2023 ANNUAL REPORT

U.S. DEPARTMENT OF ENERGY

ARM

ATMOSPHERIC RADIATION MEASUREMENT

FROM THE DIRECTOR

ARM Moves Forward on Priorities With Facility's Mission in Mind

For more than 30 years, the Atmospheric Radiation Measurement (ARM) user facility, which is managed by the U.S. Department of Energy (DOE) Office of Science, has provided freely available data and resources to scientists worldwide. Providing these services effectively requires getting out in the field and engaging with the science community. With COVID travel restrictions behind us, we are focused on connecting in person with ARM users, establishing new partnerships, and supporting fieldwork that might have waited during the pandemic.

In this report, which focuses on activities in fiscal year 2023 (FY2023), you will learn about efforts across ARM to deliver meaningful data to our users and to work with them to ensure that we are meeting their needs.

In October 2022, we packed up an ARM mobile observatory that had just completed a yearlong deployment to study the effects of atmospheric particles on storms around Houston, Texas. It was a quick turnaround to prepare the observatory for a new field campaign in La Jolla, California. This campaign, called the Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE), is collecting a year's worth of data on coastal clouds until February 2024.

On the covers:

Front – From February 2023 to February 2024, the Ellen Browning Scripps Memorial Pier in La Jolla, California, is hosting ARM instruments for the Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE).

Inside – Snow builds up on and around the ARM Mobile Facility operating as part of the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign near Crested Butte, Colorado.

Meanwhile, scientists are digging into the data from ARM's Surface Atmosphere Integrated Field Laboratory (SAIL) campaign. SAIL operations wrapped up in June 2023 after 21 months in Colorado's East River Watershed. ARM instruments gathered data on atmospheric processes that influence mountain hydrology. Model development efforts using observations from SAIL and co-located campaigns are already underway.

Tethered balloon system operations continued at SAIL and the Southern Great Plains (SGP) atmospheric observatory in Oklahoma. The SGP also hosted a series of three flight missions for our ArcticShark uncrewed aerial system. The last set of SGP flights featured the use of a chase plane to track the ArcticShark in the sky as it collected atmospheric measurements. Flying a chase plane will allow us to expand ArcticShark operations to other regions.

This report also includes updates on our other two fixed-location observatories: the North Slope of Alaska, which has collected over 25 years of data; and the Eastern North Atlantic, which celebrated its 10th anniversary in the Azores in fall 2023.

While ARM staff were busy in the field, we began to prepare for two new mobile deployments announced in FY2023. These campaigns, which will both start in calendar year 2024, will study cloud and precipitation properties in Tasmania and land-atmosphere interactions around Baltimore, Maryland. The Baltimore campaign will support a DOE-funded laboratory designed to study urban climate change.

We are also gearing up to open our newest atmospheric observatory, the Bankhead National Forest (BNF) in northern Alabama. This long-term mobile observatory is expected to operate for at least five years. Scientists plan to use BNF data to improve process understanding and model representations of aerosols, clouds, and land-atmosphere interactions.

Already, the BNF has helped us make new connections with scientific communities within and outside DOE, including underrepresented institutions in science, technology, engineering, and mathematics (STEM). We are excited about the possibilities of these emerging collaborations and what they could do for BNF science.

Making up for lost in-person time because of the pandemic, we held two joint meetings in FY2023 with scientists supported by DOE's Atmospheric System Research (ASR) program. In this report, you will read about some of the work presented at these meetings.

We also took advantage of more opportunities for science outreach through hybrid (in-person/virtual) events. Staff traveled to conferences and led short courses and workshops to educate scientists on how to use our data and capabilities. Several of these workshops included a focus on open science and facilitating access to ARM data.

ARM also continued to develop and upgrade science data products for various applications. Several data products became available for SAIL and ARM's Houston-area campaign, the TRacking Aerosol Convection interactions ExpeRiment (TRACER).

Modeling products remained a focus for ARM. While deep convection data from ARM's high-resolution modeling activity moved to production, ARM pushed ahead with planning for future scenarios. One of those scenarios will focus on marine clouds over the Eastern North Atlantic observatory.

In FY2023, ARM made a great deal of progress on recommendations from its 2020 Triennial Review and goals of its Decadal Vision.

Throughout the year, ARM staff engaged with earth system modelers to learn how they are using ARM data for model development and evaluation and to identify areas for possible collaboration. Hopefully these discussions go a long way toward advancing ARM's mission of supplying data that will improve the understanding and modeling of atmospheric processes.

Another key area of advancement for ARM was delivering new computing resources to its users, including the first phase of the ARM Data Workbench, an interactive environment that provides tools for working with ARM data. With the first phase of the workbench in place, scientists can use JupyterHub to create and reproduce complex scientific workflows and share them with others.

I hope you enjoy reading this report and learning more about ARM's activities in FY2023.

JIM MATHER

ARM Director

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On December 4, 2022, in La Jolla, California, beachgoers take advantage of the weather and frolic in the Pacific Ocean while ARM staff set up EPCAPE instruments on the Scripps Pier.

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 2023 (FY2023).

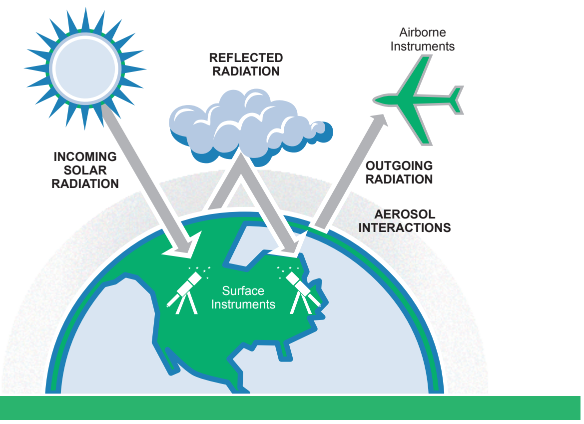
ARM is a multi-laboratory, U.S. Department of Energy (DOE) Office of Science user facility and a key contributor to national and international atmospheric and climate research efforts. ARM offers scientists cutting-edge, ground-based observatories, aerial observation capabilities, and high-performance computing. ARM's capabilities have enabled more than 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.

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

A MEASUREMENT TREASURE TURNS 10

In fall 2023, ARM's Eastern North Atlantic (ENA) atmospheric observatory celebrated its 10-year anniversary of operations on Graciosa Island in the Azores.

Over the past decade, the ENA has collected the world's largest trove of continuous long-term atmospheric data in the Earth's marine midlatitudes.

Marine stratocumulus clouds are very sensitive to even small atmospheric changes. In a climatically changing world, that adds urgency to improving models of the clouds that predominate over oceans.

With the ENA in place, thanks to close collaboration with the Regional Government of the Azores, the municipality of Graciosa, and the University of the Azores/Fundação Gaspar Frutuoso, "we can study (marine clouds) in great detail," said ARM user Mark Miller of Rutgers University. "In the last 10 years, I have learned more about stratocumulus in that region and other regions than I had in all the 20 years before that."

Researchers are also using ENA measurements to study precipitation, turbulence, and aerosols. ENA instruments have captured data on wildfire particles traveling from North America over the Atlantic.

Machine learning and advanced computing capabilities are enabling different kinds of work with ENA data. Machine learning helped scientists correct how global models represent warm rain in marine cloud decks and detect small particles that mark the early stages of drizzle's life cycle. Meanwhile, supercomputing allowed researchers to simulate how clouds organize into heavily drizzling clusters called marine boundary-layer convective complexes.

ARM's publication database includes more than 130 papers featuring ENA data, including 17 published in FY2023.

ARM's Eastern North Atlantic atmospheric observatory has provided detailed information about marine clouds since beginning operations in 2013.

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 in Oklahoma and Kansas.
- North Slope of Alaska (NSA) – Since 1997, ARM has operated a site at Utqiaġvik (formerly Barrow) near the Arctic Ocean.
- Eastern North Atlantic (ENA) – In operation since 2013, ARM's youngest fixed 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.

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.

This view overlooks the U.S. Forest Service's Black Warrior Work Center in northwestern Alabama near the future home of ARM's Bankhead National Forest atmospheric observatory. The "Black Warrior" name is commonly seen in Alabama to recognize a 16th-century Native American chief.

NEW ALABAMA OBSERVATORY MOVES TOWARD OPERATIONS

ARM met a crucial February 2023 deadline to prepare land for what will become the core of its Bankhead National Forest (BNF) atmospheric observatory in northwestern Alabama.

Most of the ARM Mobile Facility instruments will operate in a 300-by-300-foot clearing immediately south of the U.S. Forest Service's Black Warrior Work Center (BWWC). The Forest Service uses the BWWC for regular maintenance activities. ARM will have an office just north of the BWWC.

In addition, a 140-foot instrument tower will be located in mixed pine-oak forest three-quarters of a mile west of the BWWC. This area is representative of the larger Bankhead and forests in the Southeastern United States.

ARM anticipates three installation phases for the expected five-year deployment.

As ARM primed the BNF's main site for construction, staff at ARM's Southern Great Plains observatory prepared instruments and containers for the new deployment. It was the first time ARM used its Oklahoma observatory to stage and prepare a mobile facility.

Meanwhile, the BNF site science team, supported by ARM and DOE's Atmospheric System Research (ASR) program, published its science plan for the new observatory. The team aims to improve process understanding and model representations of aerosols, clouds, and land-atmosphere interactions, as well as coupled surface-atmosphere feedbacks and aerosol-cloud interactions.

Like all ARM sites, the BNF will be open to scientists to propose guest instrument deployments and to use the data in their own research projects and proposals. For example, ASR has funded an initial set of science projects using BNF data.

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 BROADENS OUTREACH TO MODELING COMMUNITY

In response to recommendations from its 2020 Triennial Review, ARM is working to develop metrics that better illustrate its impact on earth system model improvements. Staff are also engaging with modelers to learn how ARM data are being used for model development and evaluation.

To help with its metrics, ARM reviewed the process for tagging publications that are entered into its publications database. Metadata tags now include different modeling identifiers, such as earth system models, single-column models, and cloud-resolving models. New publications are assessed as they are entered online, and assessment of historical publications is underway.

Meanwhile, ARM staff are dedicating additional effort to modeling community outreach to identify areas in which ARM can further collaborate and expand its resources for model development and evaluation. A natural starting point for this effort is DOE's high-resolution Energy Exascale Earth System Model (E3SM) project.

In April 2023, ARM Modeling Translator Shaocheng Xie and ARM Associate Director for Research Jennifer Comstock met with E3SM developers Peter Caldwell and Peter Bogenschutz. The group identified several cloud regimes and ARM field campaigns of interest as important for evaluating the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM) and its doubly periodic configuration (DP-SCREAM).

ARM will keep working with the E3SM evaluation team to identify specific ARM data sets and time periods of interest to focus future development efforts.

ARM also continues to engage with its constituent groups, including the User Executive Committee, which has a subgroup focused on enhancing communication with the modeling community, including E3SM.

ARM/ASR COMMUNITY COMES TOGETHER FOR PAIR OF JOINT MEETINGS

FY2023 saw not one but two annual meetings of the ARM/Atmospheric System Research (ASR) community. ARM users, ARM infrastructure staff, and ASR scientists gathered in Rockville, Maryland, and online for hybrid joint meetings in October 2022 and August 2023.

The Joint ARM User Facility/ASR Principal Investigators Meeting is a venue to review progress and discuss scientific priorities for ARM and ASR.

Participants expressed enthusiasm about meeting in person after COVID restrictions prevented travel in 2020 and 2021. The 2022 meeting drew 431 attendees, while the 2023 edition had 421. At both meetings, most attended in person.

Both meetings began with plenary sessions, which included programmatic updates, science talks, presentations on diversity in the research community, and announcements of new ARM deployments.

At the 2022 meeting, DOE ARM Program Manager Sally McFarlane shared that ARM would conduct a 2024–2025 campaign in Tasmania to collect data on Southern Ocean cloud and precipitation properties.

During the 2023 meeting, McFarlane revealed that ARM would go to Baltimore, Maryland, in late 2024 to support a yearlong campaign aimed at understanding how different surface-atmosphere interactions around a city influence its climate.

The meetings also featured a wide array of poster and breakout sessions. Participants pored over ARM campaign data and findings, planned for future deployments, and discussed community measurement needs.

New in 2023 was a three-part set of breakout sessions focused on open science for ARM and ASR. The sessions dovetailed with the federal government's Year of Open Science initiative.

A crowd gathers during a poster session at the 2023 Joint ARM User Facility/ASR Principal Investigators Meeting in Rockville, Maryland.

USER EXECUTIVE COMMITTEE BUILDS ON PAST ACCOMPLISHMENTS

FY2023 brought a new election for ARM's User Executive Committee (UEC), a constituent group that represents facility users in interactions with ARM management.

After a record 359 voters cast virtual ballots in the fall 2022 election, eight new members joined the UEC in January 2023. All are eligible to serve four-year terms.

Jennifer Delamere of the University of Alaska Fairbanks succeeded Allison Aiken of Los Alamos National Laboratory in New Mexico as the UEC chair. In 2021, the UEC elected Delamere as vice-chair, meaning that she would automatically ascend to chair once Aiken's term ended.

