ARM

2021 ANNUAL REPORT

ATMOSPHERIC RADIATION MEASUREMENT

U.S. DEPARTMENT OF ENERGY

On the covers:

Front – Over three and a half days in June 2021, this site in Gothic, Colorado, went from an empty construction pad to eight cargo containers hosting much of the instrumentation for the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign. In this picture, site construction is finished for the day and the crane is parked.

Inside – In addition to operating ground-based instruments during SAIL, ARM is gathering data through tethered balloon system flights in Gothic.

From the Technical Director

Challenges and Progress in the Time of COVID

In fiscal year 2021 (FY2021), the COVID-19 pandemic continued to have an impact on activities within the Atmospheric Radiation Measurement (ARM) user facility. Travel was limited, which affected field activities and forced the continuation of virtual meetings. However, the ability to travel expanded significantly through the year, bringing some return to normalcy, and throughout the year, there was a great deal of activity dedicated to advancing the facility.

Because of COVID, ARM twice delayed the TRacking Aerosol Convection interactions ExpeRiment (TRACER) in the Houston, Texas, area. Originally planned to launch in the spring, TRACER started October 1, 2021, one month after the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign began near Crested Butte, Colorado. ARM teams worked onsite and remotely to make sure both campaigns could launch on this new schedule that was set early in the year.

Data from SAIL and TRACER will be critical to improving earth system models, each contributing to different sets of issues. SAIL measurements will provide insights into how precipitation forms and water travels through the Upper Colorado River Basin. TRACER scientists want to know whether tiny atmospheric particles can influence the severity of thunderstorms.

In October 2020, the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition ended after 13 months. MOSAiC data from ARM and other organizations are already helping scientists better understand how ice, atmosphere, and ocean systems are connected in the central Arctic. This report discusses some early investigations from MOSAiC, along with other ARM campaigns and activities generating prolific research.

In this report, you will also learn how research activities moved forward during the pandemic at ARM's fixed-location atmospheric observatories. There were important science applications from measurements across the facility.

ARM spent a significant amount of FY2021 looking back—and ahead. In November 2020, ARM had its Triennial Review. This review is held every three years to evaluate ARM's effectiveness in science, operations, and management. Overall, the reviewers had positive feedback regarding the breadth and impact of science activities using ARM data and the way ARM strives to meet changing user needs. The reviewers also provided some recommendations for strengthening ARM going forward.

Incorporating feedback from the review, we finalized an updated Decadal Vision document that will help guide ARM priorities in the coming years. This report describes the four themes driving ARM's Decadal Vision.

FY2021 also began a time of transition for the third ARM Mobile Facility (AMF3), which was at Oliktok Point, Alaska, since 2013. In June 2021, operations of AMF3 ceased at Oliktok so preparations could begin for its next extended deployment—in the Southeastern United States.

With travel limited, ARM pursued more opportunities to engage remotely with users and the broader scientific community. The Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting was virtual for the second year in a row, with a greater amount of user engagement than the first virtual ARM/ASR meeting. In addition, we ended up hosting virtual booths during four major scientific conferences. ARM also leveraged engagement in the expanded virtual world by conducting three successful webinars to help users better engage with the facility.

While ARM had to navigate more pandemic-related challenges in FY2021, we maintained our commitment to serving our users and providing high-quality data. I am excited to share with you ARM's accomplishments over the last fiscal year and how the scientific community is using ARM measurements to advance important science issues.

Jim Mather
ARM Technical Director

Future Directions: ARM's Updated Decadal Vision

ARM is continually changing in response to evolving science, user needs, and available technology. ARM engages with users through its constituent groups, with Atmospheric System Research (ASR) scientists (especially through the annual Joint ARM User Facility/ASR Principal Investigators Meeting), and the broader community through workshops, conferences, and collaborative activities.

In addition to interactions with the scientific community, the direction of ARM is governed by the strategic direction set by the U.S. Department of Energy (DOE).

A New Vision for ARM

Through community engagement, ARM in 2020 developed a new Decadal Vision document to address increasingly complex science challenges related to the facility's mission over the next five to 10 years. The updated vision statement is: **to provide the research community with the best array of field observations and supporting state-of-the-art data analytics to significantly improve the representation of challenging atmospheric processes in earth system models**.

This vision will be sustained by activities organized within the following four themes:

MEASUREMENTS

Provide comprehensive and impactful field measurements to support scientific advancement of atmospheric process understanding. ARM strives to deliver the highest level of information possible at its observatories. To maximize its science impact, ARM plans to continue deploying observatories where the scientific community most needs them, provide the most comprehensive and useful measurements possible, and expand the spatial footprint of ARM measurements.

DATA ANALYTICS

Achieve the maximum scientific impact of ARM measurements through increased engagement with observational data by ARM staff, including the application of advanced data analytical techniques. In addition to exploring new measurement opportunities, ARM is considering how it can extract additional benefit from existing measurements through a focus on data analysis. ARM is looking at fundamental work that needs to be done with ARM data as well as potential applications of advanced data analytics.

DATA SERVICES

Enable advanced data analytics and community use of complex ARM data sets through the advancement of computing infrastructure and data analysis. To advance data analysis applications and the usability of ARM data by the scientific community, it is important to continue to develop ARM computing platforms and tools. ARM plans to expand its computing infrastructure to support growing volume and expanding processing applications, and develop tools and software practices that would facilitate user engagement with ARM data.

OBSERVATIONS TO MODELS

Accelerate and amplify the impact of ARM measurements on earth system models (ESMs) by exploiting ARM and ESM frameworks to facilitate the application of ARM data to ESM development. ARM plans to continue advancing its strategies to support model improvement. These strategies include applying a high-resolution modeling framework to bridge scales and creating direct connections to the modeling community through diagnostics based on ARM data and supporting single-column model cases over ARM sites.

ARM PRIORITIES

Some high-priority activities stemming from the Decadal Vision work and other drivers will be captured on the ARM Priorities web page (**www.arm.gov/about/management-structure/arm-priorities**). ARM encourages its users to engage with constituent groups or facility staff on how ARM can continue to meet the evolving needs of the scientific community.

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In August 2021 in La Porte, Texas, ARM team members set up the main site for the TRacking Aerosol Convection interactions ExpeRiment (TRACER). The TRACER field campaign began in the Houston area in October 2021.

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 2021 (FY2021).

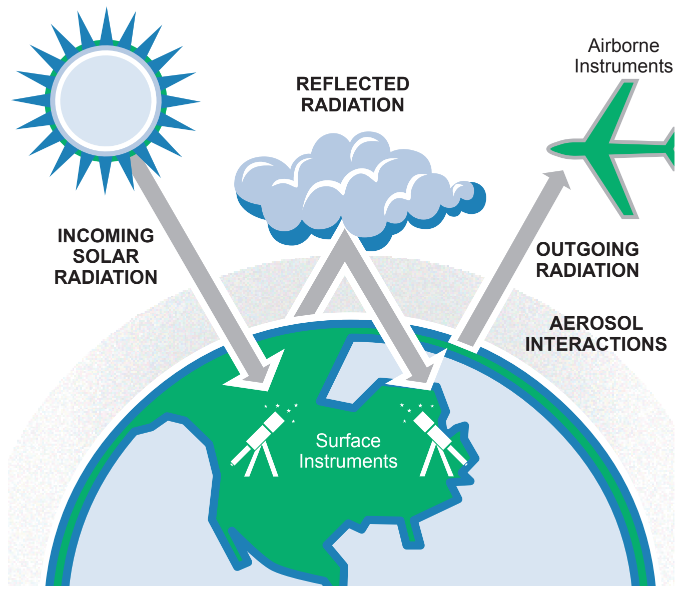
ARM is a multi-laboratory, U.S. Department of Energy (DOE) scientific user facility and a key contributor to national and international atmospheric and climate research efforts. ARM offers scientists cutting-edge, ground-based observatories, crewed and uncrewed aerial capabilities, and almost 30 years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

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

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

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

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



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

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

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

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ARM Observatories

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

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

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

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

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

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

ARM Mobile Facility Leaves Alaska; U.S. Southeast in Its Future

In June 2021, operations of the third ARM Mobile Facility (AMF3) ended after almost eight years at Oliktok Point, Alaska. AMF3 will soon move to the Southeastern United States for its next extended deployment.

In addition to collecting continuous ground-based data, the Oliktok deployment had access to special-use airspace, allowing for flights of uncrewed aerial systems and tethered balloon systems.

ARM's North Slope of Alaska sites at Oliktok and Utqiaġvik (formerly Barrow) have provided important atmospheric data for researchers studying conditions in the rapidly changing Arctic. The Utqiaġvik site is still active. Oliktok data—as with all previous AMF deployments—remain freely available from ARM.

A site science team, led by Brookhaven National Laboratory in New York, is developing the initial science plan for the upcoming AMF3 deployment. With ARM aiming to start Southeastern U.S. operations in 2023, planning for the new deployment progressed in FY2021. Representatives from ARM and the site science team visited candidate sites, evaluated their operational suitability, and met with potential university and agency collaborators in the region.

The AMF3 team continued to engage with the DOE ARM/Atmospheric System Research (ASR) community and broader scientific community about the deployment's scientific goals, siting, and possible partnerships.

Team members led AMF3 town halls during the 2020 American Geophysical Union Fall Meeting and 2021 American Meteorological Society Annual Meeting. The team also sought community feedback during the Land-Atmosphere Interactions Workshop 2021, organized by representatives from ARM, ASR, and AmeriFlux; and the 2021 Joint ARM User Facility/ASR Principal Investigators Meeting.

ARM ended operations of this mobile facility at Oliktok Point, Alaska, in June 2021 to begin preparations for its upcoming move to the Southeastern United States.

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 User Executive Committee Embraces—and Creates—Change

The ARM User Executive Committee (UEC)—the official voice of the user community to ARM management—started FY2021 with an online election for new members. (Every other year, ARM users vote for new representatives to replace those rotating off the committee.)

From the 260 votes cast, the UEC gained seven new members representing various science themes. Their terms began January 1, 2021, and most of the new members will serve four years. The early career representative will rotate off in 2023 along with the seven members who returned in 2021.

After Allison C. Aiken (Los Alamos National Laboratory in New Mexico) moved up to UEC chair, the committee selected a new vice-chair, Jennifer Delamere (University of Alaska, Fairbanks). Delamere will succeed Aiken as chair in 2023.

The new UEC quickly got to work, creating four subgroups to address new and continuing efforts in the following focus areas:

- enhancing communication with the satellite community
- enhancing communication with the modeling and DOE Energy Exascale Earth System Model (E3SM) communities
- measurement uncertainty and communicating calibrations
- undergraduate outreach and increasing diversity.

The UEC also engaged remotely with ARM users during the June 2021 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting. The committee held a networking session for new ARM users and presented a poster outlining goals and objectives for the coming year, including subgroup plans.

Toward the end of FY2021, ARM Technical Director Jim Mather tasked each subgroup with submitting written recommendations for ARM to address and potentially implement.

Triennial Review Highlights ARM's Aptitude for Enabling Impactful Science

Every three years, DOE selects an external review panel of domain and technical experts to evaluate ARM's effectiveness in science, operations, and management. ARM's latest Triennial Review happened virtually from November 4 to 6, 2020.

The reviewers found that "ARM has unique and world-leading capabilities, enables high-impact science supporting the EESSD (DOE Earth and Environmental Systems Sciences Division) strategic plan, has effective management and operations, effectively engages with the BER (Biological and Environmental Research program) user community, has started broadening outreach beyond BER, and has mostly addressed the recommendations from the 2017 review."

Though their feedback was largely positive, reviewers also provided recommendations for further strengthening and improving ARM. The recommendations related to broadening the user community; metrics; staff; data management and data products; the Decadal Vision document, which outlines ARM's vision for the next five to 10 years; and the facility's 2017 Triennial Review response.

In February 2021, ARM Technical Director Jim Mather sent a response to DOE outlining plans to address the recommendations. ARM management has begun engaging with staff and users to determine priorities and strategies for addressing issues identified through the review.

ARM leadership prepared a report to assist reviewers during ARM's Triennial Review evaluation process. The report is available upon request.

ARM/ASR Community Gathers Virtually for 2021 Joint Meeting

With the COVID-19 pandemic stretching into 2021, the Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting took place online for the second consecutive year.

Attendance at the annual meeting of ARM users, ARM infrastructure staff, and ASR-funded scientists, held June 21 to 24, tracked closely with 2020. The opening-day plenary sessions, featuring programmatic updates and science talks, drew 468 attendees from 14 countries.

DOE ARM Program Manager Sally McFarlane said that the facility was working to catch up with field campaigns delayed because of the pandemic. She also acknowledged the significant efforts of ARM staff to identify new ways of accomplishing their work remotely to keep ARM data flowing despite COVID-related challenges.

The meeting featured 12 breakout sessions that allowed participants to dive deeper into specific scientific and technical topics. Breakout sessions included findings and data products from past ARM campaigns and discussions of community needs from upcoming campaigns.

In 2021, meeting organizers brought back poster sessions by taking advantage of virtual technology. Each of the 223 posters had its own space, or channel, on Slack. In their channel, the presenter could upload their poster and chat with attendees.

Also new were informal networking sessions. Participants gathered in a virtual area made to look like an in-person meeting space.

Breakout sessions during the 2021 ARM/ASR joint meeting included one on the 2019–2020 Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition.

