ARM

U.S. DEPARTMENT OF ENERGY

2019 ANNUAL REPORT

ATMOSPHERIC RADIATION MEASUREMENT

On the covers:

Front – From October 2018 to April 2019, the first ARM Mobile Facility collected data in the Sierras de Córdoba mountain range of north-central Argentina for the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign. CACTI studied how large regional convective storms form, grow, and organize.

Inside – More than 50 ARM instruments left Tromsø, Norway, for the central Arctic in September 2019 on the icebreaker R/V Polarstern for the yearlong Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. Image is courtesy of Alfred Wegener Institute.

From the Technical Director

From Argentina to the Arctic: A Year of Major Milestones

As you will read in this report, fiscal year 2019 (FY2019) was a year of milestones for the Atmospheric Radiation Measurement (ARM) user facility, with major field campaigns in extremely different climates, the retirement of the ARM research aircraft, and the purchase of a new airborne measurement platform. In addition, ARM enhanced collaborations with organizations around the United States—and the world—and worked to take the pulse of the science community to ensure that the facility will meet research needs in the decade to come.

The year kicked off with ARM carrying out an important measurement mission in Argentina looking at the life cycle of some of the largest convective storms in the world. The data from the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign will give scientists a holistic view of the factors that control deep convection, which has the potential to improve weather and long-term forecasts, as well as earth system models.

This campaign was also the last flown by ARM's Gulfstream-159 (G-1) aircraft, built in 1961. The G-1 flew 22 research flights during CACTI. For nearly a decade, this airborne scientific platform helped ARM advance atmospheric research in field campaigns from the Arctic to the tropics.

While ARM is known for its ground-based measurements, some measurements cannot be made from the ground. Aerial measurements also provide spatial context for data—a perspective not possible from a fixed location on the ground. To fill this need, in FY2019, the U.S. Department of Energy (DOE) purchased a Bombardier Challenger 850 regional jet to expand ARM's scientific data collection capabilities. Undergoing modifications in FY2020, the Challenger 850 is expected to be ready for its first ARM campaign by the end of 2022.

While CACTI was being packed up, another of ARM's mobile facilities was being prepared for a year frozen into the central Arctic aboard the German icebreaker *R/V Polarstern* to observe, measure, and better understand this region of dramatic changes. ARM provided more than 50 instruments—including the first scanning cloud radar to operate in the arctic ice pack—as part of the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition, which involves 600 scientists, technicians, and logicians from 20 countries.

The instruments used in the CACTI campaign were then shipped to the coast of Norway within the Arctic Circle, and installation began for a campaign investigating cold-air outbreaks that occur when a cold air mass crosses open areas of warm water. The data gathered during the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) will also be important to the MOSAiC mission.

In addition, FY2019 focused on building collaborations with national and international partners, including DOE's Energy Exascale Earth System Model (E3SM) project using an extensive set of ARM cases for a single-column model, and enhancing a longtime partnership between ARM and the NASA Langley Research Center in Virginia. This ARM-NASA collaboration captures the interconnected nature of observations from space, aircraft, and the ground. We've also started to explore potential projects with the World Climate Research Programme and the European Union.

Finally, much work has been done to look toward ARM's future to ensure that the scientific community's needs will be met well into the coming decade. In FY2019, ARM enhanced its constituent group on aerosol measurements and created a new group to solicit input related to cloud and precipitation measurements to refine the measurement strategies for those complex areas. Extensive needs assessments were conducted for the next phase of the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) workflow, which integrates observations and models.

All these activities reported on in this report demonstrate ARM's continued scientific impact and its key role in atmospheric research in the United States and abroad. Much of the scientific progress that will be gained from these FY2019 campaigns will come five to 10 years down the road, as we have seen with past campaigns. For example, you will read about a new group of papers that use data from the 2009 Routine ARM Aerial Facility (AAF) Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO) field campaign. We also report on the continued success of the 1997–1998 Surface Heat Budget of the Arctic Ocean (SHEBA) field campaign, which was an inspiration for MOSAiC.

In addition, this report covers the excellent science that continues to come out of ARM's long-term Southern Great Plains, North Slope of Alaska, and Eastern North Atlantic atmospheric observatories.

This has been an exciting year fulfilling ARM's mission to support the science community and to deliver outstanding data for our scientific users. I hope you enjoy reading about the success we had in FY2019.

Jim Mather
ARM Technical Director

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ARM's Gulfstream-159 (G-1) research aircraft receives a warm—and wet—greeting in Pasco, Washington, upon returning from its final science mission, the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in Argentina. Its final arrival on December 17, 2018, marked the end of an era.