Aiken, the fourth UEC chair overall and first woman to hold the position, was instrumental in setting up four UEC subgroups to address important topics within the ARM community:

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

Comprising four to six members each, these subgroups yielded an array of recommendations and accomplishments. Highlights included fostering new interactions between the satellite community and ARM as well as engaging a diversity, equity, and inclusion speaker, Emily Fischer, for the 2022 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting.

Under Delamere's leadership, the UEC has continued with the subgroups established when Aiken was chair. The group also hosted a diversity, equity, and inclusion speaker, Solomon Bililign, during the 2023 ARM/ASR joint meeting.

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.

SCIENCE WORKSHOP OUTLINES A TRACER FUTURE

In May 2023, a team of scientists met in Houston, Texas, and online for a two-day science workshop focused on the TRacking Aerosol Convection interactions ExpeRiment (TRACER).

The TRACER campaign was a multi-agency investigation of storm evolution near Houston from September 2021 through October 2022.

While ARM provided the core instruments, 150 participants from 45 institutions collected measurements during TRACER. Researchers funded by DOE's Atmospheric System Research (ASR) program deployed their own instruments for smaller related campaigns.

Other agency partners included NOAA, the National Science Foundation, NASA, and the Texas Commission on Environmental Quality.

Texas Southern University was the host site of the science workshop. TRACER Principal Investigator Michael Jensen of Brookhaven National Laboratory in New York convened the workshop for scientists to share data, preliminary results, collaborations, and future research plans.

One key early finding was a strong seasonal signal in the observed aerosol concentrations. Summer air was cleaner than in other seasons.

An upcoming TRACER project will build upon previous work comparing the representation of aerosol-convection interactions in seven cloud-resolving models.

A recurrent theme was the combined power of satellite, surface, and aircraft observations. TRACER has produced the largest database so far on ground-based observations of isolated convective cells.

The workshop also showcased the contributions of early career scientists during TRACER, including data collection and weather forecasting. Many of the scientists are now working on data analysis and modeling efforts.

"The experience gained gives them the foundation to someday lead the next big field campaign," said Jensen.

ARM operated the main TRACER site from October 2021 through September 2022 in La Porte, Texas.

ARM-EMSL USER FACILITY RESEARCH PARTNERSHIP GROWS STRONGER

ARM and the Environmental Molecular Sciences Laboratory (EMSL) continued to enable impactful science together in FY2023.

The two DOE Office of Science user facilities co-hosted a virtual workshop to hear from DOE's Atmospheric System Research (ASR) and Environmental System Science (ESS) program communities on how to improve understanding of coupled land-atmosphere processes.

Then, for a third consecutive year, ARM and EMSL called for joint research proposals through the Facilities Integrating Collaborations for User Science (FICUS) program. FICUS support enables researchers to capture aerosols during ARM tethered balloon system (TBS) flights and analyze the samples using advanced techniques at EMSL. FICUS awardees can also analyze samples from past TBS missions or from missions already planned for a specific FY.

Two new projects were chosen to start in FY2024. Rajan Chakrabarty and Haofei Zhang will use ARM and EMSL capabilities to study land-atmosphere processes and aerosol-cloud interactions.

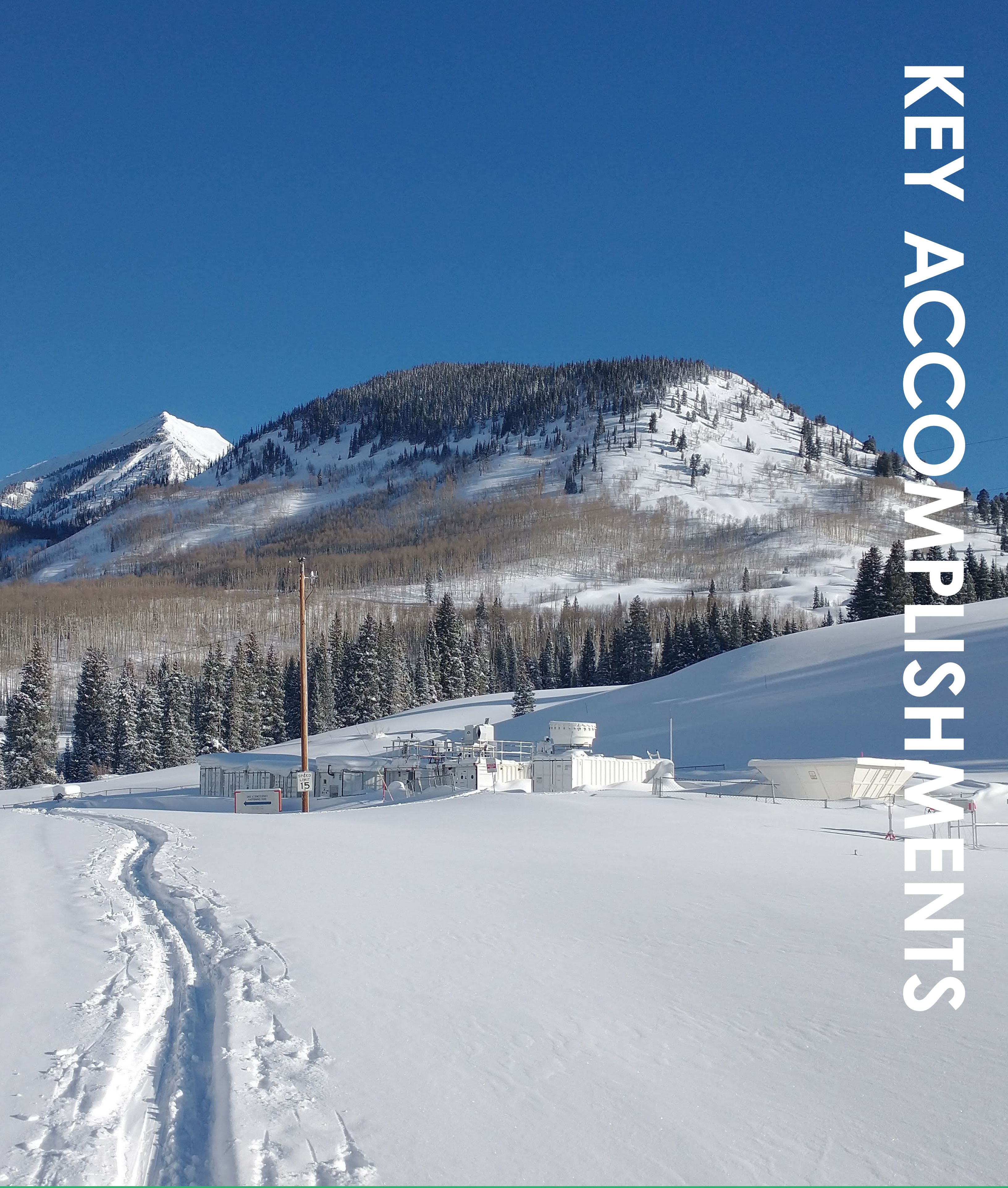
In FY2023, two EMSL-developed aerosol collectors operated during TBS flights at ARM's Southern Great Plains atmospheric observatory. The collectors also flew during the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign in Colorado.

Four new ARM/EMSL FICUS projects took place in FY2023. Allison Aiken and Maria Zawadowicz each examined the vertical profiles of aerosols sampled during SAIL. Meanwhile, Allen Goldstein researched aerosol-cloud interactions and aerosol processes, and Allison Steiner investigated vertical gradients of biological aerosols collected during the TRacking Aerosol Convection interactions ExpeRiment (TRACER) in Texas.

Since the first ARM/EMSL call was announced in January 2021, eight projects have been selected for FICUS support.

Researchers are using EMSL capabilities to study aerosol samples collected on tethered balloon system flights in Guy, Texas, during ARM's TRACER campaign.

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 FY2023.

California Campaign Zeroes In on Coastal Cloud Properties

Stratocumulus clouds cover about one-fifth of the Earth's surface, with most occurring over oceans, and create a net cooling effect globally. Such clouds are a focus of ARM's yearlong Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE), which began in February 2023 in La Jolla, California.

EPCAPE's principal investigator is Lynn Russell from Scripps Institution of Oceanography at the University of California San Diego.

Coastal stratocumulus clouds around La Jolla are influenced by a range of aerosols, including particles coming down from ports in the Los Angeles/Long Beach area.

EPCAPE researchers are studying how cloud layers form and how related processes are affected by human-made particles.

The campaign held intensive operational periods in spring and summer 2023. The intensive periods focused on observations of cloud chemistry and radiation, which could improve model simulations of coastal clouds.

EPCAPE collaborations include projects supported by DOE's Atmospheric System Research (ASR) program to collect airborne and surface data on aerosols.

As part of a project jointly funded by ASR and the Office of Naval Research, scientists flew around the EPCAPE study region on a Twin Otter research aircraft. During the flights, researchers observed cloud formation, pollution dynamics, and environmental interactions over land and water.

EPCAPE instruments also had a unique view of Tropical Storm Hilary in August 2023. Hilary was the first tropical storm to hit Southern California since 1939.

Russell hopes EPCAPE will combine ARM's comprehensive view of coastal stratocumulus clouds with a precise chemical characterization of aerosol and cloud droplets affected by urban pollution.

EPCAPE Principal Investigator Lynn Russell speaks with a journalist during a media day to help kick off the yearlong campaign in La Jolla, California.

Mountain Hydrology Investigation in Colorado Enters New Phase

Researchers are busy with next steps following the observational phase of the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign.

ARM packed up SAIL instruments in June 2023 after operating for 21 months near Crested Butte, Colorado. The instruments collected data on atmospheric processes that influence the water cycle in the Upper Colorado River Basin. Scientists are now focused on data analysis and modeling activities.

"SAIL created the foremost data set for mountain hydrology in North America—and perhaps beyond," said SAIL Principal Investigator Daniel Feldman of Lawrence Berkeley National Laboratory in California.

The data and models from SAIL will help scientists prepare for an uncertain future. Currently, two-thirds of Earth's freshwater originates in mountain ranges. Warming mountains could mean less snowmelt, shrinking water downstream.

SAIL so far has produced more than 100 data sets, which are freely available from ARM. Representing "a giant set of puzzle pieces," said Feldman, the data sets "will advance predictive understanding of water resources in the future."

Modeling experts are already using the traditional Weather Research and Forecasting model to place SAIL data in context.

Feldman led a multi-institutional team in writing an overview paper of SAIL. The *Bulletin of the American Meteorological Society (BAMS)* published the paper online in July 2023.

To help kick off new research collaborations, Feldman co-organized a "science summit" for SAIL and co-located campaigns in November 2023. Scientists are also planning to present SAIL findings at upcoming scientific conferences. The work in progress should produce "a burst of understanding," said Feldman.

Allison Aiken, a SAIL co-investigator, visits a set of instruments on Crested Butte Mountain.

NEW STUDY TO EXPLORE SOUTHERN OCEAN CLOUDS AND PRECIPITATION

Global climate projections are sensitive to aerosol-cloud-precipitation interactions in the atmosphere over the Southern Ocean. Seasonal variations in Southern Ocean aerosol properties are well documented, but to improve the accuracy of climate models, scientists need more information about the properties of low clouds and precipitation in the region.

ARM spent much of FY2023 preparing for a new campaign that will fill in knowledge gaps about the seasonal cycle of clouds and precipitation over the Southern Ocean. The Cloud And Precipitation Experiment at kennaook (CAPE-k) will take place from April 2024 to September 2025 in northwestern Tasmania.

ARM's CAPE-k instruments will operate at the Kennaook/Cape Grim Baseline Air Pollution Station. The Australian Bureau of Meteorology and Commonwealth Scientific and Industrial Research Organisation jointly manage the station, which has measured atmospheric composition since 1976.

Gerald "Jay" Mace of the University of Utah and Roger Marchand of the University of Washington, principal investigators for past ARM campaigns, will co-lead CAPE-k.

PLANNING BEGINS FOR URBAN CAMPAIGN IN MID-ATLANTIC UNITED STATES

An upcoming ARM campaign, announced in August 2023, will study surface-atmosphere interactions around Baltimore, Maryland, to see how they influence the city's climate.

Ken Davis of Pennsylvania State University will lead the yearlong Coast-Urban-Rural Atmospheric Gradient Experiment (CoURAGE), which is expected to start in late 2024.

DOE selected CoURAGE from a fall 2022 call seeking proposals for ARM campaigns that would support the DOE Biological and Environmental Research program's interest in urban climate systems.

CoURAGE data will complement measurements from the Baltimore Social-Environmental Collaborative (BSEC), one of four DOE Urban Integrated Field Laboratories that will operate in U.S. cities to explore urban climate change.

While BSEC collects long-term data on the urban atmosphere and land-atmosphere interactions, CoURAGE will provide additional coverage in the region. ARM plans to set up a mobile observatory in Baltimore and two smaller sites outside the city.

The Kennaook/Cape Grim Baseline Air Pollution Station in Tasmania will host ARM's CAPE-k campaign.

Baltimore, Maryland, will be the focus of a new ARM urban climate science campaign starting in 2024.