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.

Land-Atmosphere Workshop Connects Scientific Communities

Questions about land-atmosphere interactions are being addressed by atmospheric researchers using ARM measurements, including scientists supported by DOE's Atmospheric System Research (ASR). Ecosystem scientists are also interested in these questions, but from a different direction, looking down toward soil and vegetation instead of up into the atmosphere for answers.

Atmospheric and ecosystem scientists took a step toward answering some of those questions together by gathering virtually for the Land-Atmosphere Interactions Workshop 2021. ARM users, ARM staff, and ASR-funded scientists joined AmeriFlux surface flux community representatives as workshop organizers and presenters.

The AmeriFlux tower network, like ARM and ASR, is supported by DOE's Biological and Environmental Research program. AmeriFlux measures ecosystem carbon, water, and energy fluxes across the Americas.

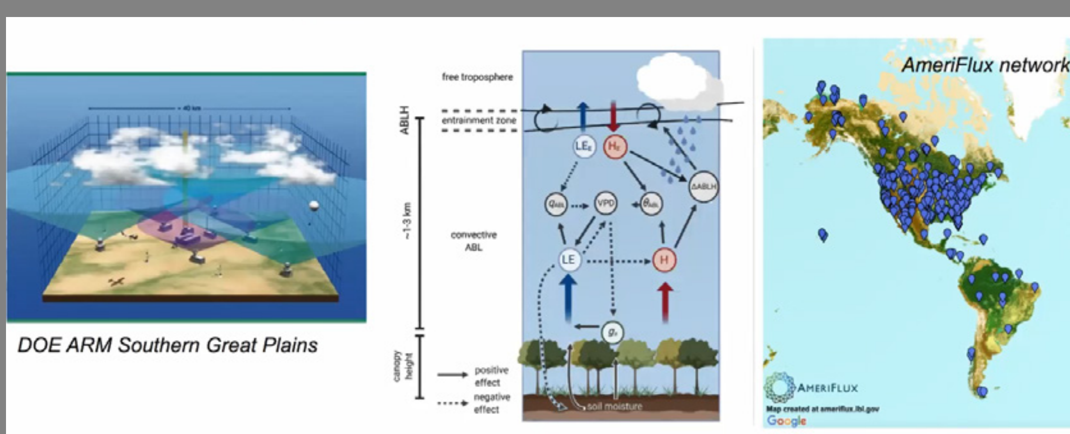
About 400 people registered for the June event, which aimed to break down communication barriers and enhance collaboration between the atmospheric science and surface flux communities.

Invited speakers included ARM Engineering and Process Manager Jennifer Comstock and members of the site science team helping with the upcoming ARM Mobile Facility deployment to the Southeastern United States.

The workshop featured additional invited talks on instrumentation and remote sensing, modeling, water fluxes, clouds, and aerosols, as well as breakout and poster sessions.

Participants pondered research questions that can be best addressed by combining existing surface flux and atmospheric measurements, and they discussed future measurement priorities. Attendees also considered how increased collaboration between ecologists, biogeoscientists, and atmospheric scientists could improve predictive understanding of biosphere-atmosphere interactions and land-atmosphere coupling.

Potential follow-up efforts include a Land-Atmosphere Interactions Workshop 2022.



The Land-Atmosphere Interactions Workshop 2021 brought together atmospheric and surface flux researchers to see how they could work together to improve understanding of land-atmosphere coupling in both directions, as illustrated in the middle graphic.

Students Squeeze Every Drop Out of Internship Opportunities

Before it even began, the TRacking Aerosol Convection interactions ExpeRiment (TRACER) benefited from contributions from high school and college students.

In fall 2020, TRACER scientists from DOE national laboratories advertised summer 2021 internships that offered the opportunity to participate in different aspects of the ARM campaign.

Five interns signed on to work with TRACER Principal Investigator Michael Jensen and his team at Brookhaven National Laboratory in New York. The interns planned to help with campaign forecasting activities and analysis of the first few months of TRACER data from the Houston, Texas, area.

The Brookhaven scientists hoped that the students could come to Long Island for in-person internships, but the continuing COVID-19 pandemic forced a change of plans. Following the postponement of TRACER's start date to October 2021—six months later than originally scheduled—and the switch to virtual internships, new research plans and goals needed to be made.

Making lemonade from lemons, the team decided to dig into existing data sets to better understand Houston's weather, clouds, and precipitation. Each intern examined the variability of different meteorological measures as a function of large-scale weather states derived from applying machine learning techniques to forecast model fields.

Meanwhile, Los Alamos National Laboratory in New Mexico had two students supporting TRACER-related work in summer 2021 through DOE's Science Undergraduate Laboratory Internships (SULI) program.

University students from Texas A&M and Texas Tech participated in forecasting activities for the NASA air quality campaign TRACER-AQ, which took place in September 2021 around Houston.

Brookhaven National Laboratory interns had daily Zoom meetings with mentors Michael Jensen (top row, center panel) and Dié Wang (middle row, far right panel).

Awardees Announced From ARM/EMSL User Facility Proposal Call

Two projects received support through a proposal call integrating capabilities of ARM and the Environmental Molecular Sciences Laboratory (EMSL).

In early 2021, ARM and EMSL—both DOE Office of Science user facilities—sought collaborative research applications through the Facilities Integrating Collaborations for User Science (FICUS) program. The FICUS program, established in 2014, enables ambitious research by providing access to specialized expertise and instrumentation from multiple user facilities.

The ARM/EMSL FICUS call, for projects starting in fiscal year 2022 (FY2022), solicited proposals related to aerosol processes and aerosol-cloud interactions. EMSL has developed a new size- and time-resolved automated aerosol sampler to fly as a guest instrument on ARM's tethered balloon system (TBS).

In FY2022, the instrument will operate during TBS flights at ARM's Southern Great Plains atmospheric observatory and as part of field campaigns in Colorado and Texas.

The FICUS support will enable researchers to capture aerosols during ARM TBS flights and analyze properties of aerosol particles using specialized techniques at EMSL.

The lead scientists of the selected FY2022 projects are Susannah Burrows of Pacific Northwest National Laboratory in Washington state and Alexander Laskin of Purdue University.

Burrows' team aims to advance understanding of the impacts of agricultural dust on ice-nucleating particle concentrations. Laskin's team will provide a physical and chemical description of individual atmospheric particles by studying the composition and physical properties of airborne particles and their deposits in snowpack.

A tethered balloon system (TBS) operates above the ARM Southern Great Plains site near Marshall, Oklahoma, in February 2021. ARM is planning more TBS flights in FY2022.

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 FY2021.

An Unprecedented Climate Observatory to Understand the Future of Water

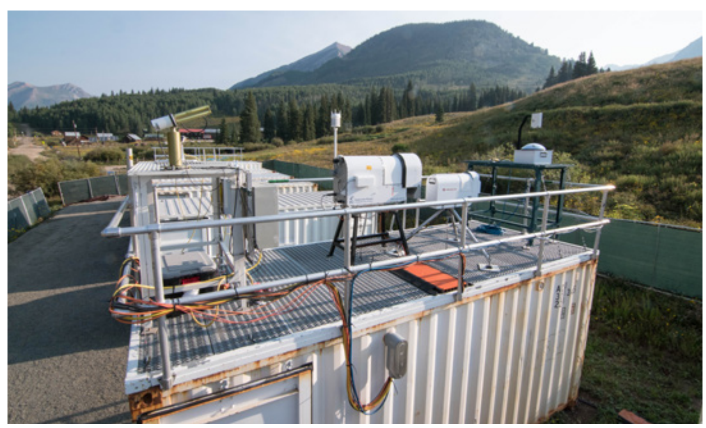
Mountain watersheds provide 60% to 90% of water resources worldwide, but there is still much that scientists don't know about the physical processes and interactions that affect hydrology in these ecosystems. Thus, earth system models struggle to predict the timing and availability of water resources from mountains.

Measurements from a field campaign in the Upper Colorado River Basin will allow researchers to better understand the future of water in the Western United States.

From September 2021 to June 2023, ARM is managing the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign near Crested Butte, Colorado. ARM instruments are collecting data on precipitation, wind, clouds, aerosols, radiation, temperature, humidity, ozone, and other elements of the atmosphere.

In close collaboration with researchers specializing in Earth's surface and subsurface, including scientists from the DOE-funded Watershed Function Scientific Focus Area project, SAIL will help scientists understand how mountains extract moisture from the atmosphere and then process the water down to the bedrock beneath Earth's surface. Ultimately, data will be fed into models so they can "get the water balance right."

"The Upper Colorado River powers more than $1 trillion in economic activity and provides an immense amount of hydroelectric power, but it's very understudied compared to how important it is," said SAIL Principal Investigator Daniel Feldman of Lawrence Berkeley National Laboratory in California. "We're starting to see really dramatic consequences from the changing water resources, but the details of what is actually going on in these places where the water's coming from—those details matter, and that's what SAIL is focused on."



Most ARM instruments for the 21-month SAIL campaign are operating in Gothic, Colorado.

Science Still Going, ARM Data Still Flowing During Pandemic

Determined to help users achieve their scientific goals during the COVID-19 pandemic, ARM has worked to ensure smooth and safe field operations at its sites.

In November 2020 in northern Alaska, the Ice Fog Field Experiment at Oliktok Point (IFFExO) proceeded after an eight-month delay—albeit with fewer people onsite than originally planned. A six-member ARM team conducted tethered balloon system (TBS) flights in ice fog.

IFFExO was the last campaign at Oliktok Point before the third ARM Mobile Facility ended operations there in June 2021.

Data continued to flow from ARM sites, including the Southern Great Plains (SGP) atmospheric observatory, where 15 of 17 campaigns were delayed in 2020. Researchers returned to the SGP in late 2020, with precautions taken to minimize interactions with others onsite.

After a year without TBS flights at the SGP, a masked, socially distanced operations crew redeployed the systems there in February 2021. The trip marked the first time TBS flew simultaneously at the SGP Central Facility and an extended facility—a smaller instrumented site nearby. Wind direction instruments also operated on the TBS for the first time.

At the Eastern North Atlantic (ENA) observatory, ARM hosted a guest instrument measuring ice-nucleating particles, which influence cloud and precipitation formation and suppression.

When the instrument could not leave for its next field campaign as planned, ARM extended the ENA campaign beyond its 45-day time frame. The instrument ended up running for about 200 days. Researchers presented early ENA findings during the 2021 European Geosciences Union General Assembly.

ARM closed out the 13-month Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition in October 2020. Despite the pandemic, technicians continued to rotate in and out of the Arctic to help monitor more than 50 ARM instruments collecting data.

Soon after MOSAiC ended, expedition co-coordinator Matthew Shupe began presenting pieces of his team's investigation of arctic clouds, which affect the sea-ice surface energy budget. Shupe was the principal investigator for the MOSAiC ARM Mobile Facility deployment.

Throughout FY2021, ARM staff worked to make sure two new major campaigns could launch their activities. The Surface Atmosphere Integrated Field Laboratory (SAIL) started near Crested Butte, Colorado, in September 2021. A month later, the twice-delayed TRacking Aerosol Convection interactions ExpeRiment (TRACER) began in the Houston, Texas, area.

Kimberly Sauceda, a graduate student at West Texas A&M University, wears a mask while collecting soil samples in November 2020 at ARM's Southern Great Plains atmospheric observatory.

Field Campaign to Study Clouds Off California Coast

DOE regularly seeks research proposals for field campaigns that use ARM resources to improve the understanding and modeling of clouds and aerosols, as well as their interactions and coupling with the Earth's surface.

In FY2021, ARM began preparations for a new campaign selected from the 2019–2020 proposal call. The Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE) is scheduled from February 2023 to January 2024 in northern San Diego, California. The campaign's lead scientist is Lynn Russell from the Scripps Institution of Oceanography at the University of California, San Diego.

EPCAPE (pronounced "ep-CAPE") aims to characterize the extent, radiative properties, aerosol interactions, and precipitation of low marine stratocumulus clouds that form off the California coast across all seasons.

EPCAPE will explore aerosol indirect effects on these clouds to help improve their representation in earth system models.

Researchers are interested in how aerosols from the nearby Los Angeles metropolitan area might influence marine aerosols and, by extension, the clouds near San Diego.

The Ellen Browning Scripps Memorial Pier is a proposed ARM instrumentation site for the 2023–2024 EPCAPE field campaign in northern San Diego, California.

Past Campaign Results

Cloud-Aerosol Interactions in a Remote Marine Environment

Three years after its conclusion, an ARM field campaign in the Azores continued to inspire prolific research on the effects of aerosols on subtropical low marine clouds.

Gathered above the eastern North Atlantic in deck-like layers, such clouds have a profound influence on Earth's climate—yet they are poorly represented in earth system models.

That deficiency set the table for investigating a cloud regime that is notoriously difficult to continuously observe. In 2017 and 2018, ARM conducted the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) campaign.

ACE-ENA used surface, radiosonde, airborne, and satellite assets to gather data on the microphysical and macrophysical structures of low marine clouds; their radiative effects; and their response to changes in greenhouse gases and aerosols. (Low marine clouds are particularly vulnerable to changes in aerosol properties.)

Most surface instruments were sited at ARM's Eastern North Atlantic (ENA) atmospheric observatory on Graciosa Island. In addition, ARM gathered airborne data with its now-retired Gulfstream-159 (G-1) research aircraft during the summer and winter campaign phases.