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 2019 (FY2019).

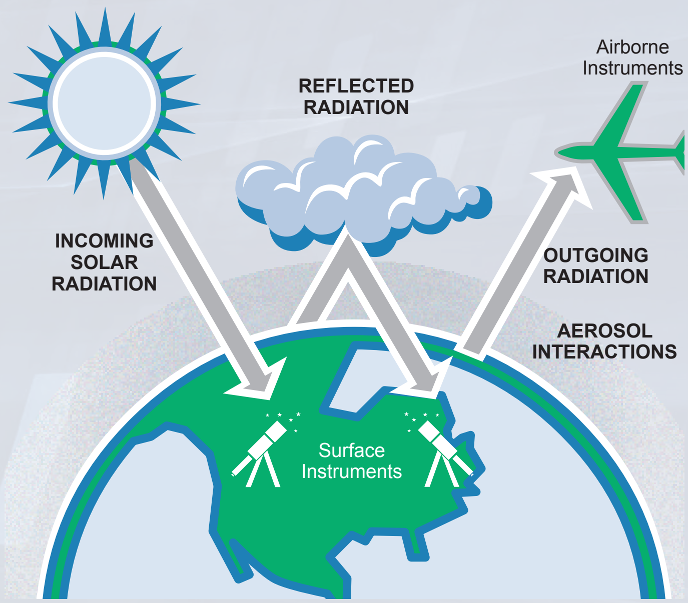
ARM is a multilaboratory, U.S. Department of Energy (DOE) scientific user facility and a key contributor to national and international atmospheric and climate research efforts. ARM offers scientists cutting-edge, ground-based observatories, manned and unmanned aerial capabilities, and more than 25 years 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 are being used to improve the accuracy of how clouds, aerosols, precipitation, and their interactions with Earth's radiant energy are represented in regional- and global-scale weather and earth system models. Better models improve the accuracy of long-term weather forecasts and help our nation develop sustainable solutions to energy and environmental challenges.

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



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

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

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

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)**—This includes a site at Barrow (officially known as Utqiaġvik) that was established in 1997 near the edge of the Arctic Ocean, and a location at Oliktok Point, where ARM has secured special-use arctic airspace.
- **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.

Each observatory operates a broad suite of advanced measurement systems to provide high-quality research data sets. The current generation of instruments includes three-dimensional (3D) 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.

ARM Helps High-Flying Science Happen on Tethered Balloons

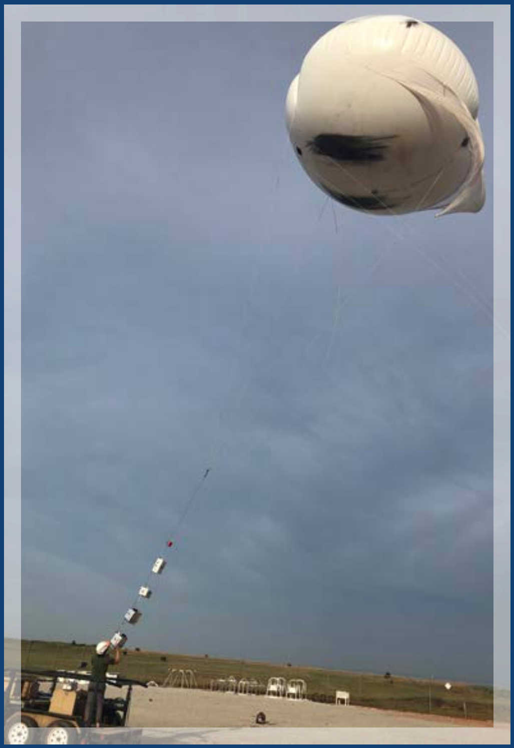
ARM continues to fly instrumented tethered balloon systems (TBS) within the clouds at Oliktok Point, Alaska, where DOE controls restricted airspace supporting these efforts. Expanding capabilities to new sites in FY2019, ARM began TBS flights in April over the Southern Great Plains (SGP) atmospheric observatory.

Staff from ARM and another DOE scientific user facility, the Environmental Molecular Sciences Laboratory (EMSL), are collaborating to measure aerosol properties from the TBS. ARM deployed an aerosol sampler on a TBS in FY2019 at both the SGP and Oliktok Point. The collected samples are undergoing analysis at EMSL. This project will provide the foundation for a future joint ARM-EMSL proposal call.

ARM also held a proposal call to fly guest instruments on its TBS. The SGP hosted those flights in July and September. The guest instruments came from Chongai Kuang at Brookhaven National Laboratory in New York and Bob Grimm at Southwest Research Institute in Colorado.