Past Campaign Results

Unique Antarctic Data Provide Snapshots of Changing Region

Researchers are watching ice in Antarctica with great interest—and concern. Between 1979 and 2017, the continent's total ice loss reportedly grew sixfold. If the West Antarctic Ice Sheet (WAIS) were to melt completely, current projections indicate that the global mean sea level would rise by 17 feet.

To gain a better understanding of how the region is evolving, scientists need more observational data than are usually possible to collect there. This is why they are thankful to have 14 months of data from the 2015–2017 ARM West Antarctic Radiation Experiment (AWARE).

Led by Dan Lubin from Scripps Institution of Oceanography at the University of California San Diego, AWARE was a joint campaign between DOE and the U.S. Antarctic Program.

Lubin is quick to praise the work being done at international research stations in Antarctica. The continent is more cold, arid, and windy than anywhere else on Earth, which can make it difficult to collect atmospheric data. But if you were to sum up the stations' instruments, said Lubin, "All of them would not equal one AWARE, (which) provided a combination of instruments that was very unique."

ARM deployed a mobile observatory at a coastal site less than a mile from McMurdo Station. In addition, for about six weeks, ARM operated a secondary site about 1,000 miles to the northwest, at the WAIS Divide Ice Camp. AWARE marked the first time since 1967 that significant atmospheric measurements were made in West Antarctica.

As of late September 2023, AWARE data appeared in 43 journal articles. The newest study described energy-balance measurements from miniaturized versions of AWARE instruments on Siple Dome, a 60-square-mile ice cap (Lubin et al. 2023). Other recent AWARE studies have a similar theme: that a new generation of simple, inexpensive, and robust automated instruments can help overcome Antarctica's harsh environment.

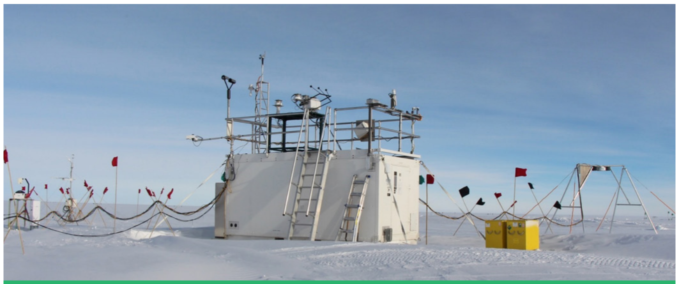
Also notable: Two interconnecting studies investigated blowing snow, which distributes aerosols and affects ice-mass balance, thermodynamics, and atmospheric radiative properties (Loeb and Kennedy 2021, 2023). Another paper outlined the main mechanisms of ice melt in West Antarctica, including warm downslope winds that can raise ambient temperatures in a matter of hours (Ghiz et al. 2021).

In the modeling arena, AWARE data informed an investigation of cold-cloud drizzle, which is more persistent in antarctic environments than previously thought (Silber et al. 2019).

AWARE data could soon pair with measurements from other ARM campaigns, such as the 2023–2024 Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) in Southern California. Data from EPCAPE and AWARE include measurements at coastal sites affected by clouds. Lubin is a co-investigator for EPCAPE.

In northwestern Tasmania, the 2024–2025 Cloud And Precipitation Experiment at kennaook (CAPE-k) could collect data that complement what AWARE gathered on the opposite side of the Southern Ocean.

McMurdo Sound sea ice melts in West Antarctica, where ARM instruments captured rare data during the 2015–2017 AWARE campaign.



This AWARE site, which operated for about six weeks on the West Antarctic Ice Sheet, gathered data early in Antarctica's summer of 2015–2016.

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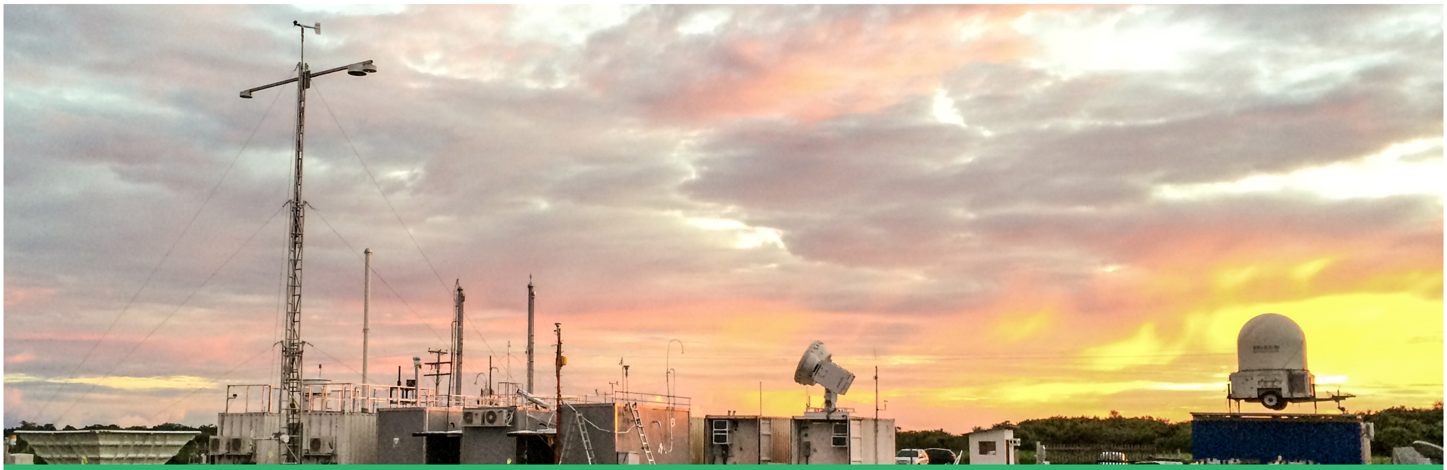
A Decade Later, Amazon Campaign Continues to Have Immense Impact

The Amazon rainforest is the closest modern observations can get to capturing land as it was in preindustrial times. The vast sea of trees has incredibly pristine areas found nowhere else in the world.

For researchers trying to study how human activities have affected the atmosphere, the Amazon represents a critical area where they can acquire data on unpolluted air.

However, the Amazon is not fully isolated. The Green Ocean Amazon (GoAmazon2014/15) field campaign, led by Scot Martin of Harvard University, gathered data in an area of the Amazon near the city of Manaus for two years.

"The length of the GoAmazon campaign was critical for its impact," said co-investigator Courtney Schumacher of Texas A&M University. "Because the data spans multiple years, we've been able to study both seasonal and annual variability in atmospheric processes."



ARM deployed this mobile observatory downwind of Manaus, Brazil, for the GoAmazon2014/15 campaign.

Manaus produces a plume of pollution that acts as the sole source of human-driven emissions for much of the surrounding forest. The study location in GoAmazon allowed the measurements to capture both the undisturbed natural environment and the influence of a large urban center.

Through the data, researchers can explore interactions between human-created aerosols and the pristine forest background. Much of the data collected from GoAmazon have provided insight into how aerosols influence processes in the atmosphere.

Scientists used GoAmazon data to show that urban emissions greatly enhance natural aerosol processes, leading to the formation of more secondary aerosols (Shrivastava et al. 2019). Another study identified how the high concentrations of aerosol particles affect the formation of storms and precipitation (Fan et al. 2018).

GoAmazon data also revealed that Amazonian forest isoprene emissions could be as much as three times higher than reported by satellite observations (Gu et al. 2017).

ARM, which deployed a mobile observatory and its now-retired Gulfstream-159 (G-1) research aircraft, did not accomplish GoAmazon alone. German scientists added more aircraft resources, and Brazilian researchers brought additional radar and aerosol instrumentation as well as local knowledge (Martin et al. 2016).

GoAmazon's impact continues to reverberate throughout the scientific community, producing the most papers of any ARM campaign thus far. Since 2015, over 160 papers have been published using campaign data. More than 20 of those papers were published in 2023 alone. Some of this recently published work uses the data to enhance modeling, either through high-level validation or by integrating the data into simulations to understand the weather and climate.

Manaus is a city of about 2 million people in the central Amazon. Pollution from Manaus travels into the surrounding rainforest.

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NORWEGIAN CAMPAIGN GRACES BAMS COVER

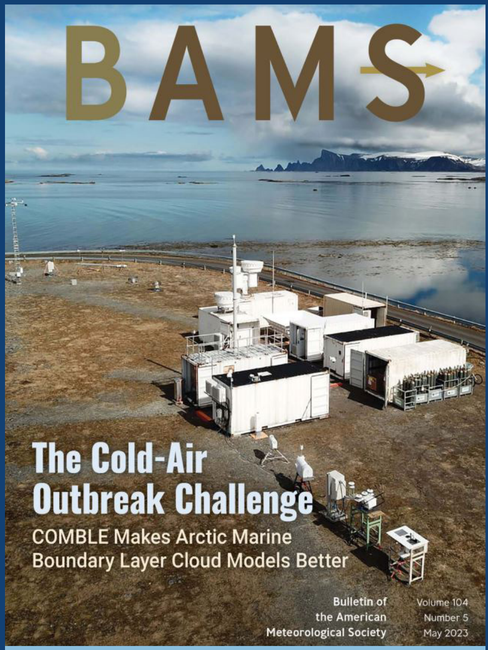
The May 2023 cover of the *Bulletin of the American Meteorological Society (BAMS)* featured an ARM mobile observatory operating in Nordmela, Norway, during the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE). David Oaks, COMBLE's lead technician, took the photo in May 2020.

The *BAMS* issue included key messages from a COMBLE overview paper published online in May 2022.

Scientists are using data from the 2019–2020 campaign to evaluate and improve the representation of mixed-phase clouds and boundary-layer processes in numerical weather prediction models.

"COMBLE has stimulated further interest in the CAO (cold-air outbreak) cloud regime … a key component of the arctic amplification puzzle," said the campaign's principal investigator, Bart Geerts of the University of Wyoming.

Geerts added that several recent and upcoming international airborne field campaigns in the far North Atlantic were "all inspired by COMBLE's pivotal measurements."



The May 2023 *BAMS* print cover features a 2020 photo of an ARM mobile observatory in Nordmela, a fishing village on the Norwegian island of Andøya, during the COMBLE campaign.

Reference

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ARCTIC CIRCLE PRIZE RECOGNIZES MASSIVE POLAR EXPEDITION

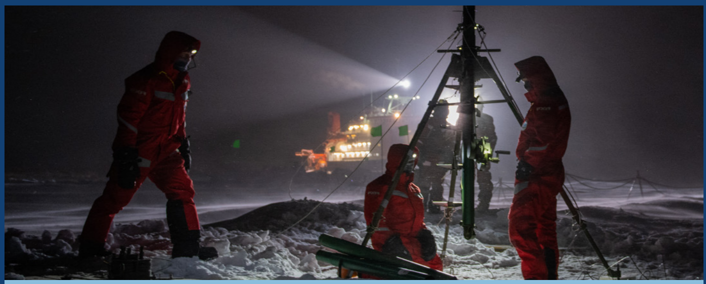
The Alfred Wegener Institute (AWI) and the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition won the 2022 Arctic Circle Prize for their extraordinary contributions toward securing a sustainable and prosperous future in the Arctic.

AWI Director Antje Boetius and expedition leader Markus Rex accepted the prize during the October 2022 Arctic Circle Assembly in Reykjavik, Iceland.

MOSAiC is the largest-ever polar expedition. A German research icebreaker embarked from Norway in September 2019. International teams of scientists, engineers, and technicians studied climate systems from the vessel as it drifted, ice-locked, through the Arctic Ocean for a year.

DOE and ARM were among the expedition's earliest supporters. ARM provided more than 50 atmospheric instruments, which helped researchers identify and quantify cloud, aerosol, weather, and other conditions during MOSAiC.

ARM is proud of its contribution to MOSAiC and its effort to expand scientific understanding of the Arctic.



In December 2019, MOSAiC personnel set up a tower on ice with the research icebreaker *R/V Polarstern* in the distance.

Research Highlights

Southern Ocean Data Useful in Tackling Cloud Modeling Issues

The Southern Ocean covers a vast region surrounding Antarctica and is quite cloudy. The response of clouds to a globally warming climate remains one of the largest uncertainties in climate prediction. Because of the area's relevance to climate change, it has been the subject of significant modeling efforts.

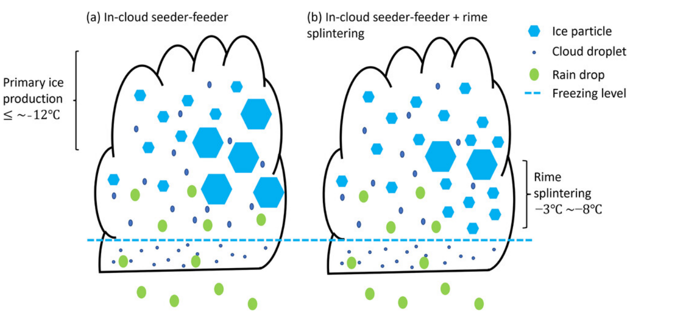
Typically, climate models produce fewer clouds over the Southern Ocean than reality. This has been attributed to a bias in how they represent clouds, such as simulating too many ice crystals in clouds and shorter cloud life cycles. A lack of low clouds means too much solar radiation absorbed by the ocean and a warm bias at the surface. Identifying specific issues in the model requires developing detailed comparisons between observations and model output.