Co-locating the ENA's long-term, continuous surface data with detailed measurements from G-1 overflights produced rich data on trace gases, atmospheric state, vertical profiles, and seasonal aerosol and cloud properties.

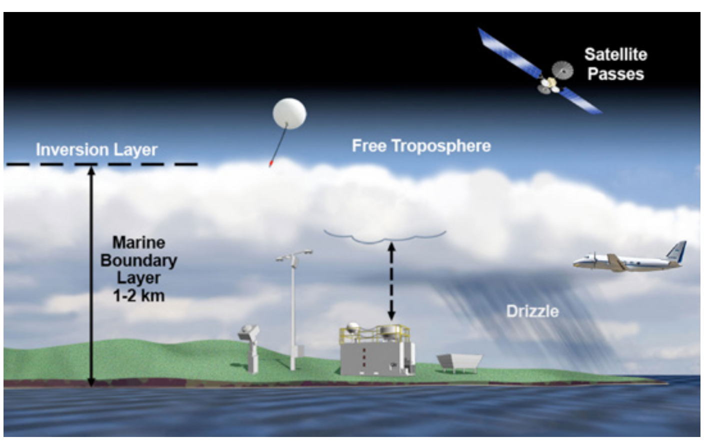
To date, ACE-ENA measurements have informed more than 30 papers and other publications, with at least 10 in 2021 alone.

A campaign summary led by ACE-ENA Principal Investigator Jian Wang at Washington University in St. Louis, Missouri, outlined observation strategies, regional weather conditions, and preliminary findings. Other studies looked at cloud and drizzle microphysics, cloud condensation nuclei budgets, and new particle formation in the upper part of the marine boundary layer.

One paper used machine learning to improve model representations of rain intensity and rate, factors that significantly influence cloud life cycles and radiative and hydrological budgets.

Another paper investigated cloud entrainment mixing, which happens when usually dry, unsaturated air mixes into a cloud laterally or vertically from outside. The study relied on data from an aircraft-mounted probe that provides three-dimensional locations of cloud droplets within the sample volume and two-dimensional images of the detected drops. By using centimeter-scale measurements from the probe, researchers avoided potential errors from averaging microphysical processes across meter-scale cloud regions.

The journals *Atmospheric Chemistry and Physics* and *Atmospheric Measurement Techniques* are accepting papers for a joint special issue featuring research from ACE-ENA and other North Atlantic campaigns. This issue is further proof of intensifying interest in low marine clouds and the impact of this campaign.



Surface, airborne, and satellite assets came into play during the ACE-ENA field campaign.

The Eastern North Atlantic atmospheric observatory in the Azores sits in a prime location for studying low marine clouds.

In the Atlantic, Crucial Inquiries on Smoke-Cloud Interactions

Off the coast of Africa, vast decks of sun-reflecting low marine clouds blanket the southeast Atlantic Ocean. Without these cloud decks, the Atlantic would rapidly heat, altering planetary temperatures and oceanic circulatory systems.

About four months every year, these clouds are influenced by smoky layers full of evolving aerosols from seasonal biomass burning events in southern Africa. As the smoke moves horizontally over the southern Atlantic, it lies atop the clouds or mixes within them or lingers below. The aerosols scatter or absorb light.

The climate effects of aerosols from African biomass burning are little known. That inspired scientists to execute a 2016–2017 ARM field campaign in the southeast Atlantic called Layered Atlantic Smoke Interactions with Clouds (LASIC). Paquita Zuidema of the University of Miami was the principal investigator.

Data streamed from satellites far above, from radiosondes within and above the clouds, and from ARM instruments on Ascension Island, a volcanic remnant 1,000 miles off the west coast of Africa.

LASIC researchers also took advantage of nearly simultaneous NASA, French, German, and British field campaigns that used airborne assets to pursue similar science goals. (Overview papers published in 2021 about the NASA and British campaigns discuss coordination with LASIC.)

Until LASIC and its sister campaigns, smoke-cloud interactions had mostly been inferred from satellite data.

A paper in review as of July 2021 integrated LASIC measurements with data from three aircraft campaigns: ORACLES (NASA) and CLARIFY (U.K.), both in the Atlantic and coordinated with LASIC; and ARM's 2013 Biomass Burning Observation Project (BBOP) in the United States. Ongoing modeling work, such as a large-eddy simulation intercomparison study, relies on data from LASIC and related campaigns.

LASIC has been important for setting up models, which require decisions on what aerosol properties to include. Campaign data also help modelers evaluate how well their simulated outputs match observations from ground instruments and radiosondes.

In 2018, Zuidema led a paper documenting significant smoke within the boundary layer above Ascension Island from June through October 2016—an impossible feat, she said, without coordinated, multi-source LASIC measurements. A July 2021 paper co-authored by Zuidema argues that cloudiness decreases when smoke is within clouds and increases when smoke is above the clouds.

LASIC and similar campaigns get continued attention through a joint special journal issue on observations and modeling related to aerosol, cloud, and climate studies in the southeast Atlantic. Zuidema is an editor of the issue, organized by *Atmospheric Chemistry and Physics* and *Atmospheric Measurement Techniques*.

By summer 2022, the issue will include an overview paper devoted solely to LASIC.

The ARM site on Ascension Island for the LASIC field campaign was well suited to observe vast, smoke-impacted cloud decks overhead.

Smoke obscures the ARM Mobile Facility on Ascension Island.

Two Field Campaigns, Many Storm Clouds

A pair of papers in the August 2021 *Bulletin of the American Meteorological Society (BAMS)* put into scientific perspective two field campaigns aimed at unraveling how thunderstorms evolve, grow, and dissipate in mountainous north-central Argentina. The region is famous for tall convective clouds that pack a lot of rain, hail, and lightning. Data collected there provide insights into such storms worldwide.

ARM's 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) campaign focused on atmospheric processes that evolve over rising terrain. Close by, in the same Sierras de Córdoba mountain range and funded by the National Science Foundation, the Remote sensing of Electrification, Lightning, and Mesoscale/microscale Processes with Adaptive Ground Observations (RELAMPAGO) campaign pursued a similar scientific mission.

RELAMPAGO, the Spanish word for "flash of lightning," shared an intensive operational period with CACTI from November to December 2018, including 22 flights by an ARM research aircraft.

References

Varble AC, SW Nesbitt, P Salio, JC Hardin, N Bharadwaj, P Borque, PJ DeMott, Z Feng, TCJ Hill, J Marquis, A Matthews, F Mei, R Öktem, V Castro, L Goldberger, A Hunzinger, KR Barry, SM Kreidenweis, GM McFarquhar, LA McMurdie, M Pekour, H Powers, DM Romps, AC Saulo, B Schmid, JM Tomlinson, SC van den Heever, A Zelenyuk, Z Zhang, and EJ Zipser. 2021. "Utilizing a storm-generating hotspot to study convective cloud transitions: The CACTI experiment." *Bulletin of the American Meteorological Society*, 102(8):E1597-E1620, https://doi.org/10.1175/BAMS-D-20-0030.1.

Nesbitt SW, P Salio, E Ávila, P Bitzer, L Carey, V Chandrasekar, W Deierling, F Dominguez, ME Dillon, CM Garcia, D Gochis, S Goodman, DA Hence, KA Kosiba, MR Kumjian, T Lang, LM Luna, J Marquis, R Marshall, LA McMurdie, E de Lima Nascimento, KL Rasmussen, R Roberts, AK Rowe, JJ Ruiz, EF São Sabbas, AC Saulo, RS Schumacher, YG Skabar, LA Toledo Machado, RJ Trapp, AC Varble, J Wilson, J Wurman, EJ Zipser, I Arias, H Bechis, and MA Grover. 2021. "A storm safari in subtropical South America: Proyecto RELAMPAGO." *Bulletin of the American Meteorological Society*, 102(8):E1621-E1644, https://doi.org/10.1175/BAMS-D-20-0029.1.

During the CACTI field campaign, ARM's G-1 research aircraft flies through clouds above Argentina's Sierras de Córdoba mountain range.

Paper Captures Early Southern Ocean Campaign Results

Initial findings from two ARM Southern Ocean field campaigns are documented in the April 2021 *Bulletin of the American Meteorological Society (BAMS)*.

ARM provided instruments for the 2017–2018 Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) campaign and 2016–2018 Macquarie Island Cloud and Radiation Experiment (MICRE). MARCUS and MICRE took place around the same time as two other major campaigns in the remote region; the *BAMS* paper discusses all four campaigns.

Data from the campaigns, when compared with existing models and satellite retrievals, illustrate how aerosols and meteorology couple to control Southern Ocean water and energy budgets. The paper's authors say that, ultimately, these data will assist researchers in determining the factors that contribute to the excess absorption of solar radiation in weather and climate model simulations over the Southern Ocean.

Reference

McFarquhar GM, CS Bretherton, R Marchand, A Protat, PJ DeMott, SP Alexander, GC Roberts, CH Twohy, D Toohey, S Siems, Y Huang, R Wood, RM Rauber, S Lasher-Trapp, J Jensen, JL Stith, J Mace, J Um, E Järvinen, M Schnaiter, A Gettelman, KJ Sanchez, CS McCluskey, LM Russell, IL McCoy, RL Atlas, CG Bardeen, KA Moore, TCJ Hill, RS Humphries, MD Keywood, Z Ristovski, L Cravigan, R Schofield, C Fairall, MD Mallet, SM Kreidenweis, B Rainwater, J D'Alessandro, Y Wang, W Wu, G Saliba, EJT Levin, S Ding, F Lang, SCH Truong, C Wolff, J Haggerty, MJ Harvey, AR Klekociuk, and A McDonald. 2021. "Observations of clouds, aerosols, precipitation, and surface radiation over the Southern Ocean: An overview of CAPRICORN, MARCUS, MICRE, and SOCRATES." *Bulletin of the American Meteorological Society*, 102(4):E894-E928, https://doi.org/10.1175/BAMS-D-20-0132.1.

ARM technician Carlos Sousa installs sensors during the MICRE field campaign in March 2016.

Research Highlights

Cloud Microphysics Simulations Move Closer to Reality

Clouds help determine the Earth's energy balance, but they contribute significantly to uncertainty in model simulations of weather and climate. For one, models still use simplified representations—or parameterizations—of cloud microphysical processes because their scales are too small to be explicitly resolved.

In the case of simulated deep convection, some details of cloud microphysical processes are commonly oversimplified. A study led by Lin Lin of Texas A&M University offers an improved convective microphysics scheme for the widely used National Center for Atmospheric Research Community Atmosphere Model version 5.3 (CAM5.3). The *Journal of Geophysical Research: Atmospheres* published the study online in April 2021.

Embedded in CAM5.3 is a decade-old convective microphysics scheme that overestimates the amount of ice in convective clouds—sometimes by more than 100% in the upper troposphere. The biggest reason for this is an underestimation of convective ice particle sedimentation, or "fall rate." That's the rate at which cloud particles fall through a parcel of air.

To arrive at this underestimation, the authors compared simulations of sedimentation with observations from the 2006 Tropical Warm Pool – International Cloud Experiment (TWP-ICE), a multiagency field campaign conducted near Darwin, Australia.

The authors' improvements to the scheme included:

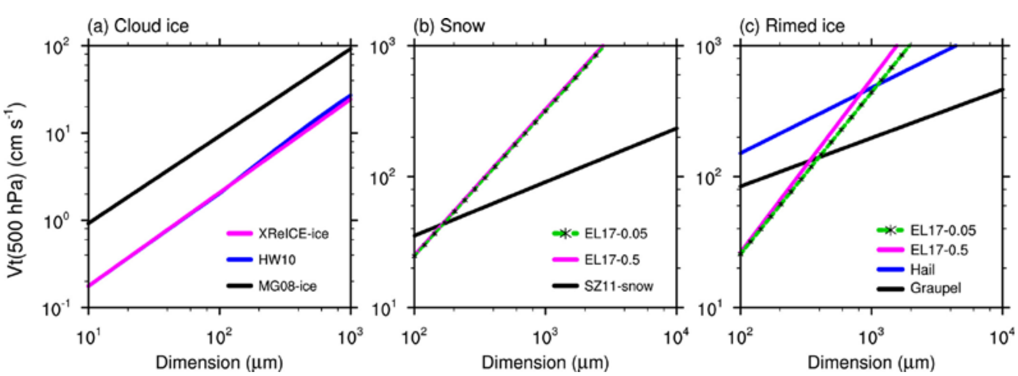
- considering sedimentation for cloud ice crystals that do not fall in the original scheme
- applying a new terminal velocity parameterization that depends on the environmental conditions for convective snow (terminal velocity is the constant speed obtained by a falling object when the upward drag on the object balances the downward force of gravity)
- adding a new hydrometeor category, "rimed ice," a reference to ice particles that collect supercooled cloud water (hydrometeors are a form of atmospheric water vapor, such as rain, snow, or clouds)
- allowing convective clouds to shed snow particles into layered stratiform clouds, a process called detrainment.

The improvements brought the vertical distribution of ice closer to the reality of TWP-ICE observations.

Reference

Lin L, Q Fu, X Liu, Y Shan, SE Giangrande, GS Elsaesser, K Yang, and D Wang. 2021. "Improved convective ice microphysics parameterization in the NCAR CAM model." *Journal of Geophysical Research: Atmospheres*, 126(9):e2020JD034157, https://doi.org/10.1029/2020JD034157.

