

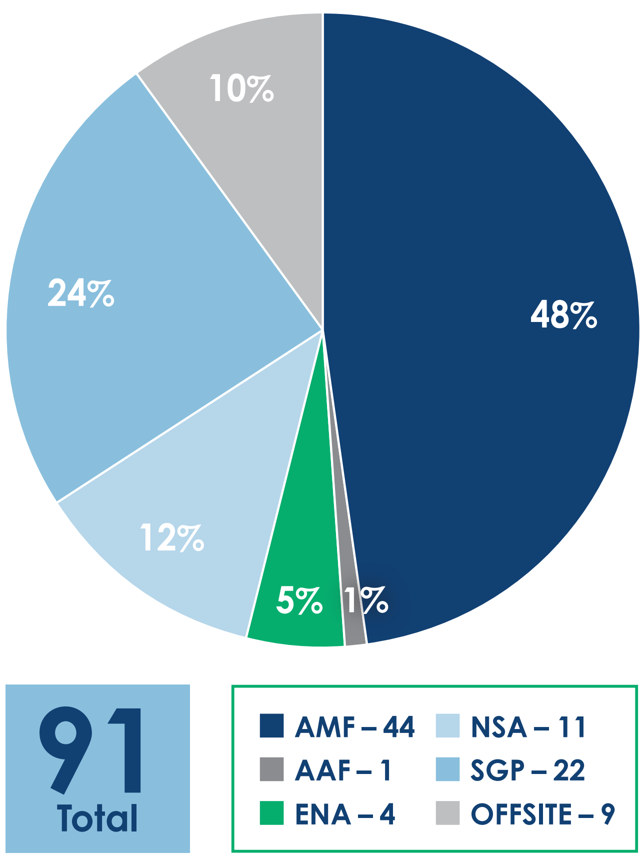
~4,000+
Journal Articles Since 1990

*Publication statistics were collected as of December 2022. Journal article numbers will continue to increase over time.

WEBSITE VISITORS



FIELD CAMPAIGNS



DATA PRODUCTS

3 released to production

- CCNSMPSKAPPA
- MPLCMASKML
- SPHOTCOD

3 approved for development

- MPLCAL
- RADCLSS
- SQUIRE

7 released to evaluation

- DLMC
- MERGEDSMPSAPS
- MICROBASEW
- PBLHTDL
- TBSMERGED
- THERMOCLDPHASE
- XSAPR-CMAC

3 existing VAPs updated

- ACSMCDCE
- AODBE
- RNCCN

To learn more about the value-added data products, visit www.arm.gov/capabilities/vaps.

Image Credits:

Thank you to the many people over the years who provided images in the ARM annual report. Here are the image contributors from FY2022 and the pages on which their images appear:

Mark Spychala, Argonne National Laboratory (Cover, Page 2, 14)

Andrea Starr, Pacific Northwest National Laboratory (Page 2)

Nathan Bilow, freelance (Page 4, 42)

Jim Mather, Pacific Northwest National Laboratory (Page 6, 11)

Chongai Kuang, Brookhaven National Laboratory (Page 9)

Sally McFarlane, U.S. Department of Energy (Page 10)

Dari Dexheimer, Sandia National Laboratories (Page 13)

Guy Tubbs, freelance (Page 15, 29)

Francesc Junyent, Colorado State University (Page 16)

Jennifer Delamere, University of Alaska Fairbanks (Page 17)

Eleanor Browne, University of Colorado Boulder/Cooperative Institute for Research in Environmental Sciences (Page 17)

Scott Collis, Argonne National Laboratory (Page 18)

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Victor Morris, Pacific Northwest National Laboratory (Page 20)

David Chu, Los Alamos National Laboratory (Page 20)

Nicki Hickmon, Argonne National Laboratory (Page 21, 34)

Jason Tomlinson, Pacific Northwest National Laboratory (Page 22, 26, 30)

Tercio Silva, Fundação Gaspar Frutuoso (Page 23, 38)

Nicholas Meskhidze, North Carolina State University (Page 24)

John Hubbe, now retired from Pacific Northwest National Laboratory (Page 25)

Giri Prakash, Oak Ridge National Laboratory (Page 31)

William Gustafson, Pacific Northwest National Laboratory (Page 32)

Chris Martin, Native Energy and Technology (Page 33)

Heath Powers, Los Alamos National Laboratory (Page 36)

Kelly Balmes, NOAA/Cooperative Institute for Research in Environmental Sciences (Page 36)

August Mikkelsen, University of Wyoming (Page 36)

ARM technician Wessley King checks a combined instrument setup during the SAIL campaign near Crested Butte, Colorado, on September 7, 2022.