Other than satellite data, few local measurements exist. To help fill that need, ARM conducted the Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) field campaign in 2017 and 2018.

Two May 2023 papers used MARCUS data to explore shallow clouds over the region. The first paper focused on analyzing observational data, while the second was modeling-based. Both paid special attention to ice formation processes.

The scientists found that the shallow clouds observed by remote sensors aboard a supply vessel during MARCUS contain substantial amounts of liquid. Their study focused on shallow clouds in the cold sector of weather systems over the Southern Ocean because previous work showed that the model bias is largest there. In the cold sector, the clouds are generally above the freezing level and contain supercooled liquid, but scientists also found that two-thirds of the clouds in the zero C to minus 5 C layer (32 F down to 23 F) contain ice.

"The observed ice concentrations at relatively warm temperatures are perplexing given the pristine nature of the Southern Ocean, which greatly limits the availability of ice-nucleating particles," said the University of Oklahoma's Zach Lebo, who co-authored both papers. "Our model simulations were unable to capture these observed occurrences of ice. Through sensitivity analysis, we identified potential mechanisms by which relatively high ice concentrations could occur in such a pristine environment."



This schematic shows the proposed mechanisms of enhanced ice concentrations in the clouds observed over the Southern Ocean during ARM's MARCUS campaign. (a) Primary ice production occurs near the cloud top, which seeds the lower levels of the cloud, enhancing ice growth. (b) The process in (a) is modified by rime splintering, which leads to more but smaller ice crystals. (Copyrighted image from the journal.)

Shallow clouds over the Southern Ocean play an important role in reflecting sunlight and affecting the climate. Here, ARM instruments operate aboard the *Aurora Australis* supply vessel during MARCUS.

Results from the modeling study showed that the standard simulation approach underestimates the amount of ice and overestimates the amount of supercooled liquid in the clouds. The researchers found that ice production in the model could be significantly improved by altering the representation and thresholds for several ice-related processes.

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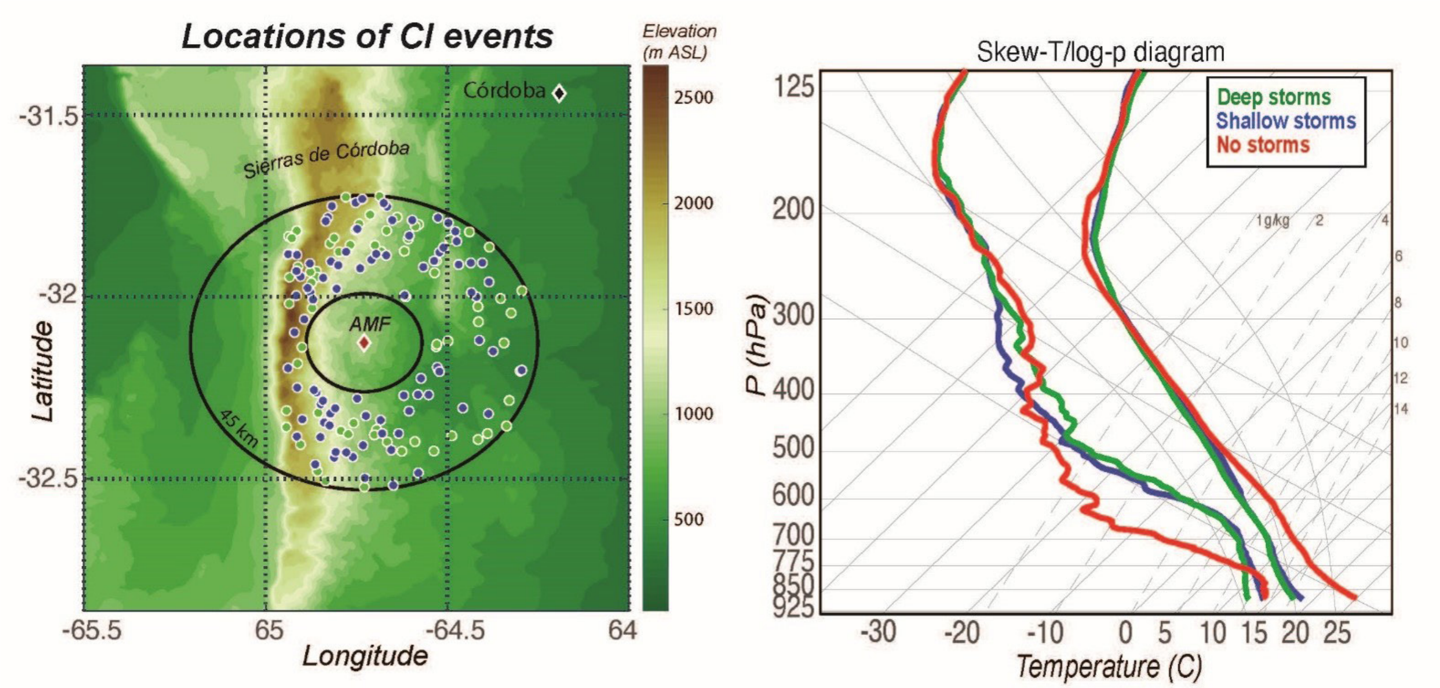
Scientists Identify Conditions That Promote Deep Cloud Growth

Puffy cumulus clouds require warm, humid, and unstable weather conditions to grow into thunderstorms. However, storms often do not form despite supposedly favorable conditions.



Composited radiosonde profiles of meteorological conditions from nearly 200 convective events show significantly moister near-cloud conditions for storm events than days without storms. However, deep and shallow storms occur in very similar conditions. (Copyrighted images from the journal.)

Research published in May 2023 used data from ARM's 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) campaign to identify the differences in meteorological conditions and cloud growth processes in events where storms did or did not form. The data are from a region of Argentina known for its intense and frequent thunderstorms.

"The extensive data collected during the CACTI campaign made this analysis possible," said lead author James Marquis of Pacific Northwest National Laboratory in Washington state. "Typically, the lack of data near growing clouds means these processes are difficult to evaluate under real-world conditions. We had enough measurements to compare deep storms, shallow storms, and periods of time without storms over numerous background meteorological conditions."

The scientists found that relative humidity aloft is strongly related to whether thunderstorms formed, but it does not necessarily dictate the ultimate intensity of storms. They also noted that the ability of the environment near the growing clouds to lift and moisten air aloft and interactions between the wind and local terrain play significant roles in thunderstorm formation.

The analysis showed correlations between these and other meteorological factors, and several physical processes that affect the growth of clouds into thunderstorms. While these connections have been predicted by theory, this work represents the first time that scientists validated the connections by observational data collected from many events.

This study also helps identify the important factors that lead to thunderstorm formation and need to be represented in models. Understanding what influences storm formation and growth is essential to creating accurate weather and climate models.

Reference

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Scientists studied convective clouds during ARM's CACTI campaign in Argentina.

Researchers Investigate Vertical Profile of New Particle Formation

Particles in the atmosphere help form clouds and scatter light, with important effects on weather and climate. While some of these particles enter the atmosphere fully developed, many form at different points in the atmosphere. In a January 2023 paper, a research team explored how height may influence the processes of new particle formation (NPF), important for accurately modeling the atmosphere.

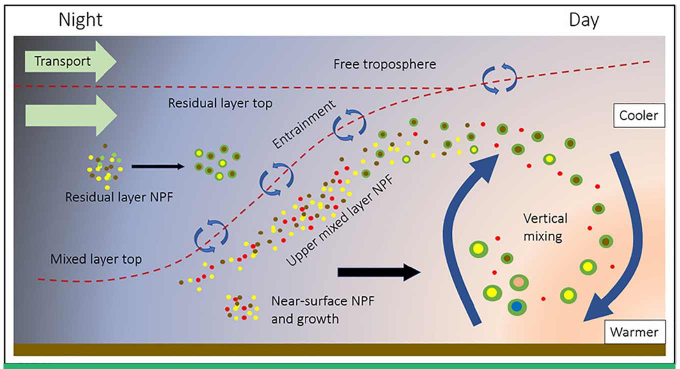
The scientists used measurements from the 2016 Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) campaign, which collected data around ARM's Southern Great Plains atmospheric observatory. They combined the observations with modeling to better understand how atmospheric gradients in temperature and gases affect NPF.

"The vertical profile of new particle formation is a key knowledge gap in our understanding of aerosols and climate," said co-corresponding author Jeff Pierce of Colorado State University. "We're grateful that the HI-SCALE campaign provided the opportunity to help constrain this profile."

Researchers looked at ground-based and aircraft data from four NPF events and two time periods without significant NPF. They compared those data with a model of the chemistry and physics associated with atmospheric particles. The team found that the model could generally reproduce the observations, with several simplifying assumptions in place.

The data showed that the temperature, gases, and amount of mixing in the air all affect NPF. New particles form the fastest at the border of the lowest and middle layers of the lower atmosphere. This is likely due to the importance of temperature on NPF in the model. Mixing the air has a significant effect on NPF, as it affects the temperature and gas composition of the different layers.

This work highlights particularly important processes for NPF. This knowledge can help guide future model development and observational data collection.



This schematic describes new particle formation, aerosol growth, and particle and air transportation mechanisms identified by modeling and analysis of data from ARM's HI-SCALE campaign. (Copyrighted image from the journal.)

A suite of measurements at ARM's Southern Great Plains atmospheric observatory allowed researchers to identify factors that influence new particle formation.

Reference

O'Donnell, S, A Akherati, Y He, A Hodshire, J Shilling, C Kuang, J Fast, F Mei, S Schobesberger, J Thornton, J Smith, S Jathar, and J Pierce. 2023. "Look Up: Probing the Vertical Profile of New Particle Formation and Growth in the Planetary Boundary Layer with Models and Observations." *Journal of Geophysical Research: Atmospheres* 128(3):e2022JD037525, https://doi.org/10.1029/2022JD037525.

ARM Data Reveal Insights Into Life Cycle of Wildfire Particles

Wildfires are becoming increasingly frequent and more intense worldwide. In addition to causing massive damage, wildfires release large plumes full of particles, including ones containing black carbon. Such particles strongly interact with sunlight, affecting atmospheric dynamics and radiative transfer.

Researchers used measurements of particles from biomass burning, including wildfire emissions, collected in the U.S. Pacific Northwest and South Atlantic to better understand how black carbon-containing particles evolve during and after wildfire events. The plumes ranged from 15 minutes to 10 days old, allowing the scientists to create a more accurate picture of how these particles evolve over time.

Analyzing ARM and NASA data, the team found three different regimes in the life cycle of the black carbon-containing particles, beginning with the local or source regime immediately following burning. There, the particles' properties are primarily controlled by the active fire and local conditions, and they rapidly attain a thick coating of mainly organic substances.

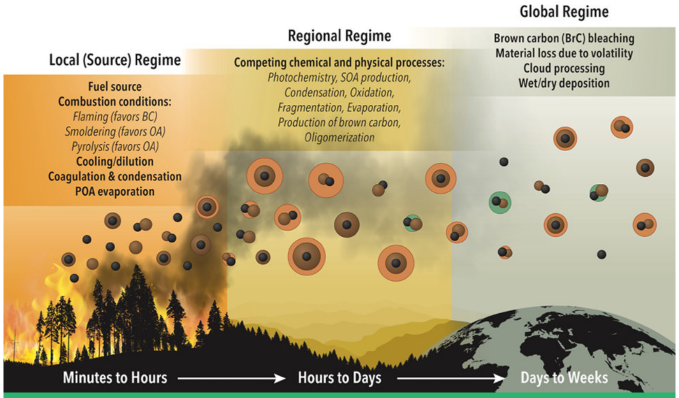
After hours to days, the particles enter the regional regime. At this point, competing chemical and physical processes determine the particles' growth.

After the regional regime, the particles move into the global regime. Here, the coating on the particles gradually decreases because of chemical processing in the atmosphere.

Eventually, the particles leave the atmosphere through rainfall or by falling out from gravity.

This research, published in October 2022, shows the complex behavior of black carbon-containing particles produced by wildfires. Models have generally used data from the local regime to represent the properties and behavior of these particles. However, the complexity identified in this work means that local data are not accurate for representing particles farther from the fire, especially in how they form clouds and interact with sunlight. In the future, models should incorporate additional information about the life cycle of black carbon-containing particles to yield better climate projections.

New research tracks how particles from wildfires change over time.



There are three primary regimes of wildfire particles. As the particles age, the processes that control their properties change, and the properties evolve. (Copyrighted image from the journal.)