In Darwin, Australia, storm clouds hover over instruments in place for the 2006 TWP-ICE field campaign.



Represented in this comparison graphic of cloud hydrometeor terminal velocities are the new Lin-Fu microphysical schemes (pink and green). The old schemes (black and blue) are widely used in cloud models. The terminal velocities are for cloud ice crystals (a), snow (b), and rimed ice (c). (*Copyrighted image from the journal.*)

Using ARM Data to Better Model the Daily Convection Cycle

Most earth system models poorly simulate the daily cycle of atmospheric moist convection—the movement of air due to temperature and moisture differences that eventually leads to rainfall. This results in a skewed output for peak rainfall over land, with models placing maximum precipitation two to four hours ahead of real-world observations. This issue has broad impacts, contributing to model biases in predictions of cloud coverage and how much energy the atmosphere absorbs and reflects.

A study published online in February 2021 by the *Journal of Geophysical Research: Atmospheres* integrated ARM data from the Green Ocean Amazon (GoAmazon2014/15) field campaign into a theoretical model to identify which factors have the greatest influence on convective development. Researchers specifically focused on factors controlling the vertical extent of atmospheric moist convection.

Analyzing the ARM data, the team identified atmospheric wind shear and moisture as important factors in determining the heights that convection can reach. Researchers then integrated the data into a model simulating the vertical motion of air all the way from the formation of clouds near their bases to the end of clouds near their tops.

"By using a novel framework to investigate the controlling factors of the convection transition process, our work provides a way to directly connect ARM observations to model practices," said lead author Yang Tian of Lawrence Livermore National Laboratory in California.

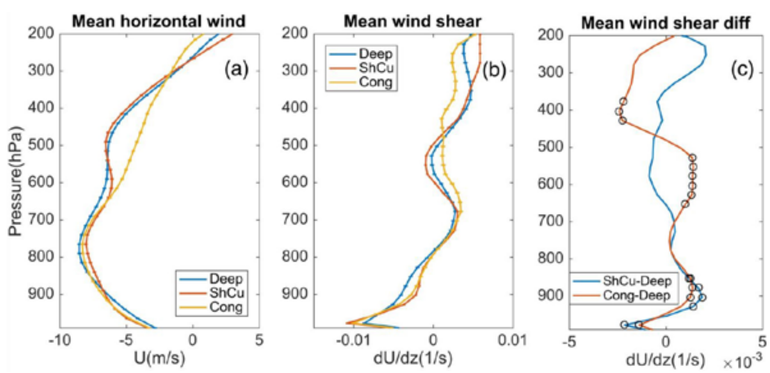
This work demonstrated the importance of entrainment—the mixing of dry air from outside a cloud with the moist air in a cloud—in the transition from shallow to deep convection.

From this study, modelers can better focus their efforts on accurately representing processes with a bigger impact on the model performance. This will help modelers effectively use computational resources while enhancing model accuracy.

Reference

Tian Y, Y Zhang, SA Klein, and C Schumacher. 2021. "Interpreting the diurnal cycle of clouds and precipitation in the ARM GoAmazon observations: Shallow to deep convection transition." *Journal of Geophysical Research: Atmospheres*, 126(5):e2020JD033766, https://doi.org/10.1029/2020JD033766.

ARM deployed a mobile facility downwind of Manaus, Brazil, for the GoAmazon2014/15 field campaign.



The graphs show differences in wind properties as a function of atmospheric pressure (e.g., height above the surface) for days with shallow cumulus (ShCu) clouds, congestus (Cong) clouds, and deep convection (Deep). (*Copyrighted image from the journal***.)**

Discoveries of How New Particles Form

Aerosol processes represent one of the largest sources of uncertainty in earth system model simulations. Improved understanding of how new particles form, particularly in isolated regions that can represent background aerosol formation without human input, is key to making models more accurate and better understanding the human impact on the earth system.

Two studies used ARM data to identify mechanisms of new particle formation in different environments.

An October 2020 paper in the *Proceedings of the National Academy of Sciences* integrated insights from laboratory measurements, chemical transport modeling, and field measurements to identify new particle formation above the Amazon.

Led by Bin Zhao at Pacific Northwest National Laboratory in Washington state, researchers used ARM data from the Green Ocean Amazon (GoAmazon2014/15) field campaign. The team found that carbon-based compounds from biological sources drive new particle formation and play key roles in producing the large number of small particles in the free troposphere over the Amazon rainforest.

In a January 2021 *Nature Communications* paper, another multi-institutional team shared its discovery of a previously undocumented new particle formation process in the remote marine boundary layer.

Analysis of ARM aircraft data from the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) campaign showed the regular and frequent occurrence of new particle formation in the upper part of the marine boundary layer. Co-author Jian Wang of Washington University in St. Louis, Missouri, led the ACE-ENA campaign in 2017 and 2018 in the Azores.

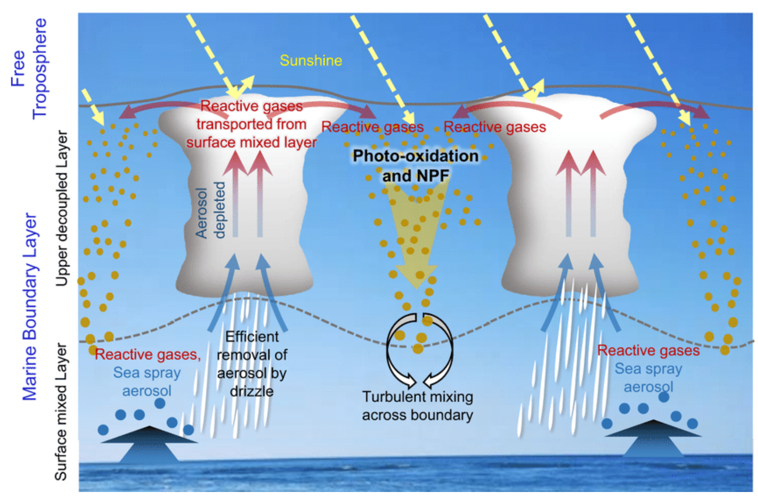
These two studies demonstrate ARM's impact on enhancing scientific understanding of new particle formation under pre-industrial-like conditions—essential for effectively modeling aerosol effects on earth systems.

References

Zhao B, M Shrivastava, NM Donahue, H Gordon, M Schervish, JE Shilling, RA Zaveri, J Wang, MO Andreae, C Zhao, B Gaudet, Y Liu, J Fan, and JD Fast. 2020. "High concentration of ultrafine particles in the Amazon free troposphere produced by organic new particle formation." *Proceedings of the National Academy of Sciences,* 117(41):25344-25351, https://doi.org/10.1073/pnas.2006716117.

Zheng G, Y Wang, R Wood, MP Jensen, C Kuang, IL McCoy, A Matthews, F Mei, JM Tomlinson, JE Shilling, MA Zawadowicz, E Crosbie, R Moore, L Ziemba, MO Andreae, and J Wang. 2021. "New particle formation in the remote marine boundary layer." *Nature Communications*, 12:527, https://doi.org/10.1038/s41467-020-20773-1.

ARM's now-retired Gulfstream-159 (G-1) research aircraft captured data needed by scientists to develop a better understanding of atmospheric processes and help improve earth system models. The G-1 flew during the GoAmazon2014/15 and ACE-ENA campaigns.



In the region between clouds, reactive gases undergo photo-oxidation and produce nucleation precursors, leading to new particle formation. (*Copyrighted image from the journal.***)**

An Improved Representation of Particle Dry Deposition

Atmospheric aerosols commonly collect on solid surfaces and come out of the air via deposition. Deposition can be either wet, involving some form of precipitation, or dry, without precipitation.

In larger-scale models, the simplified approximations of complex processes—or parameterizations—used to represent dry deposition have been poorly constrained by observational data. This leads to large uncertainties in estimating the impact of aerosols on the climate.

A research team led by Delphine Farmer at Colorado State University collected data at ARM's Southern Great Plains atmospheric observatory in Oklahoma and in a Colorado forest to develop a better parameterization for dry deposition. Researchers used new measurement techniques that allowed for more accurate size data in the observations.

Their work, published in October 2020 in the *Proceedings of the National Academy of Sciences,* combined new measurements with literature data to show that previous parameterizations overestimated the deposition of fine particles and underestimated the deposition of coarse particles. These errors produced discrepancies between observations and modeled behavior of up to an order of magnitude over land.

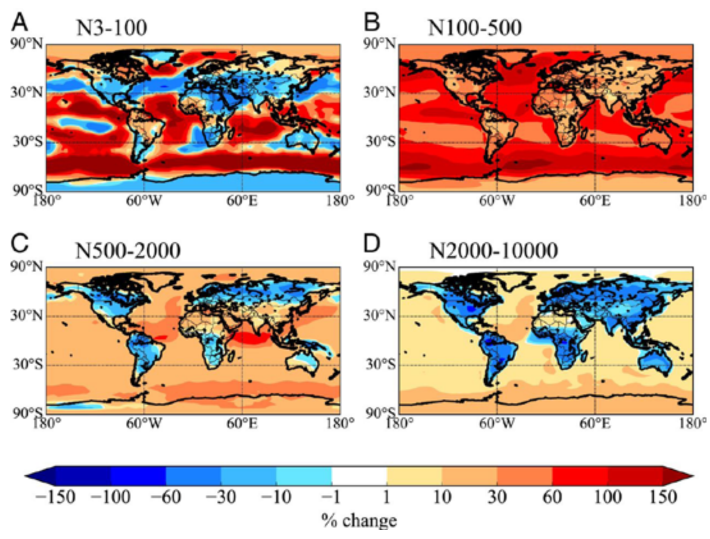
"These particle flux measurements are technically challenging, which is why such data-driven model improvements have been so elusive," said Farmer. "Combining new instrumentation with access to the well-characterized and fully supported DOE ARM site in Oklahoma was really critical for our project success."

The authors used the observational data to develop a new parameterization for aerosol models. Their data-driven representation of dry deposition should decrease the uncertainty in aerosol direct and indirect effects in larger-scale models.

Reference

Emerson EW, AL Hodshire, HM DeBolt, KR Bilsback, JR Pierce, GR McMeeking, and DK Farmer. 2020. "Revisiting particle dry deposition and its role in radiative effect estimates." *Proceedings of the National Academy of Sciences,* 117(42):26076-26082, https://doi.org/10.1073/pnas.2014761117.

Doctoral student Ethan Emerson checks instrumentation at ARM's Southern Great Plains observatory in Oklahoma, where researchers took measurements over an alfalfa field.



The figure shows percent changes in surface aerosol number concentrations for various size ranges from updating the previous default parameterization to the revised parameterization. Warm colors indicate more particles; cool colors are the opposite. (*Copyrighted image from the journal*.)

Scientists Uncover Explosive Origins of ‘Secondary’ Ice—and Snow

Snow formation generally starts when water crystallizes on atmospheric aerosols called ice-nucleating particles to create primary ice particles. However, observations have shown that clouds at temperatures between 14 and 32 degrees Fahrenheit (minus 10 to zero degrees Celsius) can have too many ice crystals for primary ice nucleation to be their only source. This has led to hypotheses of important additional “secondary” ice generation processes.

A March 2021 study in the *Proceedings of the National Academy of Sciences* used long-term observations from the Arctic to identify the frequency and potential causes of secondary ice production in slightly supercooled clouds. An analysis of six years of cloud radar and weather balloon data from ARM’s North Slope of Alaska atmospheric observatory showed that a process involving drizzle plays an important role in producing secondary ice particles.

When an ice particle hits a drizzle droplet of supercooled water—still liquid below water’s freezing point—the droplet starts to freeze. The freezing process begins at the droplet surface, forming a solid ice shell. As the freezing moves deeper into the droplet, pressure starts to build because water expands when it turns to ice. Eventually, the pressure becomes great enough that the droplet shatters, forming secondary ice particles.

Using ARM observations, researchers found that this process can be much more effective than a better-known mechanism in which relatively big, fast-falling ice particles, called rimers, accumulate and freeze tiny, supercooled cloud droplets, which then eject tiny ice particles.

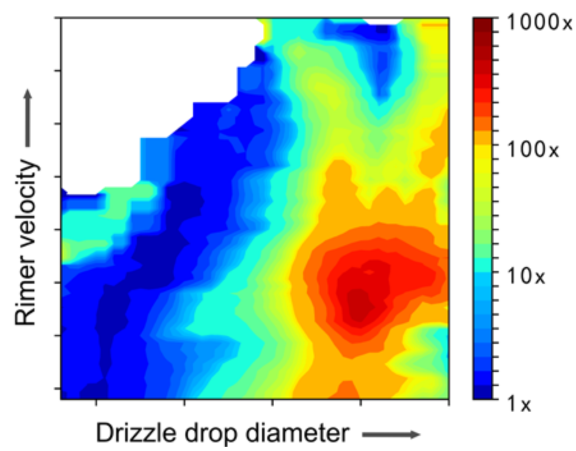
“Our results shed new light on prior lab-experiment-based understanding about how supercooled water droplets turn into ice and eventually snow,” said lead author Edward Luke of Brookhaven National Laboratory in New York.

The findings have implications for weather forecasts, earth system modeling, water supplies, and infrastructure.