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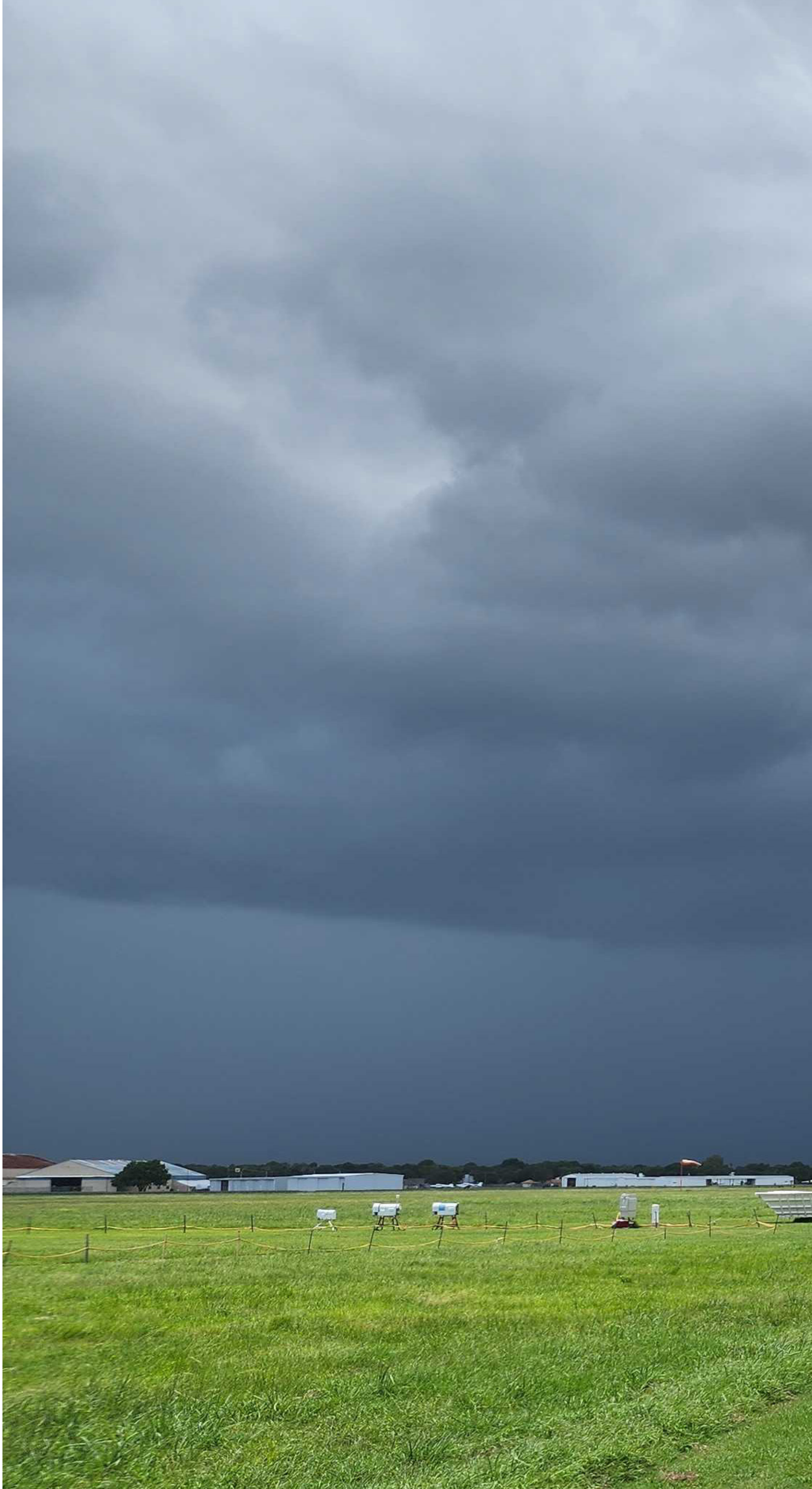

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Office of Science