Looking to measure ultrafine aerosols in the boundary layer, Kuang modified and deployed two condensation particle counters. Historically, ultrafine aerosols have mostly been measured at the surface. However, a recent study at the SGP indicated that they form about 400 to 600 meters (about 1,300 to 2,000 feet) above the surface.

Grimm tested an instrument that he said could help measure "natural electromagnetic waves that penetrate into the planet and tell us the properties of the inside of the planet." The eventual aspiration is for the instrument to fly in the atmosphere of Venus. A ground instrument would not last long there: Its average surface temperature is about 430 degrees Celsius (800 degrees Fahrenheit).



A crew member puts instruments on a tethered balloon at ARM's Southern Great Plains atmospheric observatory.

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).

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.

Major efforts in FY2019 included the kickoff of a campaign in which ARM instruments will collect data for a year aboard an icebreaker frozen into arctic ice. ARM also managed a campaign to improve understanding of the life cycle of convective storms by gathering data in the Sierras de Córdoba mountain range of north-central Argentina.

In addition, about 46 smaller user-proposed intensive operational periods were conducted at either fixed or mobile facility locations.

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 science community through the ARM Data Center to aid in further research.

Campaign Workshop Highlights Progress Toward Scientific Goals

In January 2019, an international team of more than 50 researchers gathered at Brookhaven National Laboratory in New York for a two-day workshop about the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) field campaign.

The workshop explored the state of research and data sets from ACE-ENA, which took place in summer 2017 (June and July) and winter 2018 (January and February) in the Azores. ACE-ENA focused on the study of aerosols and low clouds in a remote marine setting. The field campaign required ground-based measurements from ARM's Eastern North Atlantic atmospheric observatory on Graciosa Island and data acquired aboard ARM's now-retired Gulfstream-159 (G-1) research aircraft.

Jian Wang, ACE-ENA principal investigator from Washington University in St. Louis, organized the workshop with co-investigators Mike Jensen of Brookhaven National Laboratory and Rob Wood of the University of Washington.

Attendees received updates on campaign measurements and the development of value-added products for ACE-ENA and looked at how people are using the data for scientific investigations. Twenty-four presentations from university and national laboratory researchers covered topics such as new particle formation, chemical composition of aerosols, and modeling of cloud and drizzle properties.

The ACE-ENA campaign coordinated air and ground observations in the Eastern North Atlantic.

Attendees also identified opportunities for collaboration, needs, and next steps. Collaborative activities included characterizing aerosol composition and reconciling differences between the number of cloud condensation nuclei and cloud droplets. Workshop participants advanced the conversation at the June 2019 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting in Rockville, Maryland.

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 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's User Executive Committee in 2019: New Faces, New Directions

The ARM User Executive Committee (UEC) is the official voice of the user community in its interactions with ARM management.

The UEC began 2019 with a new chair (Sébastien Biraud, Lawrence Berkeley National Laboratory in California) and a new vice-chair (Allison Aiken, Los Alamos National Laboratory in New Mexico, who will succeed Biraud in 2021). After a virtual election in which 193 ARM users voted, the UEC gained eight new members representing various science themes. All 13 members serve four-year terms with a staggered election cycle.

At the 2019 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting, the UEC organized a networking lunch for new members of the ARM/ASR community. The lunch drew about 50 participants, including early career scientists. Informal conversations around new research topics, the ARM Data Center and Data Discovery browser, instrument mentors, and career development proved an excellent conduit for gathering user feedback.

During the joint meeting, Biraud participated in a panel discussion, "How ARM Meets the Needs of ASR Science Goals." Data quality and uncertainty quantification tutorials to educate new users were also discussed; both are on the UEC to-do list for the coming year.

In FY2019, the UEC continued to reach out to scientists and organizations outside ASR—an important part of the ARM user community—to expand ARM's use and reach.

Information Flows From 2019 ARM/ASR Joint Meeting

More than 300 atmospheric scientists attended the 2019 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting from June 10 to 13 in Rockville, Maryland.

DOE ARM Program Manager Sally McFarlane introduced the Bombardier Challenger 850 regional jet as the replacement for the Gulfstream-159 (G-1) research aircraft, which ARM retired in late 2018. McFarlane also updated the crowd on FY2019 ARM field campaigns and noted an arctic focus for FY2020.

Two days of posters—207 in all—touched on everything from ARM infrastructure developments to analyses of ARM measurements to advances in atmospheric modeling. Plenary and breakout sessions included talks on ice-nucleating particles, snow regimes in Alaska, and machine learning and deep learning applications for ARM and ASR science.