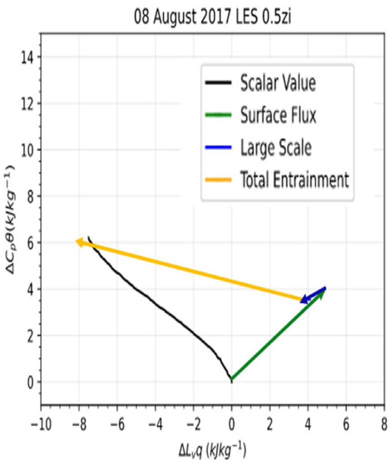
Reference

Sedlacek, A, E Lewis, T Onasch, P Zuidema, J Redemann, D Jaffe, and L Kleinman. 2022. "Using the black carbon particle mixing state to characterize the lifecycle of biomass burning aerosols." *Environmental Science & Technology* 56(20):14315-14325, https://doi.org/10.1021/acs.est.2c03851.

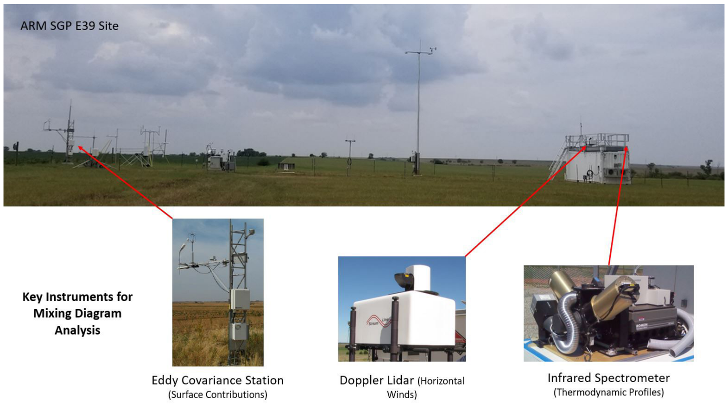
Study Characterizes Evolution of Boundary-Layer Energy and Moisture

Water and energy cycles are meaningfully affected by land-atmosphere interactions. For example, the amount of moisture in the soil or the type of plants can alter how much water enters the lower layer of the atmosphere. Similarly, the mixing of air between the boundary layer and middle of the troposphere also affects the moisture level in the boundary layer.

To understand the complicated relationships and processes that occur, researchers can use mixing diagrams. These represent changes in the moisture and energy of the lower boundary layer as well as different processes that affect energy and moisture flows. These diagrams quickly illustrate the relative contributions from below, the side, and above to the overall evolution of the boundary layer.



This mixing diagram shows the evolution of the convective boundary layer (black line), with the contributions from the surface (green), horizontal advection (blue), and entrainment from above (yellow). (Copyrighted image from the journal.)



A new approach uses a network of ground-based instruments to quantify changes in heat and moisture in the atmosphere.

In a July 2023 paper, scientists described how ground-based data from ARM's Southern Great Plains atmospheric observatory helped them create mixing diagrams of the local environment. Humidity and temperature profiles derived from an infrared spectrometer at the site provided crucial information that enabled the analysis.

Scientists used a network of infrared spectrometers co-located with Doppler lidars, which measure wind profiles, to determine the horizontal transport of water vapor and energy. Combining data from an infrared spectrometer in the center of the domain with surface measurements of water vapor and energy, the researchers were able to create accurate mixing diagrams.

The high resolution of the measurements allowed the team to study how boundary-layer energy and moisture evolve during daytime hours.

"This work provides a unique way to quantify the magnitude of entrainment of dry air from above into the boundary layer," said NOAA's Dave Turner, who led the project. "Entrainment is difficult to measure, often probed with aircraft or a combination of advanced lidar systems. While ARM has advanced lidars, most other sites do not. This approach generates new opportunities to study boundary-layer evolution at a wider range of sites."

Reference

Wakefield, R, D Turner, T Rosenberger, T Heus, T Wagner, J Santanello, and J Basara. 2023. "A methodology for estimating the energy and moisture budget of the convective boundary layer using continuous ground-based infrared spectrometer observations." *Journal of Applied Meteorology and Climatology* 62(7):901-914, https://doi.org/10.1175/JAMC-D-22-0163.1.

Sea Salt Produced by Blowing Snow Contributes to Arctic Warming

The Arctic is warming four times faster than the global average. Researchers have shown that aerosols play an important role in the Arctic's dramatic climate change. Arctic aerosol studies have found significant amounts of sea salt particles during the spring and winter, but their production mechanisms and impacts on the Arctic's climate have remained unclear.

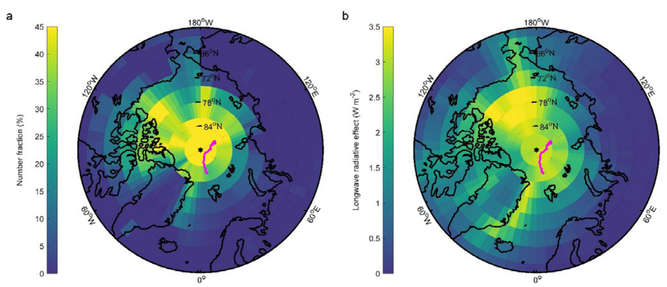
In a September 2023 paper, scientists used ARM data from the 2019–2020 Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition to identify the sources and climate effects of the sea salt aerosols. Comprehensive MOSAiC measurements of aerosols, blowing snow, clouds, and meteorological variables allowed the researchers to make comparisons across seasons.

"Our study reveals that local blowing snow, which produces fine sea salt particles, contributes a substantial fraction to the total aerosol population in the central Arctic," said corresponding author Jian Wang of Washington University in St. Louis.

From November to April, there is blowing snow over 20% of the time in the central Arctic. This blowing snow produces a substantial amount of sea salt aerosols. These aerosols represent approximately 30% of all particles observed during the MOSAiC expedition in months with high blowing snow.

The significant amount of sea salt aerosols dramatically increases the number of particles that can act as formation sites for cloud droplets over the Arctic. Having more of these particles present affects the properties of clouds, leading them to trap and emit more infrared radiation and warm the surface.

Identifying the source of the sea salt aerosols is important for accurately modeling the Arctic's climate. The scientists used a representation of blowing snow producing aerosols in a model and found that it more accurately reproduced the MOSAiC data. They could then estimate surface warming due to the sea salt particles generated by blowing snow.



Blowing snow produces a significant amount of sea salt aerosols. Scientists found that these particles are contributing to warming in the central Arctic. (Copyrighted image from the journal.)

Light beams from the icebreaker *R/V Polarstern*, illuminating blowing snow during the MOSAiC expedition.

Reference

Gong, X, J Zhang, B Croft, X Yang, M Frey, N Bergner, R Chang, J Creamean, C Kuang, R Martin, A Ranjithkumar, A Sedlacek, J Uin, S Willmes, M Zawadowicz, J Pierce, M Shupe, J Schmale, and J Wang. 2023. "Arctic warming by abundant fine sea salt aerosols from blowing snow." *Nature Geoscience* 16(9):768-774, https://doi.org/10.1038/s41561-023-01254-8.

A New Picture Develops of Shallow Cloud Formation

Complicated interactions between the land and atmosphere help shape both weather and climate. Aspects of the land surface, such as moisture content and temperature, can affect how energy moves through the atmosphere.

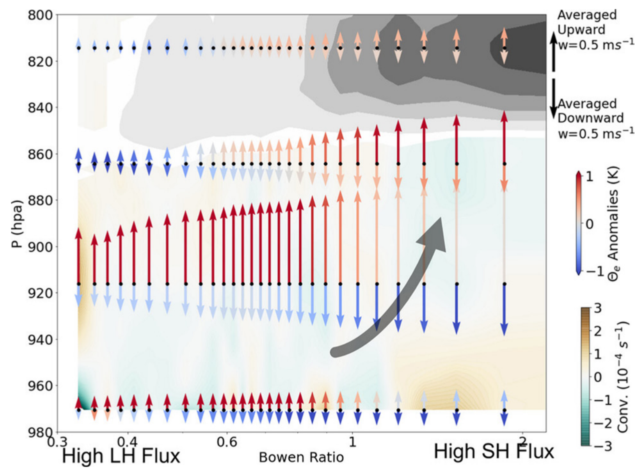
Researchers conducted simulations using data from ARM's 2016 Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) field campaign in Oklahoma to explore how the land surface affects cloud formation. They combined detailed atmospheric simulations with an interactive land model. By removing background wind, they could isolate the specific role of land surface variations on atmospheric energy movement. Their findings appeared in a February 2023 paper.

"Our work allowed us to deeply study the intricate interplay between the land surface, boundary layer, and clouds," said lead author Jingyi Chen of Pacific Northwest National Laboratory in Washington state. "We discovered that variations in the land surface, such as moisture content and temperature, exert a profound influence on how energy circulates within the atmosphere."

Scientists specifically focused on areas with the same potential temperature. Their work shows that shallow clouds form over areas with high amounts of water vapor, reflected in high energy values. They also found that soil moisture plays a significant role in the movement of energy.

Having a larger difference in moisture from one area to another creates bigger moisture gradients. These bigger gradients are associated with stronger air mixing and greater energy movement.

The results of this work provide an important perspective on how shallow clouds form. It helps create a deeper understanding of how soil moisture and the land surface affect cloud formation. This knowledge could lead to improvements in predicting where clouds form and where rain will fall.



Mixing of moist and dry air over heterogeneous land surfaces contributes to the formation of shallow clouds. (Copyrighted image from the journal.)

Soil moisture and atmospheric energy affect where clouds form across the Southern Great Plains.

Reference

Chen, J, S Hagos, H Xiao, J Fast, and Z Feng. 2023. "Multiscale Analysis of Surface Heterogeneity–Induced Convection on Isentropic Coordinates." *Journal of the Atmospheric Sciences* 80(4):983-1001, https://doi.org/10.1175/JAS-D-21-0198.1.

EDGE COMPUTING OFFERS EXCITING POTENTIAL FOR ARM DATA PROCESSING

Understanding and characterizing cloud behavior requires wind and precipitation data. Doppler lidars at ARM's Southern Great Plains atmospheric observatory provide these measurements, but transmission and management of such large data can be challenging.

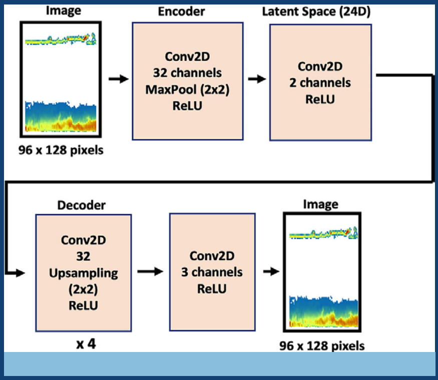
In response, researchers developed a machine learning method to identify cloudy periods, when the data are most useful. The scientists trained the algorithm on hand-labeled lidar images, with typical signal-to-noise ratios, to classify clear and cloudy periods with about 96% accuracy.

Their approach, detailed in a September 2023 paper, retains only the data from cloudy periods by classifying the data in near-real time using an edge computing platform in the field. This is intended to streamline the transfer of full Doppler spectra and their associated data from the instrument to the ARM Data Center.

Researchers will be able to use the spectra to develop a more detailed understanding of turbulence, wind, and precipitation near the Earth's surface.

Reference

Jackson, R, B Raut, D Dematties, S Collis, N Ferrier, P Beckman, R Sankaran, Y Kim, S Park, S Shahkarami, and R Newsom. 2023. "ARMing the Edge: Designing edge computing-capable machine learning algorithms to target ARM Doppler lidar processing." *Artificial Intelligence for the Earth Systems* 2(4):220062, https://doi.org/10.1175/AIES-D-22-0062.1.



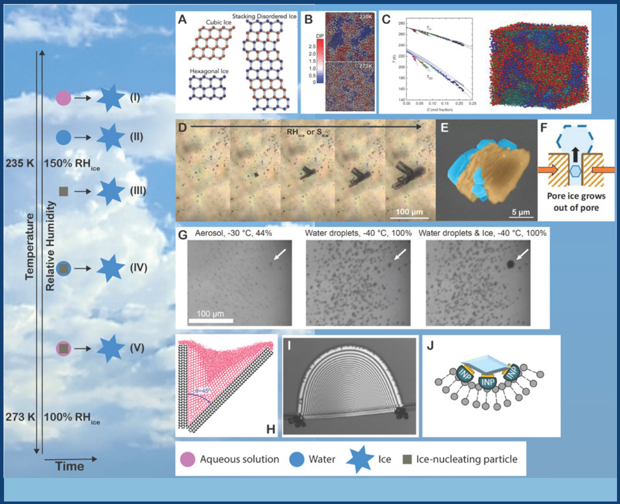
These processing steps convert lidar spectra into analyzable data for the machine learning algorithm. (Copyrighted image from the journal.)

FUNDAMENTALS OF ICE NUCLEATION

Atmospheric ice nucleation plays a central role in precipitation, affects cloud properties, and influences the climate. Ice nucleates through different pathways, across varying temperatures and humidity and other conditions. These aspects make ice formation challenging to accurately model in large-scale climate simulations.

In a March 2023 paper, a pair of scientists explored the current scientific understanding of ice nucleation. They focused on the theoretical understanding of how the process occurs, an essential connector between laboratory-based experiments, large-scale models, and data from ARM and other entities.