Reference

Luke EP, F Yang, P Kollias, AM Vogelmann, and M Maahn. 2021. “New insights into ice multiplication using remote-sensing observations of slightly supercooled mixed-phase clouds in the Arctic.” *Proceedings of the National Academy of Sciences,* 118(13):e2021387118, https://doi.org/10.1073/pnas.2021387118.

ARM’s North Slope of Alaska atmospheric observatory collected information on cloud and precipitation processes used in a study on the formation of “secondary” ice.



The skewing of ice multiplication quantities to the right side of the graph indicates that drizzle drop diameter plays a more significant role than the velocity of fast-falling “rimer” ice particles in ice multiplication. (*Copyrighted image from the journal*.)

Getting Warm Rain Right in Models

A paper published online in December 2020 by *Geophysical Research Letters* addresses common discrepancies in the way global models represent warm rain in the marine boundary layer.

Weather and climate models typically predict that such rain will be too frequent, too light, or too heavy. This "intermodal spread" can vary from observed rain by as much as an order of magnitude.

Accurately simulating the rate and intensity of warm rain is important. Ocean precipitation, including drizzle, significantly influences cloud life cycles, radiative budgets, and hydrological outputs.

The study, led by Christine Chiu at Colorado State University, describes a new parameterization for autoconversion, a water-coalescence process for expressing the rate at which cloud droplets collide and stick together. In boundary-layer clouds, autoconversion is pivotal in forming drizzle and precipitation.

In models, autoconversion represents how clouds begin to form rain. In climate simulations, predicted surface temperatures are extremely sensitive to the autoconversion representation.

To calculate autoconversion rates, Chiu and her co-authors analyzed about 93,000 in situ cloud drop size distributions.

The data came from ARM's Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) field campaign, conducted in 2017 and 2018 in the Azores.

With an uncertainty of nearly 15%, their predicted autoconversion rates outperformed common models. The estimates came from training cloud droplet distribution data with a deep neural network. This type of artificial network mimics the neuron-and-synapse sorting process of the human brain.

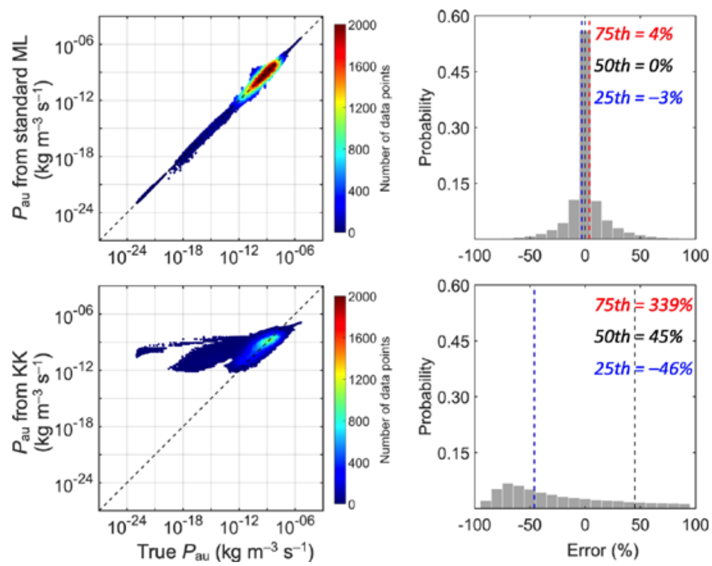
Such machine learning methods can capture complex, nonlinear relationships like those of coalescing water droplets. In turn, relational decisions derived from machine learning can be applied to ARM long-term radar observations.

"This is a critical step," said Chiu, "and a great example of how ACE-ENA will continue to have scientific significance."

Reference

Chiu JC, CK Yang, PJ van Leeuwen, G Feingold, R Wood, Y Blanchard, F Mei, and J Wang. 2020. "Observational constraints on warm cloud microphysical processes using machine learning and optimization techniques." *Geophysical Research Letters*, 48(2):e2020GL091236, https://doi.org/10.1029/2020GL091236.

Common in the Azores, drizzle significantly influences cloud life cycles and radiative and hydrological budgets.



Plots show predicted versus true autoconversion rates from the machine learning model (upper panels) and a commonly used parameterization (lower panels). Blue, black, and red dashed lines in the right panels represent the 25th, 50th, and 75th percentiles of the data. Corresponding errors for these lines are indicated in each subplot. (*Copyrighted image from the journal***.)**

First Results Reported From Aerosol-Ice Formation Closure Study

Scientists know that airborne dust particles are involved in the formation of atmospheric ice crystals, though relatively few dust particles act as ice-nucleating particles (INPs). Yet researchers still seek to understand which particle types initiate ice formation so they can predict INP number concentration, thereby helping earth system modelers constrain the number of ice crystals in a cloud.

The 2019 Aerosol-Ice Formation Closure Pilot Study at ARM's Southern Great Plains (SGP) atmospheric observatory evaluated predictive knowledge of INPs in an air mass for the first time using a "closure study." Researchers characterized INPs using aerosol measurement instruments and laboratory techniques, then evaluated model parameterizations against these data.

A paper published in June 2021 by the *Bulletin of the American Meteorological Society (BAMS)* describes this milestone study.

Led by principal investigator Daniel Knopf of Stony Brook University, the co-authors began with the knowledge that prediction of ice formation in clouds is difficult because several ice nucleation pathways lead to crystal formation. Aerosols also have many properties that affect ice nucleation. As a result, obtaining INP number concentrations from the ambient aerosol population remains highly uncertain in cloud-resolving and climate models.

A front similar to this one approaching the Southern Great Plains Central Facility provided the basis for a case study featured in a 2021 paper.

In this study, measurements of particle composition and INP number concentrations became input in several immersion freezing model parameterizations for prediction of INP number concentrations.

The *BAMS* paper details one closure case study in which a front passed through the SGP, changing ambient particle and INP populations. The case study achieved closure in some circumstances, emphasizing the need for freezing parameterizations of more INP types.

Overall, the study shows that underestimation of fine mineral dust concentrations is one reason for model underestimation of INP number concentrations.

"This campaign significantly improved our understanding of how to characterize and predict ice-nucleating particles," said Knopf. "These results will guide further advances in our predictive capability needed to improve cloud and climate models."

Reference

Knopf DA, KR Barry, TA Brubaker, LG Jahl, KAL Jankowski, J Li, Y Lu, LW Monroe, KA Moore, FA Rivera-Adorno, KA Sauceda, Y Shi, JM Tomlin, HSK Vepuri, P Wang, NN Lata, EJT Levin, JM Creamean, TCJ Hill, S China, PA Alpert, RC Moffet, N Hiranuma, RC Sullivan, AM Fridlind, M West, N Riemer, A Laskin, PJ DeMott, and X Liu. 2021. "Aerosol-ice formation closure: A Southern Great Plains field campaign." *Bulletin of the American Meteorological Society,* early online, https://doi.org/10.1175/BAMS-D-20-0151.1.

This schematic lays out the concept of the 2019 Aerosol-Ice Formation Closure Pilot Study at ARM's Southern Great Plains atmospheric observatory. (*Copyrighted image from the journal.*)

Dust, Irradiance, and the Convening Power of LASSO

Agricultural dust and solar irradiance might not seem to have much in common, but two recent papers on these topics relied on products from ARM's high-resolution modeling activity. The Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity combines atmospheric observations and LES modeling to provide data bundles for easier comparison and evaluation.

One paper used LASSO to simulate the vertical turbulence that moves soil dust particles high enough into the atmosphere to influence clouds. Regional dust emissions can modify how long clouds live and how much incoming solar energy they directly absorb. Modelers have a hard time representing this complex movement of air. In a January 2021 study, Gavin Cornwell and colleagues at Pacific Northwest National Laboratory in Washington state simulated dust transport at very fine resolutions, in predictive grids measured in meters instead of kilometers.

In an October 2020 paper, a team led by NOAA researcher Jake Gristey used LASSO and machine learning algorithms to quantify the effects of puffy, rain-free shallow cumulus clouds on surface solar irradiance. That's the measure of how much energy from the sun reaches the planetary surface. Clouds modulate surface solar irradiance, but that transfer of energy is hard to calculate when broken shallow cumulus clouds get in the way.

Both papers employed LASSO data bundles from ARM's Southern Great Plains atmospheric observatory. In early 2021, ARM shifted its LASSO efforts to data from deep convective storm systems recorded in Argentina, but almost 100 shallow cumuli cases remain freely available for use.

References

Cornwell GC, H Xiao, LK Berg, and SM Burrows. 2021. "Simulated dust transport in the convective boundary layer." *Journal of Geophysical Research: Atmospheres,* 126(5):e2020JD033429, https://doi.org/10.1029/2020JD033429.

Gristey JJ, G Feingold, IB Glenn, KS Schmidt, and H Chen. 2020. "On the relationship between shallow cumulus cloud field properties and surface solar irradiance." *Geophysical Research Letters,* 47(22):e2020GL090152, https://doi.org/10.1029/2020GL090152.

To Improve Solar Forecasting, Researchers Turn to ARM Data

With more people and industries relying on solar energy, better solar resource forecasting is necessary to help improve energy management and grid operation. Existing data-driven models tend to forecast a single term known as the global horizontal irradiance (GHI). This is the total amount of energy from the sun reaching a flat plane on the Earth's surface.

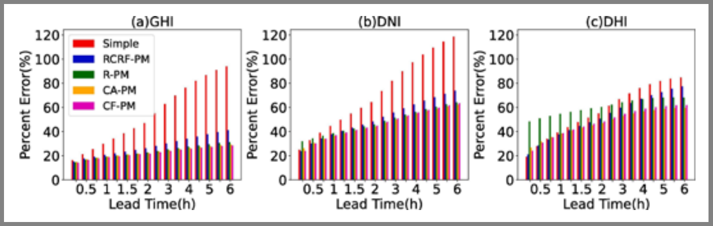
GHI is a function of two different components, known as direct and diffuse solar irradiance. For some types of solar energy production, it is useful to be able to forecast each component separately, as well as the total GHI. In addition, the models struggle with forecasting under cloudy conditions because they do not fully capture complex cloud-radiation interactions.

To address the challenges, a multi-institutional team developed a set of physics-informed models for simultaneously forecasting the three components of solar irradiance. Researchers used 16 years of data (1998 to 2014) from ARM's Southern Great Plains atmospheric observatory to evaluate the new models against existing models. The team found that the new models had better forecast accuracy at longer lead times. This finding supports the idea of incorporating physical relationships into data-driven models and the need to consider all of the components of solar irradiance together in physical models.

DOE's Solar Energy Technologies Office—part of the Office of Energy Efficiency and Renewable Energy—and Atmospheric System Research (ASR) supported this work in the February 2021 issue of *Solar Energy*.

Reference

Liu W, Y Liu, X Zhou, Y Xie, Y Han, S Yoo, and M Sengupta. 2021. "Use of physics to improve solar forecast: Physics-informed persistence models for simultaneously forecasting GHI, DNI, and DHI." *Solar Energy* 215:252-265, https://doi.org/10.1016/j.solener.2020.12.045.



This figure compares the percent errors of different models for forecasting global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) at different lead times. (*Copyrighted image from the journal.***)**

Advancing **Capabilities**

Infrastructure Achievements

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

Despite a Pandemic, ARM Launches Two Major Field Campaigns

ARM team members were busy in 2021 preparing for the launch of two major field campaigns: the Surface Atmosphere Integrated Field Laboratory (SAIL) near Crested Butte, Colorado; and the TRacking Aerosol Convection interactions ExpeRiment (TRACER) around Houston, Texas.

In June, the ARM Mobile Facility arrived at Gothic, Colorado, for site construction and instrument installation ahead of SAIL, which began official operations September 1. The campaign will run until June 2023.

The SAIL campaign includes the use of the second ARM Mobile Facility in Gothic, Colorado. In addition, an ARM Aerosol Observing System and a Colorado State University scanning precipitation radar are operating on nearby Crested Butte Mountain.

On October 1, the yearlong TRACER field campaign launched after a six-month delay caused by the COVID-19 pandemic. TRACER avoided significant impacts from Hurricane Ida during the late-summer installation of the first ARM Mobile Facility in La Porte, Texas, and a scanning ARM precipitation radar about 20 miles away in Pearland.

Despite having two major campaigns starting so close together, ARM team members across multiple DOE national laboratories worked onsite and remotely to contribute to the successful launches of SAIL and TRACER.

In Gothic, Colorado, John Bilberry supervises instrument installation at the main site of the SAIL campaign. Bilberry is the project manager for the ARM SAIL deployment.

Development Work Centers on Facilities, Instruments, and Data

Each year, ARM prioritizes development activities for maximum benefit and impact to the scientific community. Examples include adding instruments, upgrading facilities, and developing data products.

In FY2021, ARM deployed mobile facilities for the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign in Colorado and the TRacking Aerosol Convection interactions ExpeRiment (TRACER) in Texas. Both campaigns have new optical particle counters. In addition, a new time-of-flight aerosol chemical speciation monitor is measuring particle mass and chemical composition during TRACER.

After almost eight years, ARM ended operations of the third ARM Mobile Facility at Oliktok Point, Alaska, to begin preparations for its next deployment in the Southeastern United States.

ARM's Southern Great Plains atmospheric observatory replaced its Guest Instrument Facility with a building almost twice as big to accommodate larger instruments.