Winners of the first ARM Service Awards gathered with DOE and ARM leadership.

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 program to meet the objectives of DOE's Climate and Environmental Sciences Division, ARM 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. These collaborations are key to ARM's success.

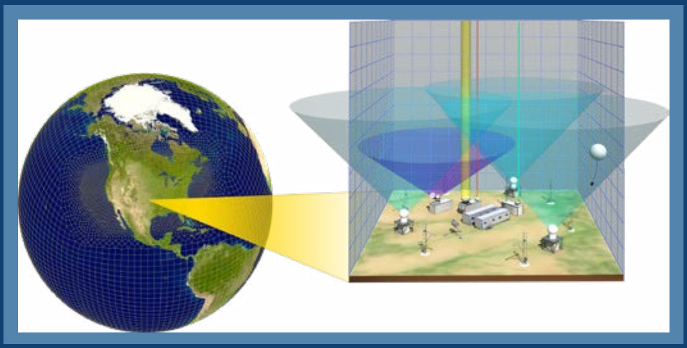
ARM Collaborates on Single-Column Model for DOE Project

Around the globe, ARM instruments gather data required for atmospheric research. A growing number of scientists are using ARM data to better represent processes in earth system models.

These models segment areas of interest into a grid with individual cells that may range from just a few kilometers to several hundred kilometers in width. A powerful tool for model evaluation and development—a single-column model (SCM)—encompasses a vertical column over one grid cell in a model from the surface to the top of the atmosphere.

In FY2019, scientists for DOE's Energy Exascale Earth System Model (E3SM) project made public and expanded the scope of their SCM. Working with ARM and researchers from DOE's Atmospheric System Research (ASR) program, the E3SM project team significantly expanded an SCM library with numerous ARM cases spanning multiple locations and meteorological regimes.

"If you are looking to validate or improve a parameterization (a simplified representation) to be used in an earth system model, it helps to first test it locally," said L. Ruby Leung, E3SM chief scientist from Pacific Northwest National Laboratory in Washington state. "Constraining it over a specific location in a single-column model allows a more 'apples-to-apples' comparison of your simulation with observational data."



ARM's Southern Great Plains observatory supports single-column modeling efforts.

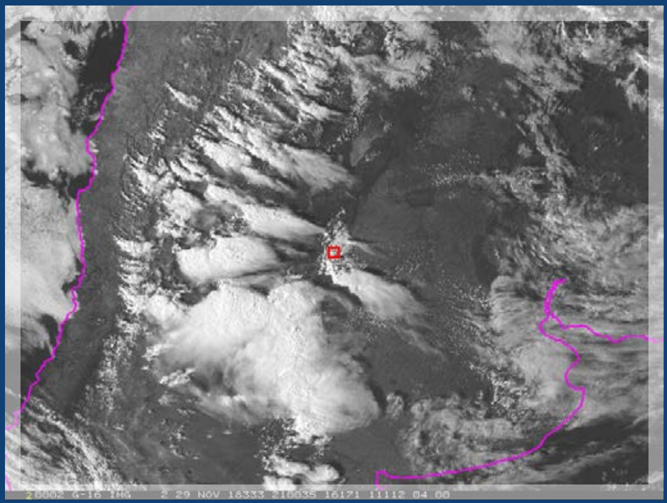
ARM Technical Director Jim Mather said the SCM library of ARM cases is a powerful way to support E3SM development: "It has proven to be an outstanding mechanism for ARM-ASR collaborations with the global modeling community."

ARM-NASA Partnership Links Observations at Many Levels

A longtime federal partnership between ARM and the NASA Langley Research Center in Virginia captures the interconnected nature of observations from space, aircraft, and the ground. The 25-year collaboration has produced satellite retrievals of radiation and cloud properties over and around ARM atmospheric observatories and during ARM field campaigns.

While ARM provides comprehensive ground-based measurements, NASA Langley offers data visualizations of cloud conditions spanning hundreds of kilometers. Together, these sky and ground observation systems help present a more complete picture of the atmospheric column.

NASA Langley houses a satellite data-processing system now called the Satellite Cloud Observations and Radiative Property retrieval System (SatCORPS). SatCORPS draws data over ARM's fixed and mobile observatories. For ARM field campaigns, it can develop a special suite of products focused on a campaign's domain—sometimes adjusting the data's space or time resolution.



A satellite image shows the main site of the CACTI field campaign in Argentina. Image is courtesy of the NASA Langley Research Center.