Research over the past two decades shows that a measurable quantity directly related to ambient humidity, known as particle water activity, serves as a predictor for ice nucleation. For several ice nucleation pathways, theoretical underpinnings connecting water activity to freezing temperature and specific particle composition already exist. Use of particle water activity in models will help improve representation of ice nucleation, leading to more reliable predictions of cloud properties and future climate.



At the coldest temperatures, ice nucleates from aqueous solution (I) or water (II) droplets. Ice deposits from the supersaturated vapor phase onto an ice-nucleating particle (III). An ice-nucleating particle immersed in supercooled water (IV) or aqueous solution (V) can initiate freezing. (Copyrighted image from the journal.)

Reference

Knopf, D, and P Alpert. 2023. "Atmospheric ice nucleation." *Nature Reviews Physics* 5:203-217, https://doi.org/10.1038/s42254-023-00570-7.

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.

Data Flow Again From Alaska After Undersea Cable Cut

ARM found an alternate solution to restore data transmission from its North Slope of Alaska (NSA) atmospheric observatory to the ARM Data Center after a severed undersea fiber optic cable disrupted telecommunications service in the region.

The North Slope Borough issued an emergency declaration related to the internet and phone outages, which began in June 2023. The NSA had enough onsite storage to hold more than 30 days of incoming data, but connectivity to the observatory was minimal, which increased the difficulty in monitoring and troubleshooting instruments.

ARM and many other customers in the region ended up turning to Starlink satellite internet, which ARM's tethered balloon system team uses in the field. The Starlink systems took a few weeks to be shipped and installed, but the NSA continued to collect data during that time and did not lose any data.

Eventually, it took 14 weeks to fix the cable about 34 miles north of Oliktok Point. The cause of the cable cut was ice scouring, which is when ice drifts into shallower waters and drags along the seafloor.

A Starlink system is shown at ARM's North Slope of Alaska atmospheric observatory.

ARM Adds JupyterHub Access to Further Enable Open Science

One of the newest additions to ARM's available computing resources is JupyterHub, a popular tool for supporting scientific analysis through notebook-based computational environments.

In JupyterHub, people can build and execute interactive Jupyter Notebooks. Much like physical notebooks one might use in a classroom, Jupyter Notebooks contain text notes and equations, as well as a software environment, which allows users to run code next to their notes. This enables users to document their work and reproduce the code they used to obtain their scientific results.

Users can work with ARM data in individual or shared workspaces managed by ARM system administrators. JupyterHub does not require setup or installation, and it is accessible from ARM's Data Discovery home page.

Different service levels are available to ARM users depending on their computing and access needs.

JupyterHub functions as part of the ARM Data Workbench, a new ecosystem for interacting with ARM data. Currently in development, the workbench will offer a free suite of tools for users to select, access, visualize, and analyze data.

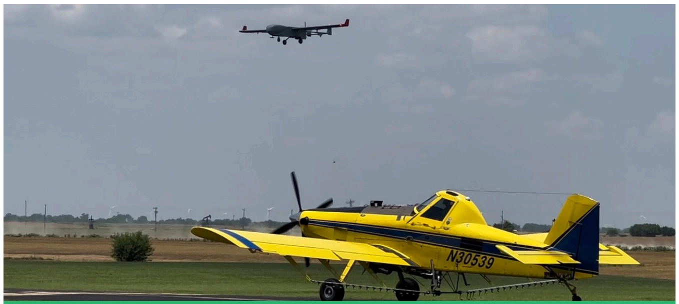
In April 2023, ARM hosted a webinar to educate scientists on how to use JupyterHub on the ARM Data Workbench.

ARM Marks New Set of Engineering and Development Achievements

ARM prioritizes its engineering and development activities each fiscal year to meet user needs and achieve mission-critical facility goals.

In FY2023, priorities included preparation for the Bankhead National Forest atmospheric observatory in Alabama. A major accomplishment was the design, procurement, and development of instrument systems for the observatory's 140-foot walk-up tower. Systems will be deployed in FY2024.

Other ARM instrument development activities revolved around expanding aerosol instrumentation at the North Slope of Alaska observatory and upgrading existing instrumentation, such as Ka-Band ARM Zenith Radars.



ARM's ArcticShark uncrewed aerial system flies above a crop duster in northern Oklahoma in June 2023.

Meanwhile, ARM completed site data system network infrastructure upgrades for the Southern Great Plains (SGP) observatory and second ARM Mobile Facility.

In March, June, and August 2023, the ARM Aerial Facility conducted a successful series of flights over the SGP with the ArcticShark uncrewed aerial system. Atmospheric data collected during the flights are available for use. At the end of September, ARM opened a proposal call for FY2024 ArcticShark flights in the SGP region.

In the science products area, ARM continued to focus on developing user-requested value-added products (VAPs) for boundary-layer, aerosol, and precipitation processes, and model evaluation.

Developers also used a new workflow for reprocessing VAPs. The main goal is to ensure that VAPs are reprocessed when input data change. The workflow streamlines the process, enabling faster data delivery to users.

To further support users, ARM's data services team released the first phase of the ARM Data Workbench, an ecosystem for working with ARM data. The team also updated ARM's Online Metadata Editor tool, which scientists can use to submit guest instrument data from ARM field campaigns and principal investigator products.

NEW FRONTIERS AHEAD FOR ARM'S HIGH-RESOLUTION MODELING ACTIVITY

The Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity provides high-resolution model simulations vetted by ARM observations. In FY2023, LASSO's development team moved forward with plans to expand the activity to new sites and atmospheric phenomena.

LASSO's initial scenario targeted shallow clouds at ARM's Southern Great Plains atmospheric observatory. For its second scenario, the LASSO team focused on deep convection observed during a 2018–2019 ARM field campaign in Argentina. Production data from this scenario became available in the summer of 2023.

In July, the LASSO team hosted a workshop for scientists to provide feedback on the development of a marine cloud scenario at ARM's Eastern North Atlantic observatory.

The team later announced it would hold a Future of LASSO Workshop in November. To build the workshop agenda, the team asked researchers to submit white papers on how LASSO might further evolve for greatest scientific impact.

The LASSO activity produced new model simulations based on deep convection observed during an ARM field campaign in Argentina.

New Data Products

ARM Provides More Products for Aerosol Community

For scientists studying the intricacies of tiny atmospheric particles, ARM expanded its collection of aerosol value-added products (VAPs) in FY2023.

Production data for nine ARM sites became available from a VAP that calculates hygroscopic—moisture-absorbing—properties of aerosols from cloud condensation nuclei (CCN) measurements and aerosol size distributions from the scanning mobility particle sizer (SMPS).

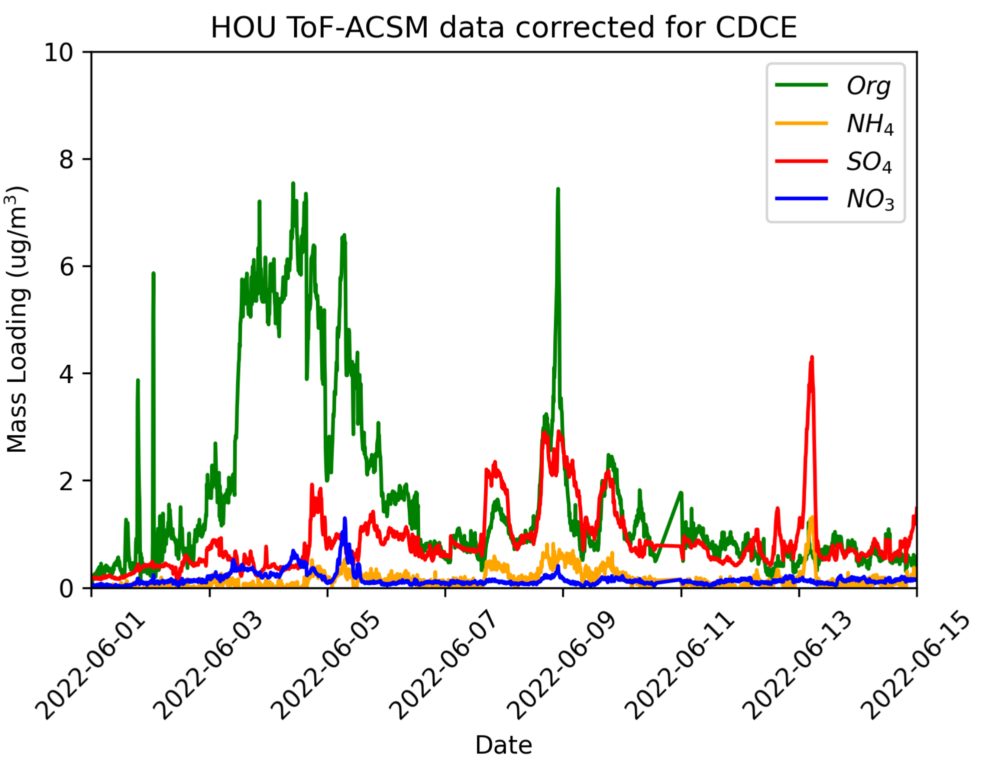
A new VAP calculates hygroscopic properties of aerosols using CCN and size distribution measurements from the ultra-high-sensitivity aerosol spectrometer (UHSAS). This VAP will provide data for sites without an SMPS.

Both VAPs derive the hygroscopicity parameter kappa, which quantifies a particle's capacity to activate into a cloud droplet. Scientists can use these kappa products to evaluate aerosol properties simulated in global earth system models.

ARM now provides a set of products that merge aerosol size distribution measurements from several sources. Individual instruments measure different size ranges of aerosols, so the merged products create consistent size distributions across wider size ranges.

The original VAP merges measurements from the SMPS and aerodynamic particle sizer (APS). A new VAP merges SMPS- and UHSAS-measured size distributions. Another new VAP improves the quality of the merged SMPS/APS data through machine learning.

The merged products can help scientists calculate aerosol scattering and mass loading, estimate the impact of aerosol on clouds, and verify aerosol-related quantities in models.



This sample plot from ARM's TRACER campaign near Houston, Texas, shows a selection of aerosol mass concentrations from the time-of-flight aerosol chemical speciation monitor corrected for composition-dependent collection efficiency.

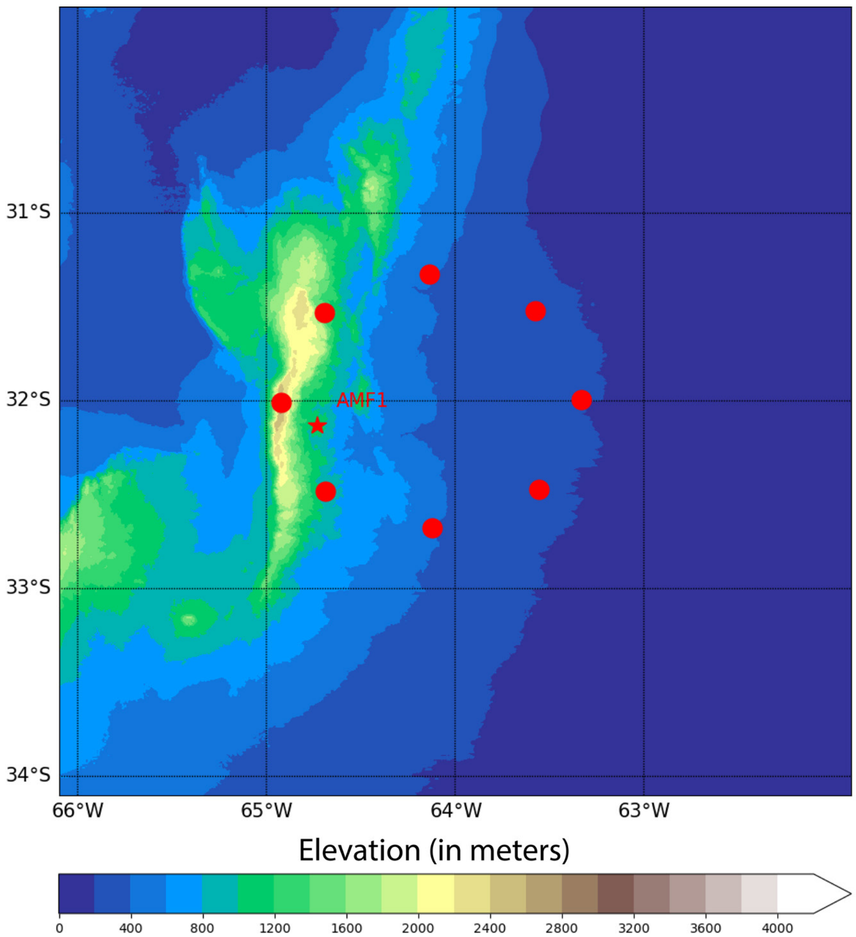
ARM also developed a VAP that corrects time-of-flight aerosol chemical speciation monitor data for composition-dependent collection efficiency, or the non-unity detection of particle mass by the instrument. This VAP brings the instrument data into better agreement with co-located aerosol measurements.

ARM Delivers Modeling Products for Stormy Campaign in Argentina

In FY2023, ARM released new modeling products for the 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign, which captured unique views of convective clouds in central Argentina.

The Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity generated high-resolution simulations of deep convection observed during CACTI. Scientists can use the production version of the LASSO-CACTI data set to learn more about convective processes and potentially improve their representation in climate models.