Across its sites, ARM added a new channel to shortwave spectral instruments. The new channel will contribute to more accurate retrievals of aerosol properties. ARM also continued to replace older instruments that have reached the end of their operational life with newer or upgraded versions, including its sun photometers (measuring aerosol optical depth), radar wind profilers (wind profiles), Doppler lidars (wind profiles and vertical wind statistics), and 3-channel microwave radiometers (liquid water path and precipitable water vapor).

The ARM Data Center rolled out new features in Data Discovery, where users can find and order ARM data online, and performed database upgrades. The data center also released a new dashboard providing field campaign information, including daily reports, maps, and data plots.

ARM continued to work on calibration methods and data products for radars. In addition, ARM released new aerosol data products, including one that calculates moisture-absorbing properties of measured particles.

The new Guest Instrument Facility at ARM's Southern Great Plains Central Facility is 2,800 square feet, almost twice as big as the triple-wide trailer it replaced.

ARM Data Center Passes Milestone, Stays Focused on Quality Service

The ARM Data Center, which houses almost 30 years of ARM measurements, reached 3 petabytes of archived data in April 2021.

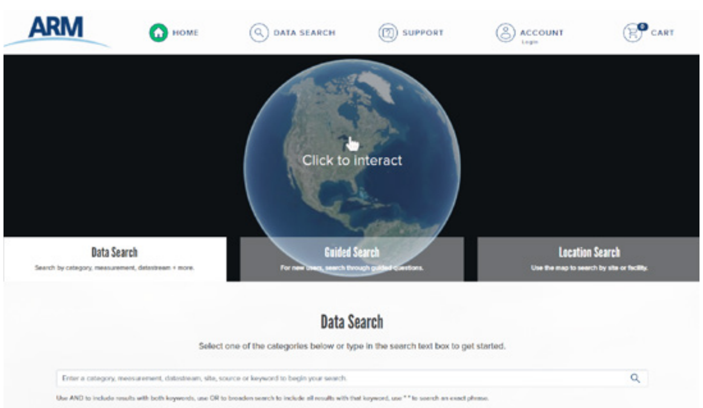
Data are accumulating in the ARM Data Center with increasing speed. ARM completed its first petabyte of archived data in December 2016, then crossed the 2-petabyte mark in March 2020.

A paper published by the journal *Earth Science Informatics* in June 2021 tells the story of ARM's constantly growing trove of data. Written by ARM Data Center staff, the paper details the steps ARM takes to archive data and make them accessible to users.

The paper also describes the recent redevelopment of ARM's Data Discovery, where users can access and order ARM data online. During the redesign process, the ARM Data Center incorporated user requirements and stakeholder recommendations.

The new Data Discovery went live in the spring of 2020, but it continues to undergo upgrades in response to user feedback.

In 2021, DOE's Office of Science designated ARM as one of its Public Reusable Research (PuRe) Data Resources. PuRe resources are key data repositories, knowledge bases, analysis platforms, and other activities that strive to make data publicly available to advance scientific or technical knowledge.



ARM's Data Discovery provides extensive search capabilities, including a keyword search, guided search, and location search.

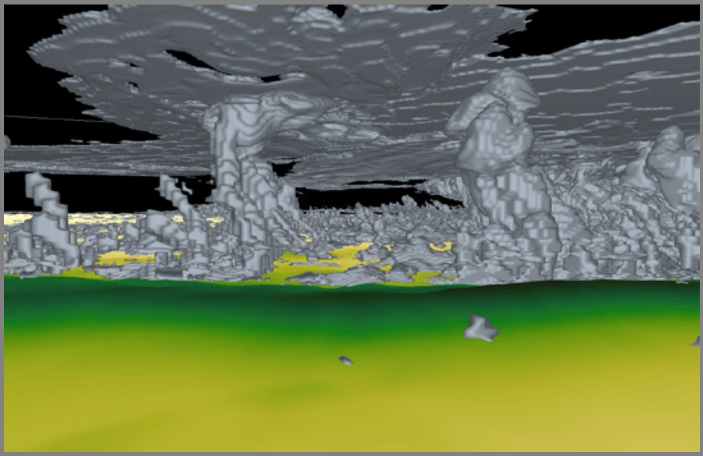
ARM Modeling Activity to Explore Deep Convection in Argentina

In July 2021, the team leading ARM's high-resolution modeling activity provided a sneak peek of its next scenario of focus and gathered feedback from potential users during a virtual community session.

Forty-five people attended the session presented by William Gustafson and Andrew Vogelmann, the principal investigators for the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity.

LASSO, which previously combined observations and LES simulations of shallow convection at ARM's Southern Great Plains atmospheric observatory, is expanding to deep convection. Specifically, the LASSO team is focused on deep convection during ARM's 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in Argentina.

In 2022, the LASSO team plans to release results of LES simulations for about 10 CACTI case dates with varying convective behavior. These high-resolution simulations will provide detailed information about the processes within deep convective clouds. The team estimates that, in total, data from the LASSO-CACTI scenario will exceed a petabyte in size.



This image captures a test simulation of deep convection on January 25, 2019, during the CACTI field campaign in Argentina.

New Data Products

Data Products Accommodate Upgraded Shortwave Spectral Instruments

In FY2021, ARM updated two value-added products (VAPs) to support upgrades of shortwave spectral instruments at its ground-based sites.

ARM added a seventh channel to its multifilter rotating shadowband radiometers, multifilter radiometers, and normal incidence multifilter radiometers. Data from these instruments are used to derive properties such as aerosol optical depth, cloud optical depth, and surface albedo (reflectivity).

The new channel is in the near-infrared spectral range at 1625 nm wavelength. This longer wavelength helps constrain the size distribution of large aerosol particles, resulting in more accurate retrievals of aerosol optical properties. The new channel also helps improve retrievals of cloud optical depth and particle size. In addition, the longer wavelength better constrains surface spectral albedo to improve characterization of vegetation with strong spectral dependence across the visible and near-infrared wavelengths.

The Aerosol Optical Depth (AOD) and Langley calibration VAPs for the multifilter rotating shadowband radiometers are now updated to support the 1625 nm channel.

In FY2022, ARM plans to complete an update of the Surface Spectral Albedo (SURFSPECALB) VAP that will also incorporate the new channel. SURFSPECALB produces a near-continuous best estimate of spectral albedo using measurements from multifilter radiometers.

ARM updated multifilter rotating shadowband radiometers and other shortwave spectral instruments at its ground-based sites.

Stereo Camera Data Sets Provide Cloud Insights at ARM Sites

Data products from stereo cameras at ARM sites are helping researchers glean more information about clouds.

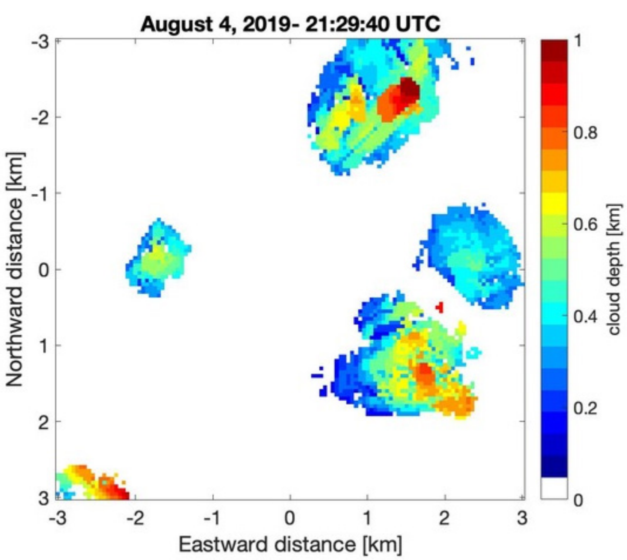
David Romps and Rusen Öktem, scientists from the University of California, Berkeley, and Lawrence Berkeley National Laboratory, oversee an array of six stereo cameras—three pairs—at ARM's Southern Great Plains (SGP) atmospheric observatory. The three-dimensional (3D) positions of clouds captured by these cameras are available as the Point Cloud of Cloud Points (PCCP) product.

From PCCP, researchers can extract cloud-base and cloud-top heights, the structure of cloud boundaries, and cloud-level horizontal velocities.

PCCP data are processed into the Clouds Optically Gridded by Stereo (COGS) product. Newly available to ARM users in FY2021, COGS provides a four-dimensional (4D) map of cloudiness observed by the cameras.

Romps and Öktem led a team using the COGS SGP product to gain insights into the life cycle of puffy, rain-free clouds known as shallow cumuli. The product also helped Romps, Öktem, and others test a new algorithm that distinguishes swarms of insects from clouds of liquid water. Both studies appeared in FY2021 journal articles.

ARM recently started using stereo cameras during mobile deployments. PCCP is now available from the 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in Argentina.



This sample plot from the COGS value-added product provides a heat map of cloud depth at 21:29:40 UTC (Coordinated Universal Time) on August 4, 2019, at ARM's Southern Great Plains atmospheric observatory.

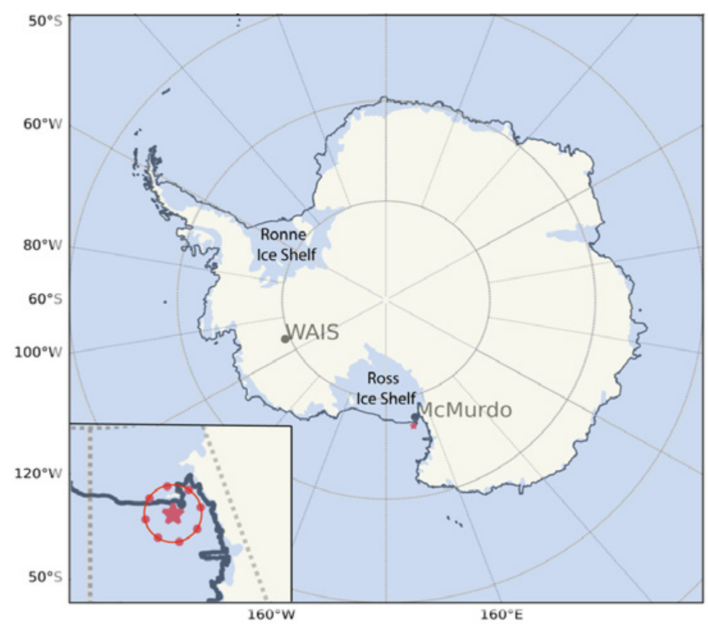
ARM Supports Modelers With New Campaign Data, Diagnostics Package

ARM provides high-frequency and long-term data sets to help develop and improve earth system models.

In FY2021, ARM Best Estimate (ARMBE) data sets became available for campaigns in Argentina and Norway. ARMBE products contain best estimates of several quantities often used in model evaluation. For both campaigns, the ARMBE data sets include cloud, radiation, and basic atmospheric quantities.

In addition, continuous large-scale forcing data became available for the ARM Mobile Facility deployment at McMurdo Station during the ARM West Antarctic Radiation Experiment (AWARE). The data, derived based on a constrained variational analysis approach, cover four months in 2016. Scientists can use the forcing data to drive single-column models, cloud-resolving models, and large-eddy simulations for different cloud and convective systems. The VAP includes diagnostic fields to help validate model simulations.

ARM also has a data-oriented metrics and diagnostics package to further enable the use of its ground-based measurements in model evaluation. This package is now integrated into the diagnostics package of DOE's Energy Exascale Earth System Model (E3SM). Users can test E3SM output at multiple ARM sites against climatology and time-series files generated from ARM data.



The map of Antarctica displays the variational analysis domain, enclosed by the red circle in the left bottom corner, for the AWARE campaign. The domain is centered near McMurdo Station on Ross Island. During AWARE, ARM had instruments at McMurdo and on the West Antarctic Ice Sheet (WAIS).

Data Offerings Increase From Cloud Campaign in Argentina

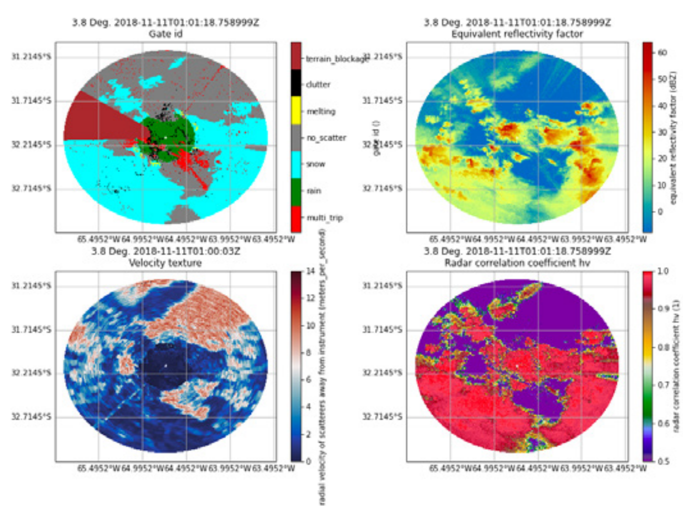
The 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign explored the cloud life cycle in Argentina's Sierras de Córdoba mountain range. The region is home to some of the world's most powerful thunderstorms.

In FY2021, ARM ramped up its release of CACTI value-added products (VAPs) so users could dig deeper into the campaign's rich data sets.