During the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign, which took place from October 2018 through April 2019 in Argentina, SatCORPS ran a convective products algorithm. This algorithm identified regions and properties of storm updrafts that went higher and got colder than their surrounding anvil clouds.

In general, SatCORPS data also help determine cloud properties such as altitude and depth, reflectivity, temperature, water density, and cloud phase. In turn, data from ARM observatories help SatCORPS tune its algorithms.

Scientist Strengthens Ties Between ARM Data and Global Modeling

In a partnership of more than two decades, ARM data helped to evaluate and improve global modeling at the European Centre for Medium-Range Weather Forecasts (ECMWF). While the active research collaboration ended in 2019, a mutually beneficial data exchange continues between ARM and ECMWF, and a wealth of important achievements resulting from the research collaboration will live on.

This includes ECMWF supporting ARM with forecast and analysis data for its fixed and mobile atmospheric observatories.

Several scientists at ECMWF, including Maike Ahlgrimm, worked directly with ARM data over the years to improve understanding and modeling of the atmosphere. Since 2008, Ahlgrimm spent the bulk of her career digging into data from ARM's observatories around the world to continue improving the ECMWF model, which typically produces forecasts up to two weeks ahead.

"Over the last number of years, Maike's been key to that relationship, not only to work with that particular model, but to provide a window into the global modeling community in general," said ARM Technical Director Jim Mather.

In July 2019, Ahlgrimm moved on from the England-based ECMWF. The Berlin native now works for the German weather service.

Maike Ahlgrimm used ARM data to improve global modeling at the European Centre for Medium-Range Weather Forecasts (ECMWF).

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 fiscal year 2019.

ARM's Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign, which closed in April 2019, explored the life cycles of convective storms in the Sierras de Córdoba mountain range—thought to be the birthplace of the biggest thunderstorms in the world. Nearly 200 scientists and students from seven countries participated, including researchers from a concurrent National Science Foundation campaign studying severe weather in the region.

An ARM Mobile Facility—serving as the main CACTI observatory—was close enough to the mountains to yield clear views of developing big storms.

Multifaceted Research Sheds Light on Thunderstorm Origins

Seven months of measurements in Argentina will deliver insights into how deep convective systems begin, grow, and organize. Such systems generate storms that can produce high winds, lightning, floods, and hail.

CACTI marked an ARM milestone: the deployment of the second-generation C-Band Scanning ARM Precipitation Radar. The instrument delivered three-dimensional (3D) hemispheric scans showing the complex structure of evolving convective systems.

ARM also collected data aboard its Gulfstream-159 (G-1) research aircraft, which was retired after CACTI.

Argentine Campaign Gets a Nod in *Nature*

The journal *Nature* highlighted ARM's Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in November 2018 for its aim to improve understanding of storm development in north-central Argentina.

CACTI took place from October 2018 through April 2019 in the Sierras de Córdoba mountain range. Researchers are using ARM ground and airborne data to help fill in knowledge gaps about how convective storms form, grow, and organize.

CACTI ran concurrently with a National Science Foundation campaign in the region—Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations (RELAMPAGO)—designed to improve predictions of severe weather.

Lightning strikes near Argentina's Sierras de Córdoba mountain range, which experiences some of the world's largest and most destructive thunderstorms.

“CACTI is giving us a holistic view of the components that go into deep convection.”

—Adam Varble, CACTI principal investigator from Pacific Northwest National Laboratory

Researchers plan to assemble a database of every storm observed (an impressive 80 within the campaign’s 212 days), coordinated with a database capturing all the environmental conditions around storm cells.

“CACTI is giving us a holistic view of the components that go into deep convection,” says Adam Varble, CACTI principal investigator from Pacific Northwest National Laboratory in Washington state. “You can see what controls the life cycle of these deep convective clouds.”

Polar Convergences: ARM Observations Support Worldwide Initiative

After completing its two-year core phase in mid-2019, an international initiative called the Year of Polar Prediction (YOPP) continues its work to improve polar modeling and forecasting capabilities. ARM’s major observational contributions to YOPP in FY2019 came through:

MOSAiC: Beginning in September 2019, ARM is providing some of the most critical atmospheric instruments during the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. MOSAiC, which involves scientists from 20 nations, is observing the atmosphere, biogeochemistry, and ecology of the central Arctic through October 2020.

COMBLE: ARM set up a mobile facility for the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) expedition, which will take place from December 2019 through May 2020 in northern Norway. COMBLE will deliver data and insights on the open-sea shallow convection cloud regimes that form during cold-air outbreaks.