ARM also produced two versions of continuous large-scale forcing data for CACTI. Both versions are based on atmospheric reanalysis data and constrained by observed surface precipitation and satellite-derived top-of-atmosphere radiative fluxes. Scientists can use these data to drive single-column models, cloud-resolving models, and LES models for different cloud and convective systems.



The map shows the analysis domain (enclosed by the red circle) for the CACTI large-scale forcing data. The first ARM Mobile Facility (AMF1) at Córdoba, Argentina, is located near the southwestern corner of the domain.

One version was originally designed for a cylindrical atmospheric column. It uses an algorithm that assumes the analysis domain has a flat surface, with the surface pressure equal to the pressure at the center of the domain.

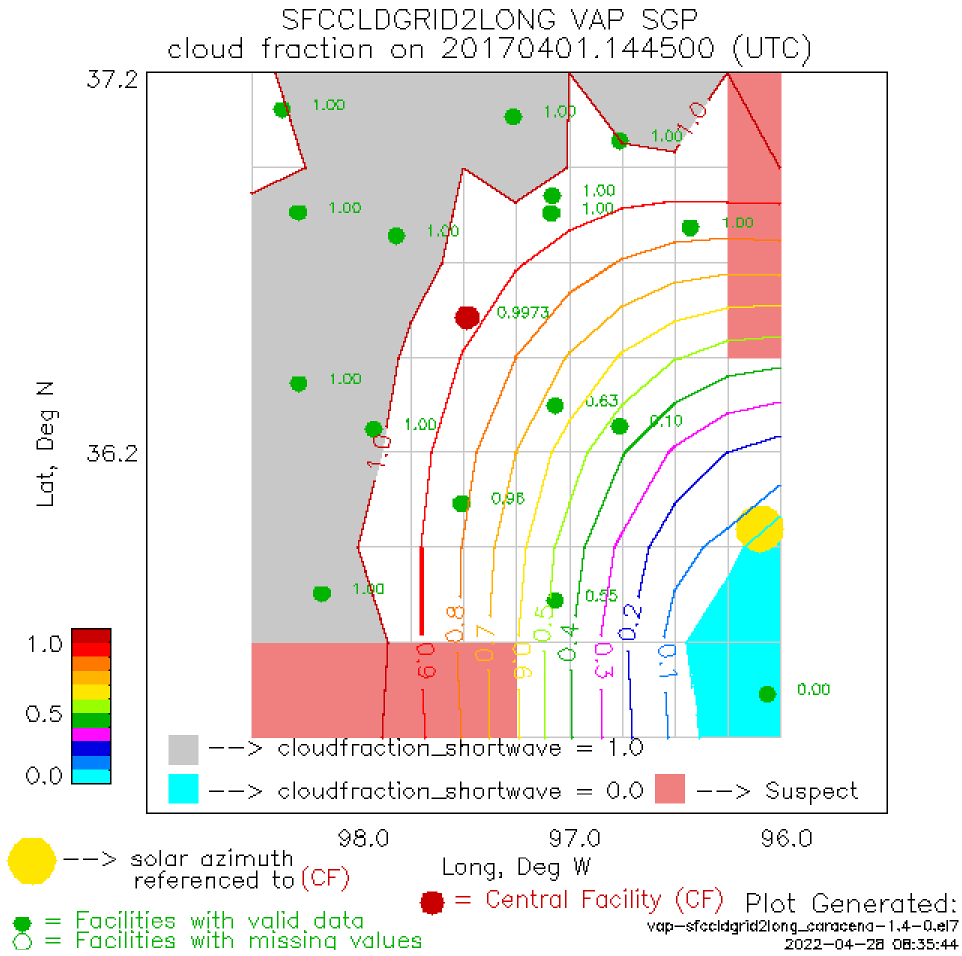
The other version uses a new algorithm designed to better treat the varying slope of the terrain in the analysis so that the effect of the surface terrain on the derived large-scale forcing fields can be captured and represented.

Gridded Data Products Give Scientists a Unique Look at Clouds

ARM offers several gridded value-added products (VAPs) that deliver a multidimensional view of clouds.

In FY2023, two gridded VAPs—Surface Cloud Grid (SFCCLDGRID) and Clouds Optically Gridded by Stereo (COGS)—transitioned from evaluation to production.

SFCCLDGRID compiles spatially distributed measurements of cloud and radiation properties over ARM's Southern Great Plains (SGP) atmospheric observatory. These values enable more accurate comparisons of model/satellite grid boxes and ground-based SGP observations, as well as an estimate of the regional variability of cloud and radiation properties.



The figure illustrates SFCCLDGRID cloud fraction on the morning of April 1, 2017, when the Southern Great Plains (SGP) atmospheric observatory experienced partly cloudy conditions with clear skies to the east and overcast conditions to the west and north. The yellow ball represents the sun in the sky, the SGP Central Facility is noted in red, and other SGP facilities are noted in green.

COGS provides a four-dimensional (4D) map of cloudiness generated by stitching together reconstructed cloud points from a ring of stereo cameras at the SGP. The VAP also includes a vertically projected cloud fraction and cloud base height estimate. Scientists can use COGS data to study the life cycles and macrophysical attributes of shallow cumulus clouds.

Meanwhile, the Scanning ARM Cloud Radar Grid (SACRGRID) family of VAPs provides radar moments and quantities on a Cartesian grid. For a past campaign in Norway, ARM produced two new SACRGRID releases for evaluation. These releases use calibrated data from two different types of scans as input.

SACRGRID products make it easier to use scanning ARM cloud radar observations from the entire campaign.

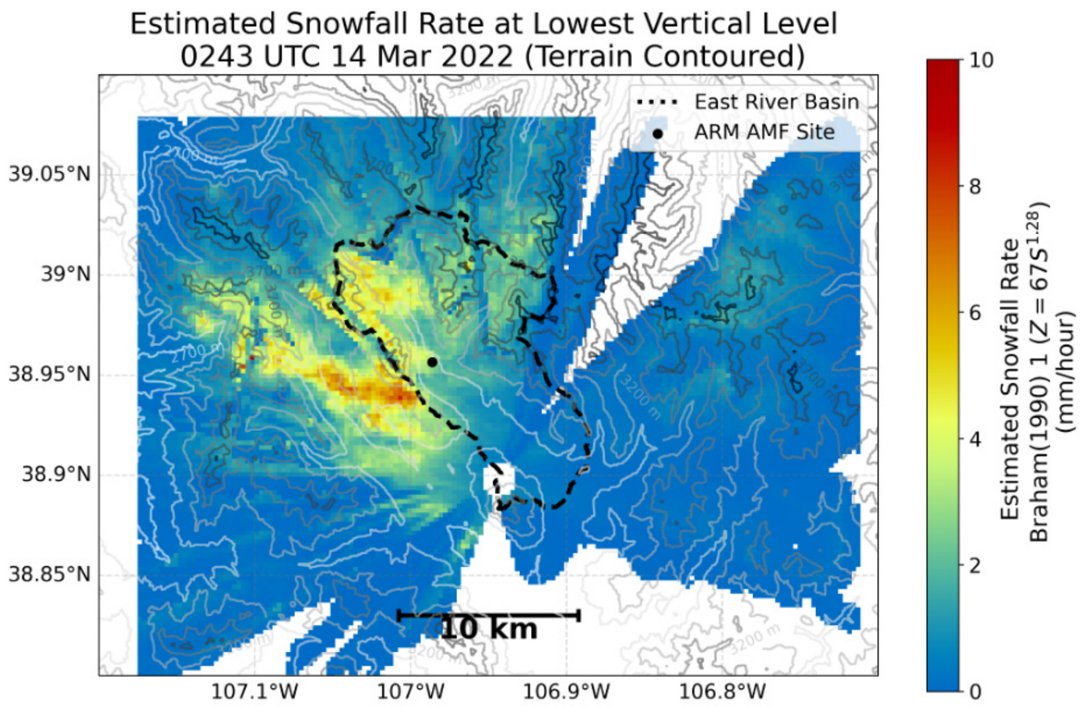
New Workflow Eases Challenges of Interacting With Radar Data

During the 2021–2023 Surface Atmosphere Integrated Field Laboratory (SAIL) campaign near Crested Butte, Colorado, ARM supported the deployment of an X-band scanning precipitation radar from Colorado State University. Mountains often blocked the radar beam, which could present challenges for data users.

To help overcome these challenges, ARM processed the radar data using a new workflow called Surface Quantitative Precipitation Estimation (SQUIRE). The SQUIRE workflow projects the data from native antenna coordinates to Cartesian coordinates (e.g., x, y or latitude, longitude). It also extracts the lowest gate, or 3-dimensional (3D) grid point, available for each grid cell in the domain. This provides data fields on a grid that modelers or other scientists can add to their analysis, including surface estimates of liquid precipitation.

For input, SQUIRE uses data from the Corrected Moments in Antenna Coordinates (CMAC) value-added product. CMAC corrects raw scanning radar data for atmospheric phenomena and instrument characteristics, and it also retrieves precipitation quantities from the radar measurements.

CMAC precipitation estimates are derived from an ensemble of existing radar reflectivity and snowfall rate relationships. Within SQUIRE, the estimates are mapped to a Cartesian grid. To address terrain complexity, reflectivity and snowfall rates are projected from the lowest valid elevation to the surface.

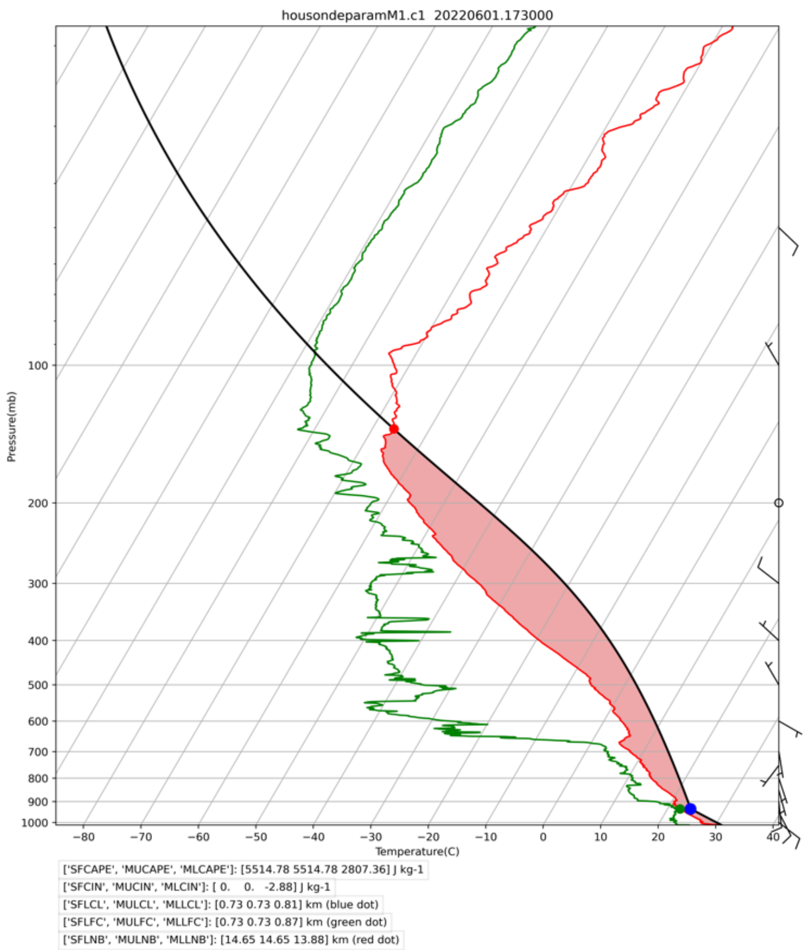


This map of the gridded estimated snowfall rate from Colorado State University's X-band radar on March 14, 2022, highlights the East River Watershed and ARM Mobile Facility (AMF) site in Gothic, Colorado, northwest of the radar on Crested Butte Mountain.

Diverse Group of Data Products Generated From Texas Campaign

In FY2023, ARM prioritized the delivery of data products from the TRacking Aerosol Convection interactions ExpeRiment (TRACER). Scientists are using data from the 2021–2022 campaign to study the effects of aerosols on thunderstorms around Houston, Texas.

TRACER data became available from existing ARM value-added products (VAPs) for assessing surface radiation measurements, calculating radiative fluxes, retrieving variables from microwave radiometer measurements, determining cloud microphysical properties, and generating cloud masks from lidar data.



This skew-T plot shows the pressure and temperature recorded by a radiosonde launched June 1, 2022, at the ARM Mobile Facility site in La Porte, Texas, during the TRACER campaign. Red, blue, and green dots indicate different radiosonde parameters.

ARM released merged aerosol size distribution data from TRACER instruments, in addition to ice-nucleating particle concentrations based on filter samples.

For the evaluation of global climate models, ARM produced best-estimate atmospheric, cloud, and radiation quantities from TRACER. Also, scientists can use large-scale forcing data from the campaign to drive models of different cloud and convective systems.