ARM updated the Corrected Moments in Antenna Coordinates Version 2 (CMAC2) VAP to work with the scanning precipitation radar used during CACTI. CMAC2 corrects raw radar data and retrieves precipitation quantities from the measurements. Scientists can use the CACTI CMAC2 product to learn more about convective processes around complex terrain.

Disdrometers are instruments that help characterize raindrop size distribution. The new Video Disdrometer Quantities (VDISQUANTS) VAP, like the previously released Laser Disdrometer Quantities (LDQUANTS) VAP, provides calculated radar-equivalent quantities such as radar reflectivity and differential reflectivity. These data products are important for interpreting and characterizing precipitation radar and rain gauge measurements and evaluating models.

CACTI was the first ARM mobile deployment to capture cloud positions with stereo cameras. The three-dimensional (3D) locations of those clouds are now available as the Point Cloud of Cloud Points (PCCP) VAP.



Plots from the CACTI field campaign show, clockwise from top left, hydrometeor classification (gate ID), reflectivity, cross-correlation coefficient, and velocity texture generated from the CMAC2 value-added product for November 11, 2018.

ARM Responds to User Needs With New Aerosol Products

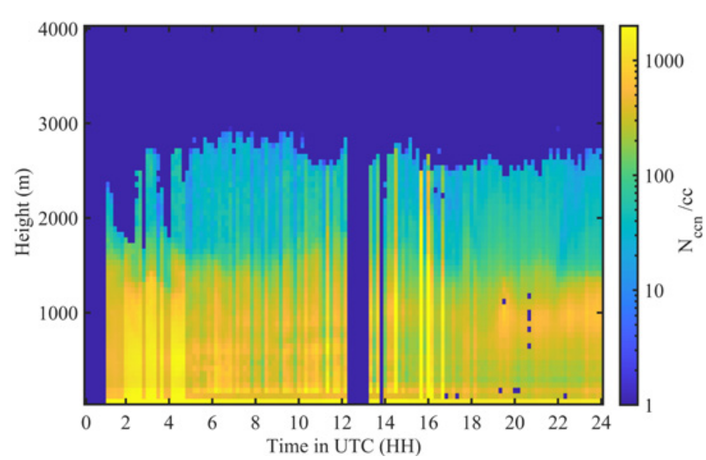
In FY2021, ARM released a set of value-added products (VAPs) that ARM's Aerosol Measurement Science Group identified as critical to advance aerosol science.

Hygroscopicity describes the ability of aerosols to absorb moisture from the atmosphere. The hygroscopicity parameter kappa quantifies a particle's capacity to activate into a water droplet. One new VAP available for evaluation uses cloud condensation nuclei (CCN) and scanning mobility particle sizer measurements to derive kappa. The VAP could help scientists evaluate aerosol properties simulated in global earth system models.

Another new evaluation VAP provides the vertical distribution of CCN number concentrations to better represent aerosol indirect effects in climate models. This VAP gives users the vertical profiles of CCN concentrations at the five supersaturation values measured by the CCN particle counter. (Supersaturation occurs when the relative humidity is at least 100%.) The VAP also routinely provides measurements of CCN near cloud base, which is a proxy for the aerosol that is entrained into clouds and leads to droplet formation.

A new production VAP corrects aerosol chemical speciation monitor data for non-unity detection of particle mass by the instrument. The VAP brings the instrument data into better agreement with other co-located aerosol measurements.

All three VAPs are available for the Southern Great Plains atmospheric observatory.



This sample plot from a day at ARM's Southern Great Plains atmospheric observatory shows the retrieved number concentration of cloud condensation nuclei at 0.4% supersaturation.

BAMS Paper Encourages Use of ARM's Spectral Measurements

A March 2021 *Bulletin of the American Meteorological Society (BAMS)* paper makes a case for more scientists to incorporate ARM's spectral radiation measurements into their studies.

Ground-based shortwave sensors measure the ultraviolet, visible, and near-infrared spectral ranges that make up the solar energy spectrum. Earth absorbs and reflects this solar energy, and it emits infrared energy back into space. If the balance of energy coming to and leaving from Earth changes, this leads to changes in global temperature.

Scientists must understand the processes in the atmosphere that drive changes in the radiation budget to predict their impact on earth systems.

The strength of ARM's shortwave spectral radiometry capabilities lies in their placement with ground-based aerosol and remote-sensing instruments. Working in tandem, the instruments provide observations that inform scientists about processes such as cloud-aerosol interactions and their radiative effects.

Reference

Riihimaki LD, C Flynn, A McComiskey, D Lubin, Y Blanchard, JC Chiu, G Feingold, DR Feldman, JJ Gristey, C Herrera, G Hodges, E Kassianov, SE LeBlanc, A Marshak, JJ Michalsky, P Pilewskie, S Schmidt, RC Scott, Y Shea, K Thome, R Wagener, and B Wielicki. 2021. "The shortwave spectral radiometer for atmospheric science: Capabilities and applications from the ARM user facility." *Bulletin of the American Meteorological Society*, 102(3):E539-E554, https://doi.org/10.1175/BAMS-D-19-0227.1.

Radiometers and multiwavelength spectrometers at ARM's Southern Great Plains atmospheric observatory gather information about solar energy, a large variable in the earth system equation.

Science Outreach

ARM Seeks Out Community Engagement During Virtual Conferences

As the ongoing COVID-19 pandemic made for another year of virtual conferences, ARM seized opportunities to connect with the scientific community by exhibiting in four major FY2021 scientific conferences. All four events included presentations by ARM users.

During the 2020 American Geophysical Union Fall Meeting and 2021 American Meteorological Society Annual Meeting, scientists presented research from the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) field campaign. ACE-ENA generated a unique collection of ground and aerial observations in summer 2017 and winter 2018. Both meetings also spotlighted findings from the 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) campaign in Argentina.

The 2021 European Geosciences Union General Assembly featured a session on the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition, which ended six months prior. MOSAiC co-coordinator Matthew Shupe, the principal investigator for the ARM MOSAiC deployment, gave a highlighted presentation about atmospheric processes in the central Arctic during the expedition.

For the first time, ARM participated in the Asia Oceania Geosciences Society Annual Meeting. The 2021 meeting drew more than 2,000 attendees from 51 countries. ARM hosted a meet-and-greet chat to help familiarize participants with ARM and how to access its data.

ARM expanded its outreach to the scientific community with a virtual exhibit during the Asia Oceania Geosciences Society Annual Meeting in August 2021.

Webinars, Virtual Scientific Workshops Click With ARM Users

After the virtual 2020 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting, ARM began a webinar series on topics of interest to the user community.

The series launched in March 2021 with a webinar on how to use ARM's Data Discovery browser. Then in May, the team leading the Large-Eddy Simulation (LES) Symbiotic Simulation and Observation (LASSO) activity gave a tutorial on using shallow convection data bundles from ARM's Southern Great Plains atmospheric observatory. In July, the LASSO team held a virtual community session on its upcoming deep convection scenario.

Virtual scientific workshops also became more common within the ARM/ASR community in FY2021. In October 2020, almost 200 people attended a two-day workshop on machine learning, statistical constraints, and other emerging methods for streamlining investigations of earth systems and weather. The workshop took the place of a breakout session that would have occurred had the 2020 ARM/ASR joint meeting been held in person.

Following a breakout session during the 2021 ARM/ASR meeting, researchers held a two-day workshop on high-latitude marine boundary-layer clouds. The September workshop provided additional time to discuss modeling activities tied to recent ARM campaigns in Norway and the Southern Ocean.

ARM's Hickmon Participates in DOE Climate Roundtable

In July 2021, ARM Associate Director for Operations Nicki Hickmon was a featured panelist during a livestreamed roundtable discussion about climate research within the DOE Office of Science.

Energy Secretary Jennifer Granholm, who led the discussion, said that ARM "boasts an unparalleled ability to observe interactions between changes in our atmosphere and changes in our climate."

Hickmon answered a question from Jane Lubchenco, deputy director for climate and environment at the White House Office of Science and Technology Policy. Lubchenco asked how ARM helps combine observations, models, and artificial intelligence to more rapidly enhance climate predictions.

"For climate prediction, we need to understand processes that are on tiny timescales or decades-long or longer timescales," said Hickmon. ARM data provide a three-dimensional picture of the atmosphere over time.

In terms of modeling, Hickmon referred to an ARM activity producing high-resolution model simulations that users can compare with ARM observations. In addition, the output can be used for model validation and analysis.

Hickmon also discussed DOE's Artificial Intelligence for Earth System Predictability (AI4ESP) initiative. AI4ESP is a multi-laboratory effort exploring how to use AI with observations and models to enhance earth system predictability.

ARM Associate Director for Operations Nicki Hickmon speaks during a livestream on climate research within the DOE Office of Science.

Budget Summary and **Facility Usage**

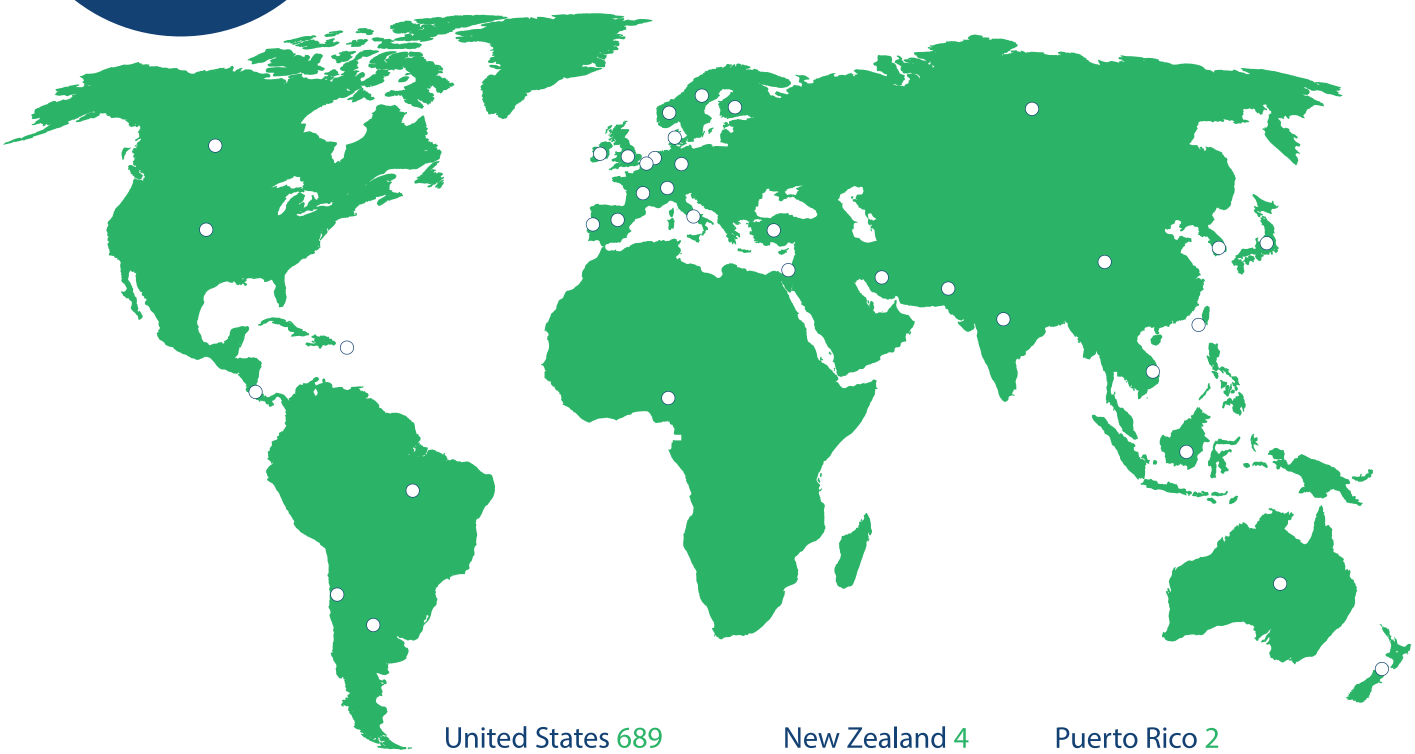
Fiscal Year 2021 Statistical Overview

INFRASTRUCTURE BUDGET

$70,110K

960
TOTAL SCIENTIFIC USERS

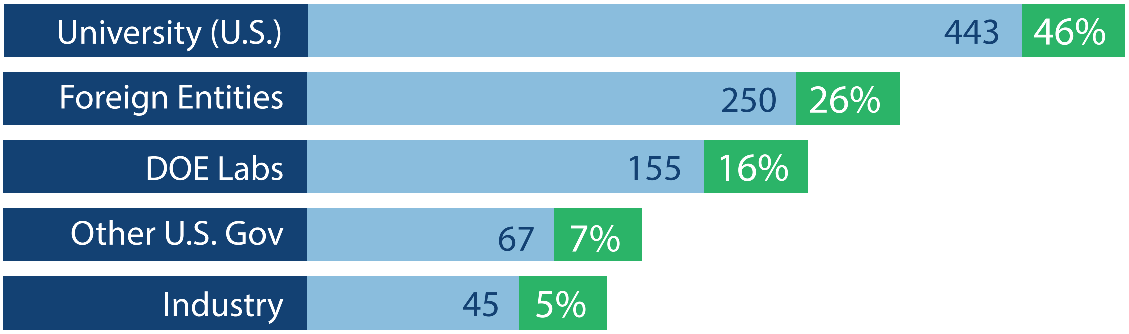
USERS BY COUNTRY



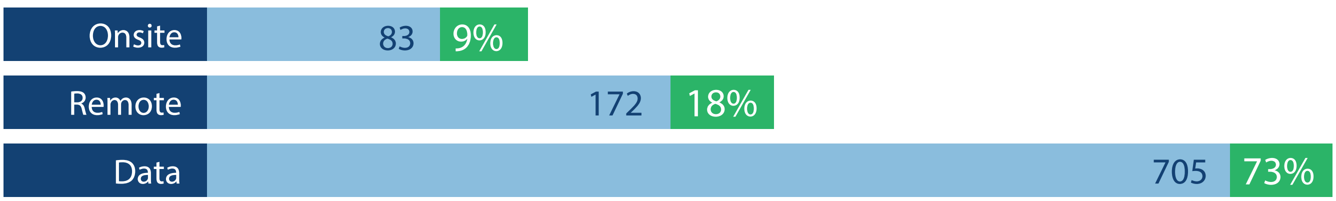
United States 689	New Zealand 4	Puerto Rico 2
China 57	Norway 4	Russia 2
Germany 41	Portugal 4	Belgium 1
Brazil 28	Spain 4	Chile 1
United Kingdom 25	Switzerland 4	Costa Rica 1
Canada 16	Israel 3	Denmark 1
India 14	Italy 3	Indonesia 1
Sweden 12	Taiwan 3	Iran 1
Australia 10	Finland 2	Nigeria 1
France 6	Ireland 2	Pakistan 1
South Korea 6	Japan 2	Turkey 1
Argentina 5	Netherlands 2	Vietnam 1