Since YOPP began, ARM has contributed through:

ICECAPS: ARM has been part of the Integrated Characterization of Energy, Clouds, Atmospheric state, and Precipitation at Summit (ICECAPS) project since mid-April 2010. Designed to better understand regional cloud and atmosphere processes above the Greenland ice sheet, the project is funded primarily by the National Science Foundation. From the beginning, ICECAPS included ARM instruments, which will operate through August 2020 to help determine the height and properties of optically thin clouds above the Summit Station site.

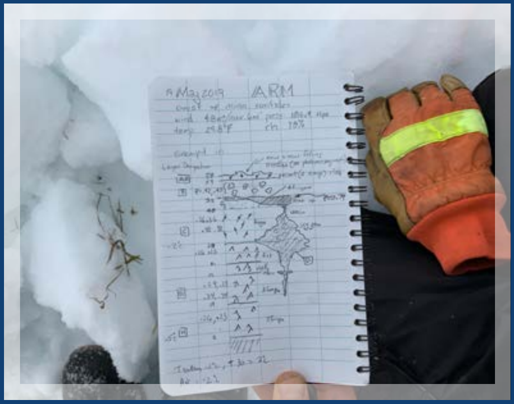
POPEYE: The 2018 Profiling at Oliktok Point to Enhance YOPP Experiments (POPEYE) field campaign ran from July through September at ARM’s North Slope of Alaska atmospheric observatory. Researchers collected 121 hours of tethered balloon data on aerosol properties, temperature, and humidity from below, within, and above the clouds. Data analysis began in FY2019.

Alaskan Campaign Digs Into Snowmelt and Surface Effects on Local Energy Balance

The reflectivity, or albedo, of snow can vary widely. Fresh snowfall has a high albedo, but aging or melting snow reflects less light, which warms the surface underneath. Nearby surfaces also can influence the albedo by slowing or accelerating snowmelt. Models struggle to capture these processes and how the surface looks as snow melts.

ARM’s North Slope of Alaska atmospheric observatory is the center of the Snow ALbedo eVOlution (SALVO) campaign, led by Matthew Sturm from the Geophysical Institute at the University of Alaska, Fairbanks. From 2019 to 2021, Sturm’s team is collecting premelt snow and albedo measurements each April at the ARM site in Barrow (officially known as Utqiaġvik) and on nearby tundra and sea ice. It is repeating the measurements during the melt from May through June.

Measurements of the snow’s optical properties will feed into a radiative transfer model to help calculate radiative fluxes and heating rates in the atmosphere.



A pencil and paper are effective for diagramming a snow pit dug to gather measurements during the SALVO field campaign.

Past Campaign Results

Pioneering 2009 Cloud Data Campaign Still Has Impact on Models

Ten years after it began, an ARM investigation of continental boundary-layer clouds is still spinning off influential papers and improving weather and earth system models.

The Routine ARM Aerial Facility (AAF) Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO) field campaign ran from January through June 2009. Led by Andrew Vogelmann, an atmospheric scientist from Brookhaven National Laboratory in New York, RACORO investigated low-level liquid-water clouds above ARM's Southern Great Plains (SGP) atmospheric observatory.

Within the boundary layer, reflective shallow, warm clouds help regulate the Earth's surface energy budget by controlling incoming radiation. Despite their importance, such clouds remain a major source of uncertainty in weather and earth system models.

During RACORO, ARM's ground-based sensors at the SGP measured cloud fraction, optical depth, and other descriptors of cloud, aerosol, and atmospheric state in the boundary layer.

RACORO was a first-of-its-kind cloud data campaign, collecting airborne measurements over an extended period (more than five months) to improve the statistical characterization of continental boundary-layer clouds.

The airborne data came from instruments aboard a U.S. Navy Twin Otter research aircraft on loan from the Center for Interdisciplinary Remotely-Piloted Aircraft Studies in California.

"RACORO has been a great option for aircraft measurement data for boundary-layer cloud studies," said Satoshi Endo, a scientific associate at Brookhaven National Laboratory who has led or contributed to many papers using the campaign's data set. "It provides many cases of boundary-layer clouds of different types."

Most papers using RACORO data have touched on cloud-aerosol interactions or entrainment—how dry or moist air is mixed into clouds from the environment outside them.

RACORO data have informed how cloud processes work at a microphysical level and paved the way for case studies and large-eddy simulations.

Scientists have been able to evaluate fine-scale models and data retrieved from commonly deployed remote-sensing platforms, calculate cloud albedo (reflectivity), refine retrieval algorithms, and improve cloud simulations.