Meanwhile, ARM included TRACER in the initial releases of three new VAPs. One of the VAPs calculates radiosonde parameters within convective cloud environments. Another combines data from the tethered balloon system and ground-based ceilometer to allow for examination of cloud-base and boundary-layer heights. ARM also released a VAP that corrects time-of-flight aerosol chemical speciation monitor data for non-unity detection of particle mass by the instrument.

A principal investigator product includes data on more than 1,000 convective cells tracked under a framework that helped capture fast-evolving radar parameters associated with dynamical and microphysical cloud processes. ARM funded the development of the cell tracking software used for TRACER.

COASTAL CAMPAIGN GETS FIRSTHAND LOOK AT HISTORIC TROPICAL STORM

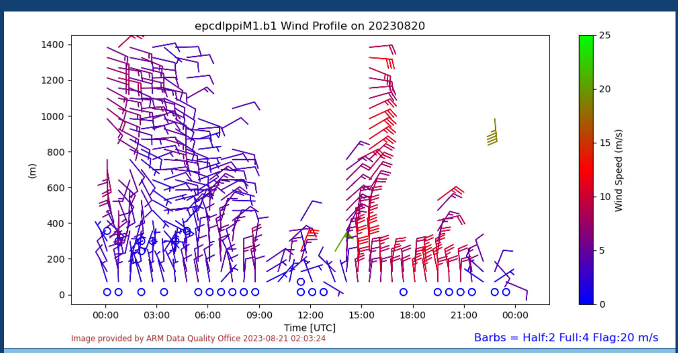
In August 2023, ARM instruments recorded an unexpected event during the Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) in La Jolla, California.

Hurricane Hilary moved up Mexico's west coast before becoming the first tropical storm to hit Southern California in 84 years, generating extensive rainfall and strong winds. Most of the ARM instruments at EPCAPE (excluding the scanning radars, which were shut down because of the high wind predictions) acquired data as the cyclone moved through the region.

Rain totals at EPCAPE surpassed 3 inches in about 18 hours. Data from the Ka-Band ARM Zenith Radar indicated a melting layer above which snow particles were generated. The particles then precipitated to the surface as relatively fast-falling rain.

Meanwhile, ARM's Doppler lidar captured persistent high winds (exceeding about 45 mph) and wind veering features.

EPCAPE data from Tropical Storm Hilary are freely available in the ARM Data Center.



This figure from the EPCAPE campaign shows lower-troposphere 3D wind profiles retrieved by the Doppler lidar during Tropical Storm Hilary on August 20, 2023.

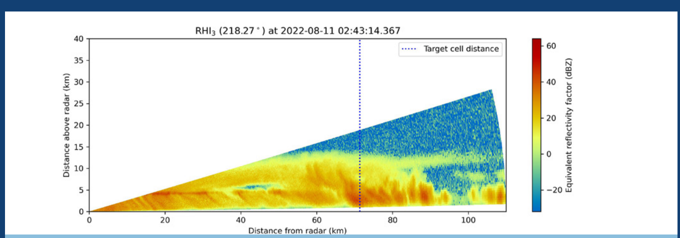
A DECADE OF THE PYTHON ARM RADAR TOOLKIT

In 2012, DOE scientists developed an open-source package to interact with ARM radar data. Since becoming publicly available a decade ago, the Python ARM Radar Toolkit (Py-ART) has built up a worldwide community of thousands of users working with radar data from ARM and other organizations.

Py-ART is a Python library organized by modules oriented to different functions: storage, formatting, display, correction, gridding and mapping data, and calculation of geophysical variables such as rainfall rate.

A main use of Py-ART is extracting information needed to improve weather and climate models, but radars can observe more than clouds and precipitation. In a growing universe of applications, Py-ART users have mapped mayfly populations, surveyed waterfowl in flight, visualized the life cycles of storm clouds generated by massive wildfires, and identified likely meteorite fall zones.

Anyone can use Py-ART, and many users give back by contributing new code.



This Py-ART image from ARM's TRACER campaign near Houston, Texas, showcases vertical cross-sections through deep convective cells.

Science Outreach

ARM Activities Support Federal Year of Open Science Initiative

In January 2023, the White House Office of Science and Technology Policy launched the Year of Open Science to advance national open science policies across the federal government.

Since 1992, ARM has made its data freely available to scientists worldwide, but open-source capabilities are opening up new ways to work with the data.

ARM staff and users have developed open-source tools that make it easier to visualize and analyze ARM data and are teaching others how to use them.

Before the 2023 American Meteorological Society (AMS) Annual Meeting in Denver, Colorado, ARM organized a short course on open science and working with data from the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign. This daylong short course was the result of a collaboration between ARM field campaign scientists, data translators, and developers. The course drew 20 attendees, including professors, research scientists, and graduate students.

The short course was also a concrete example of activities that ARM is supporting to advance its Decadal Vision by enabling open-source software practices to support code sharing across the ARM community.

Following science-focused discussion on SAIL, attendees received tutorials on ARM data, ARM's open-source software tools, the GitHub software development platform, and different computing resources available from ARM.

Open science was also a key focus of the August 2023 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting in Rockville, Maryland. The meeting included a three-part set of breakout sessions focused on open science for ARM and ASR.

The sessions included an introduction to open science in ARM, toolkit tutorials, and solicited talks.

A few weeks later, the 40th AMS Conference on Radar Meteorology in Minneapolis, Minnesota, featured an open radar short course organized by ARM staff. More than 40 attendees explored using open-source toolkits to work with weather radar data, primarily C- and S-band data near the new ARM observatory in Alabama's Bankhead National Forest.

AMS open radar short course students and instructors pause for a photo.

Back In Person, ARM Makes Splash at Major Scientific Conferences

After COVID altered meeting plans the previous two years, FY2023 brought a welcome return to in-person scientific conferences for many members of the ARM community.

ARM users and staff flocked to the December 2022 American Geophysical Union (AGU) Fall Meeting in Chicago, Illinois. Right after the new year came the 2023 American Meteorological Society (AMS) Annual Meeting in Denver, Colorado.

An ARM exhibit drew close to 300 visitors at AGU and more than 500 at AMS.

With eyes on ARM's future, ARM Director Jim Mather led an AGU town hall on new capabilities and establishing development priorities within the user facility.

Demonstrating the scientific impact of ARM data, the ARM community reported 168 presentations at AGU and 74 at AMS.

Despite ending two months before AGU, the TRacking Aerosol Convection interactions ExpeRiment (TRACER) had plenty of early results to report. The yearlong ARM campaign gathered data near Houston, Texas, to help scientists understand how aerosols might affect thunderstorms.

Researchers also mined data from ARM's Surface Atmosphere Integrated Field Laboratory (SAIL) campaign near Crested Butte, Colorado. SAIL, which ended in June 2023, collected data about physical processes and interactions that affect mountain hydrology.

An AMS short course showed attendees how to use ARM-supported open-source tools to work with SAIL data.

ARM welcomes visitors to its exhibit during the 2022 AGU Fall Meeting in Chicago, Illinois.

SHARING ARM'S UNCREWED AERIAL SYSTEM WITH THE NEXT GENERATION

While in Oklahoma for a June 2023 deployment of ARM's ArcticShark uncrewed aerial system (UAS), ARM Aerial Facility (AAF) staff introduced the UAS technology to an aspiring group of young aviators from the Northern Oklahoma Flight Academy.

Ranging from sixth graders to high school seniors, the students toured the UAS Mobile Operations Center, ground control station, hangar, and maintenance areas. They learned about the AAF mission and how ARM uses different instruments to collect aerial data.

"It was gratifying to see the next generation stepping up with so much interest in climate science and aviation," said AAF Manager Beat Schmid. "I mean, holy cow! These kids are the smartest of the smartest, and they asked great questions. It was an honor to share what we do and hopefully make an impact on their future."

ARM Aerial Facility Manager Beat Schmid describes ArcticShark components to a group of young aviators from the Northern Oklahoma Flight Academy.

FACILITY USAGE

1,157 TOTAL SCIENTIFIC USERS

34

COUNTRIES/TERRITORIES

Users by country/territory

United States **842**
China **88**
Germany **46**
United Kingdom **24**
Brazil **22**
Canada **20**
France **12**
Sweden **11**
Netherlands **10**
Puerto Rico **10**
India **9**
Japan **9**
Switzerland **8**
Italy **7**
South Korea **6**
Australia **5**
Finland **4**
Argentina **3**
Spain **3**
Norway **2**
Pakistan **2**
Taiwan **2**
Armenia **1**
Austria **1**
French Polynesia **1**
Greece **1**
Indonesia **1**
Ireland **1**
Israel **1**
Kenya **1**
New Zealand **1**
Poland **1**
Portugal **1**
Russia **1**

USER STATISTICS

Universities (U.S.)	524	45%
Foreign Entities	315	27%
DOE Labs	194	17%
Other U.S. Gov.	77	7%
Industry	47	4%

PUBLICATIONS USING ARM* 1,455 TOTAL

- **1,202** Abstracts and Presentations
- **190** Journal Articles
- **58** Technical Reports
- **3** Book Chapters
- **2** Conference Papers

*Publication statistics were collected as of December 2023. Journal article numbers will continue to increase over time.

FACILITY USAGE

Data	Remote	Onsite
800	221	136
69%	19%	12%

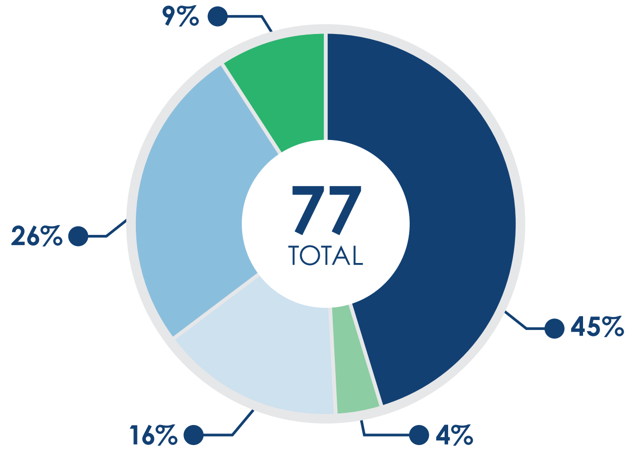
7,000+
Publicly Available Datastreams

460+
Instruments Collect Atmospheric Data

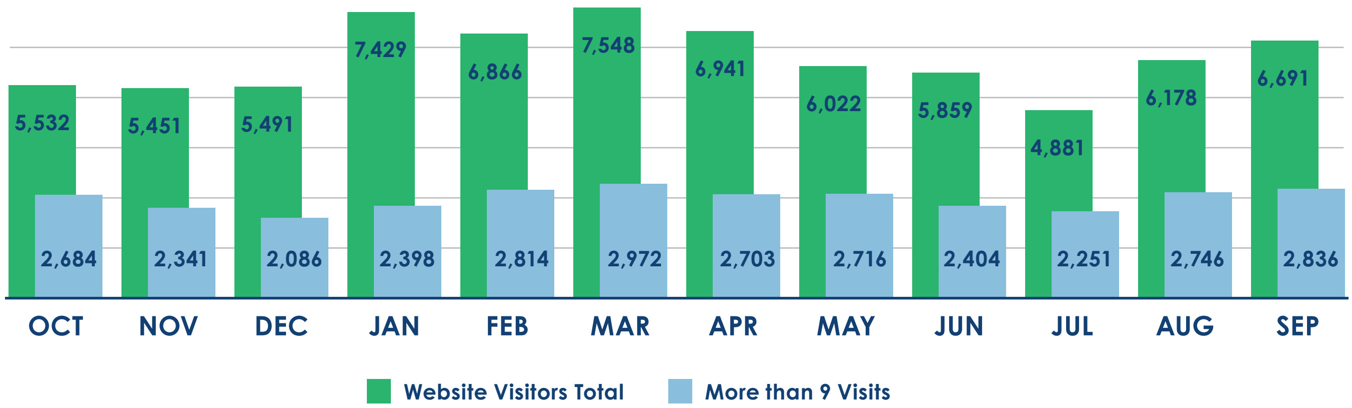
4,500+
Journal Articles Since 1990

FIELD CAMPAIGNS

- AMF **35**
- SGP **20**
- NSA **12**
- OFFSITE **7**
- ENA **3**



WEBSITE VISITORS



DATA PRODUCTS

3
Released to Production

- COGS
- MERGEDSMPSAPS
- SONDEPARAM

7
Released to Evaluation

- CCNUHSASKAPPA
- DLMCPROF-WIND
- MERGEDSMPSAPSML
- MERGEDSMPSUHSAS
- MPLCAL
- SQUIRE
- XPRECIPCMAC

8
Approved for Development

- AAFMERGED
- AMERIFLUX
- CLOUDRADARCOR
- CSAPR2-CMAC
- LIDARAEROMASK
- Mixed Phase
- PPHIYD
- RWPPRECIPCOR

3
Existing VAPs Updated

- AREALAVEALB
- AOD-MFRSR
- MFRSRCLDOD1MIN

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

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On Graciosa Island in the Azores, ARM's decade-old Eastern North Atlantic atmospheric observatory, seen here in September 2023, collects continuous cloud, precipitation, and aerosol data.

DOE/SC-ARM-23-047