36
Countries

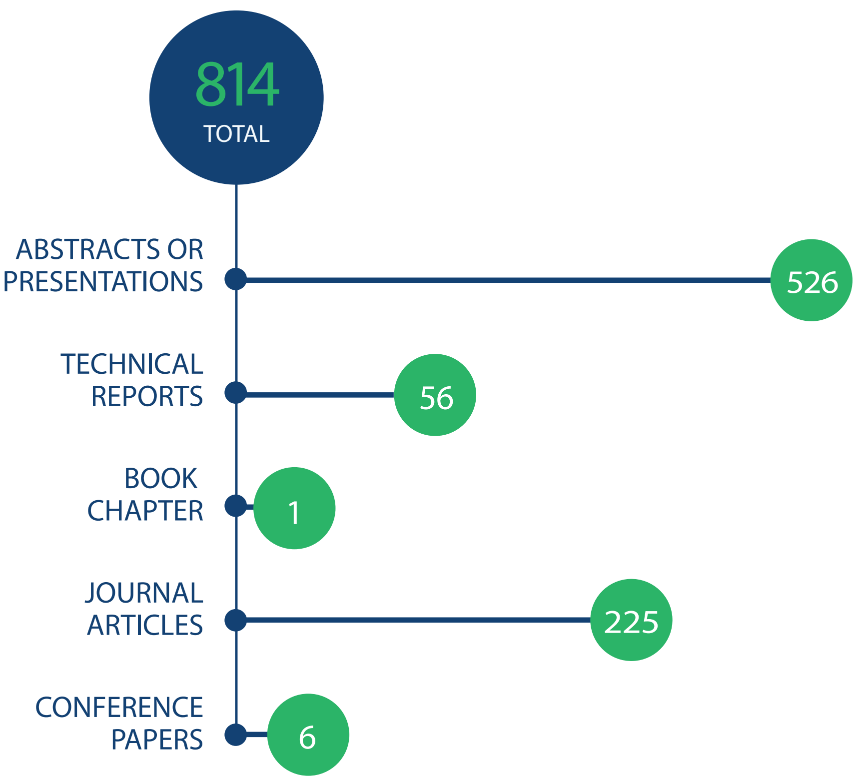
USER STATISTICS



FACILITY USAGE

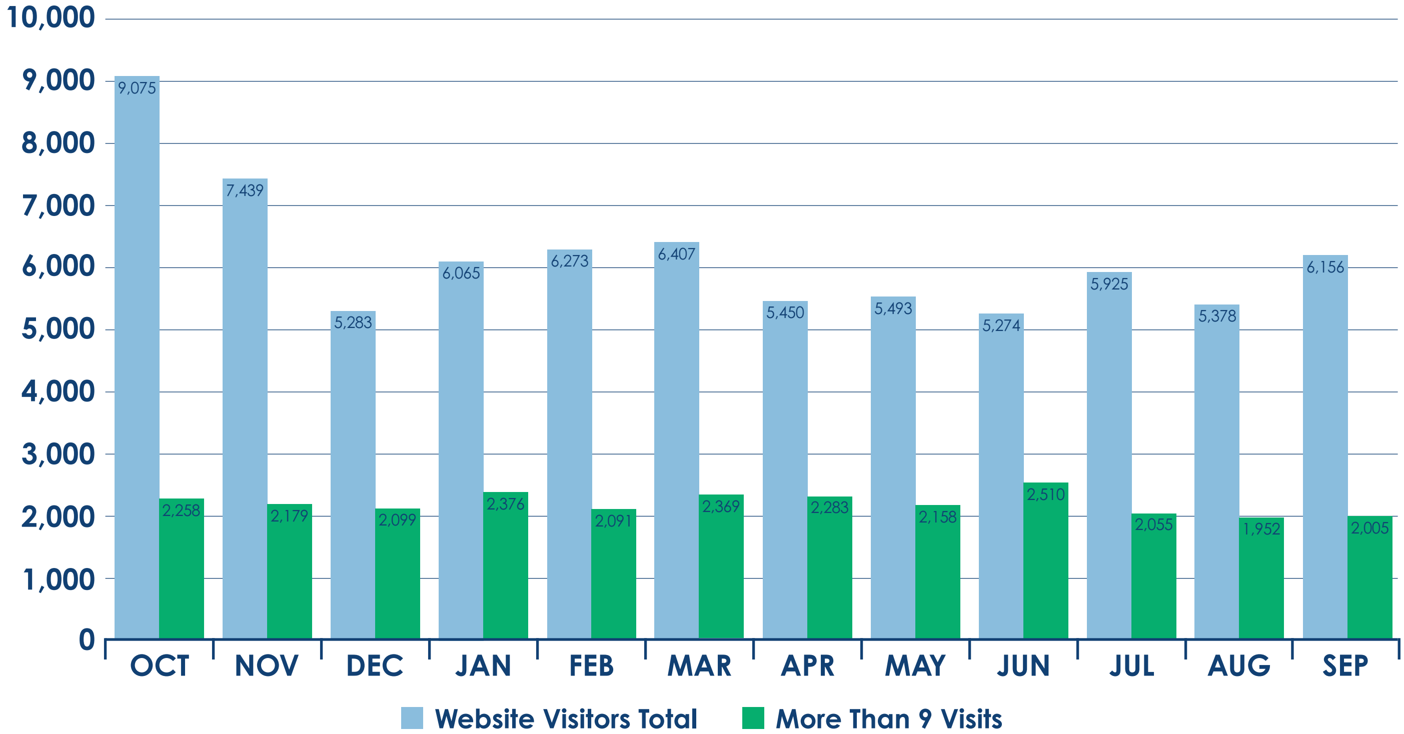


PUBLICATIONS USING ARM*

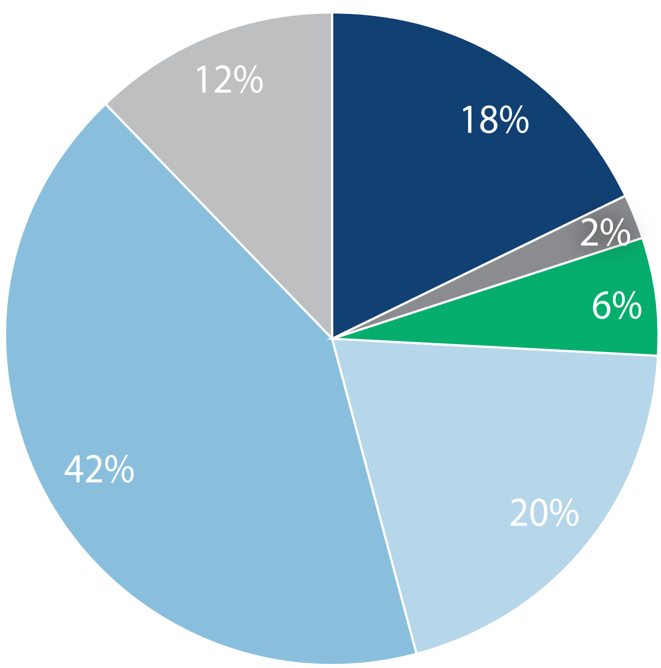


*Publication statistics were collected as of December 2021. Journal article numbers will continue to increase over time.

WEBSITE VISITORS



FIELD CAMPAIGNS



50 Total

- AMF – 9
- AAF – 1
- ENA – 3
- NSA – 10
- SGP – 21
- OFFSITE – 6

DATA PRODUCTS

2 released to production

- ACSMCDCE
- KAZRARSCLCLOUDSAT

6 approved for development

- CLDPHASE
- DLMC
- HSRLRLPROFFEX1THOR
- MERGEDSIZEDISTR
- MICROBASEWAPLUS
- TBSMERGED

6 released to evaluation

- CCNSMPSKAPPA
- COGS
- KASACRGRIDPPI
- MPLCMASKML
- RNCCN
- SONDEPARAM

7 existing VAPs updated

- AERIOE
- AODBE (formerly QCAOD)
- AOD-MFRSR (formerly MFRAOD)
- LANGLEY
- MFRSRCLDOD1MIN
- NDROP
- RLPROF-FEX

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

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Thank you to the many people over the years who provided images in the ARM annual report. Here are the image contributors from FY2021 and the pages on which their images appear:

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Brent Peterson, Sandia National Laboratories (Page 2, 14, 15, 42)

Andrea Starr, Pacific Northwest National Laboratory (Page 3)

Heath Powers, Los Alamos National Laboratory (Page 6, 29)

Nicki Hickmon, Argonne National Laboratory (Page 8)

Fred Helsel, Sandia National Laboratories (Page 10)

Lianna Nixon, University of Colorado, Boulder (Page 12)

Manuel Helbig, Dalhousie University (Page 13)

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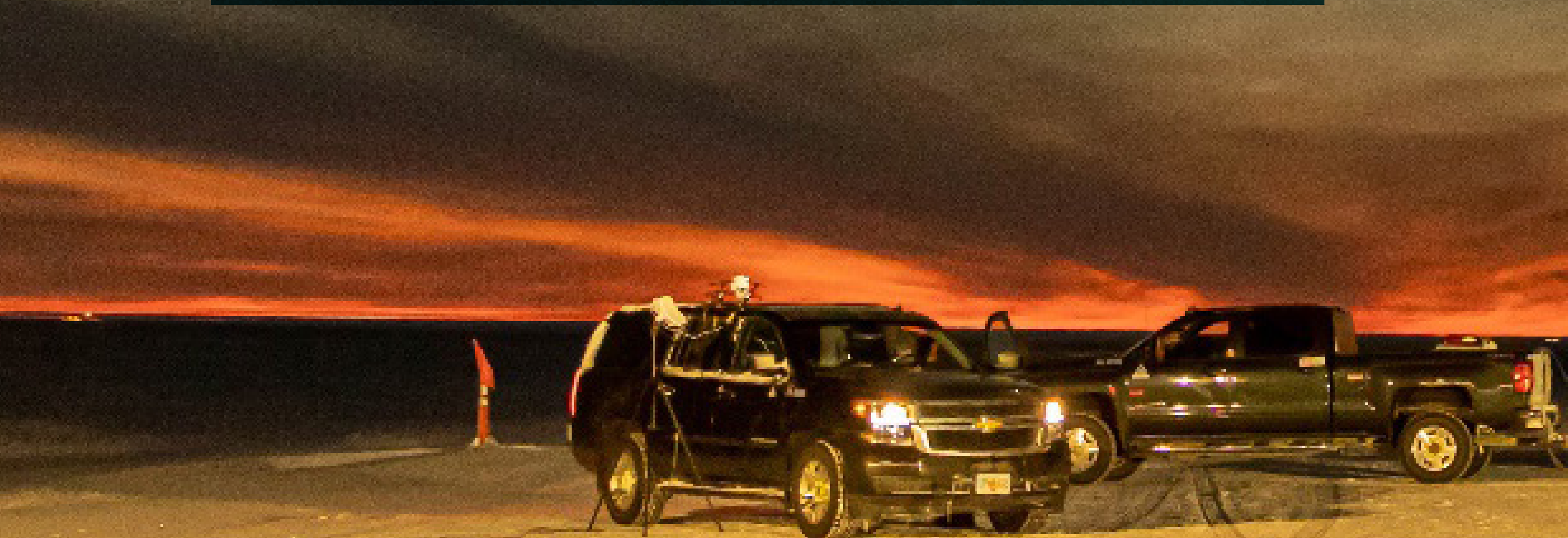

In November 2020, ARM conducted the final tethered balloon flights at its site at Oliktok Point, Alaska. Operations of the third ARM Mobile Facility at Oliktok Point ended in June 2021 after almost eight years. The mobile facility's next extended deployment will be in the Southeastern United States.

DOE/SC-ARM-21-023

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Office of Science