A 42-paper special section of *Journal of Geophysical Research: Atmospheres*, last updated online in July 2019, shows how RACORO data have improved researchers' understanding of fast physical processes involving clouds, aerosols, and precipitation.

The U.S. Navy Twin Otter research aircraft takes to the skies during the RACORO field campaign.

Researchers pause for a group photo during RACORO. In the center, wearing a blue jacket, is principal investigator Andrew Vogelmann of Brookhaven National Laboratory.

The concept and methodology of RACORO also helped to develop the high-resolution Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) workflow. Vogelmann co-developed LASSO with William Gustafson at Pacific Northwest National Laboratory in Washington state.

Arctic Campaign Continues to Break Ground Two Decades Later

One day in September 1997, the Canadian Coast Guard icebreaker *Des Groseillier*s froze into Arctic Ocean ice pack a few hundred miles northeast of Prudhoe Bay, Alaska, within one of the most poorly observed regions in the world. To close knowledge gaps over a full year of intentional drifting, instruments on the floating observatory—some of them from ARM—took comprehensive measurements of ocean, ice, and cloud properties.

The resulting data—gathered over a meandering course of 1,200 nautical miles—were for the Surface Heat Budget of the Arctic Ocean (SHEBA) field campaign, supported primarily by the National Science Foundation and the Office of Naval Research. The yearlong campaign investigated the atmosphere-ice-ocean system and measured ice-albedo and cloud-radiation feedbacks to improve predictive models.

SHEBA also helped to inspire the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) field campaign, which launched in September 2019.

The SHEBA team collected observations from within an imaginary cylinder, which stretched from the top of the atmosphere down though snow and sea ice into the first 100 meters (about 300 feet) of the ocean. Supplementary data came from research aircraft, helicopters, and submarines.

SHEBA data have inspired many papers—at least 130, according to Web of Science statistics—and spun off hundreds of citations. A 2002 paper describing SHEBA in the *Bulletin of the American Meteorological Society (BAMS),* with Taneil Uttal of the National Oceanic and Atmospheric Administration as lead author, had 447 citations near the end of FY2019.

A highly cited October 1999 article in *Eos*, on feedback processes governing the thermodynamics of the ice pack, tallied 199 citations by the close of FY2019. Its lead authors were Uttal and SHEBA chief scientist Donald K. Perovich, now at Dartmouth College.

Another 1999 paper was used right away to inform single-column models. Yet the SHEBA story is about more than impactful studies.

"We all felt, right from the beginning, that, sure, we would all do our publications, but the real legacy was the data set," said Perovich. "Create a good data set, integrated across disciplines, and people use it. We built it, and they came."

The Canadian Coast Guard icebreaker *Des Groseilliers* and the escort vessel *Louis St. Laurent* head out into the Arctic Ocean.

***Des Groseilliers*—instrumented and ready—settles into pack ice for a year of collecting data.**

Amazon Study Reveals Urban Impact on Natural Particles

A March 2019 *Nature Communications* paper using ARM data from the Green Ocean Amazon (GoAmazon2014/15) field campaign reported how urban pollution greatly alters natural aerosol processes in the Amazon rainforest.

Researchers found that nitrogen oxide emissions in a pollution plume from Manaus, Brazil, increased particle formation from natural forest carbon by 60 to 200 percent on average and as much as 400 percent.

The study, led by ManishKumar Shrivastava at Pacific Northwest National Laboratory in Washington State, also showed that the nitrogen oxide emissions in the plume were 10 to 50 times greater than those from the soils.

A paper using ARM GoAmazon2014/15 data found that nitrogen oxide emissions from the Amazonian city of Manaus, Brazil, greatly increased the formation of particles from natural rainforest carbon.

Reference

Shrivastava M, MO Andreae, P Artaxo, HMJ Barbosa, LK Berg, J Brito, J Ching, RC Easter, J Fan, JD Fast, Z Feng, JD Fuentes, M Glasius, AH Goldstein, E Gomes Alves, H Gomes, D Gu, A Guenther, SH Jathar, S Kim, Y Liu, S Lou, ST Martin, VF McNeill, A Medeiros, SS de Sá, JE Shilling, SR Springston, RAF Souza, JA Thornton, G Isaacman-VanWertz, LD Yee, R Ynoue, RA Zaveri, A Zelenyuk, and C Zhao. 2019. "Urban pollution greatly enhances formation of natural aerosols over the Amazon rainforest." *Nature Communications*, 10(1):1046, https://doi.org/10.1038/s41467-019-08909-4.

Papers Zero In on Southern Great Plains Campaign

In FY2019, the 2016 Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) field campaign at ARM's Southern Great Plains atmospheric observatory produced more significant research.

An article in the May 2019 *Bulletin of the American Meteorological Society (BAMS)* used HI-SCALE data to demonstrate how land use and soil properties influence temperature and humidity with unexpected strength.

In September, the publication *Eos* highlighted another new HI-SCALE paper, which showed that soil moisture plays a crucial role in cumulus cloud formation. The paper appeared in *Journal of Advances in Modeling Earth Systems*.

HI-SCALE's principal investigator, Jerome Fast of Pacific Northwest National Laboratory in Washington state, was the lead author of both papers.

ARM's HI-SCALE field campaign gathered data on meteorological, cloud, and aerosol properties around the Southern Great Plains atmospheric observatory.

During HI-SCALE, researchers looked to gather detailed measurements of processes affecting the life cycle of shallow cumulus clouds. The team deployed airborne and ground instruments during monthlong intensive operational periods in the spring and summer.

References

Fast JD, LK Berg, L Alexander, D Bell, E D'Ambro, J Hubbe, C Kuang, J Liu, C Long, A Matthews, F Mei, R Newsom, M Pekour, T Pinterich, B Schmid, S Schobesberger, J Shilling, JN Smith, S Springston, K Suski, JA Thornton, J Tomlinson, J Wang, H Xiao, and A Zelenyuk. 2019. "Overview of the HI-SCALE field campaign: a new perspective on shallow convective clouds." *Bulletin of the American Meteorological Society*, 100(5):821-840, https://doi.org/10.1175/BAMS-D-18-0030.1.

Fast JD, LK Berg, Z Feng, F Mei, R Newsom, K Sakaguchi, and H Xiao. "The impact of variable land-atmosphere coupling on convective cloud populations observed during the 2016 HI-SCALE field campaign." *Journal of Advances in Modeling Earth Systems*, 11(8):2629-2654, https://doi.org/10.1029/2019MS001727.

Research Highlights

Cloud Radar Data Help Derive Melting-Layer Attenuation at Higher Frequencies

The melting layer is where snowflakes melt into raindrops. It is a relatively narrow layer in precipitation systems, but it has a significant impact on telecommunication and remote-sensing applications.

For spaceborne and ground-based radar measurements, an unaccountable reduction in the amplitude of a signal—known as attenuation—may cause significant errors in retrievals of melting-layer rainfall rate and ice-cloud properties.

Quantifying attenuation in the melting layer in millimeter wavelengths is increasingly important. For instance, radio waves in commercial communications and Earth satellite links often use the higher-frequency bands.

Modeling studies exist in the literature for quantifying attenuation in the melting layer, but there is a shortage of observational studies to constrain the models. A *Journal of Geophysical Research: Atmospheres* study from August 2019 addresses this shortage. Researchers from the University of Helsinki in Finland present a technique for deriving the melting-layer attenuation at Ka and W bands using X-, Ka-, and W-band vertically pointing radar Doppler spectra.

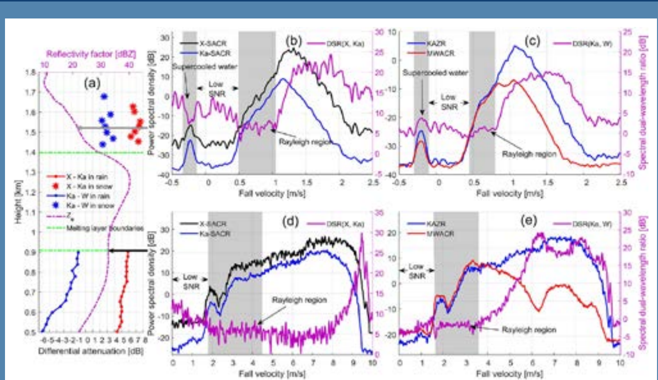
This study—said to be the first to derive melting-layer attenuation at Ka and W bands from cloud radar observations—used multifrequency Doppler spectra observations from ARM's 2014 Biogenic Aerosols – Effects on Clouds and Climate (BAECC) field campaign in Finland. BAECC helped obtain important details on processes related to aerosol, cloud, and snow formation that are not well understood or well represented in earth system models.

The retrieval technique is based on the measurements of differential attenuation, which avoids potential issues such as radar calibration and wet radomes. (A radome is a structure that protects the radar antenna. A wet radome can worsen attenuation.)

Authors Haoran Li and Dmitri Moisseev said that their technique will help advance knowledge of the melting process and improve models of melting-layer attenuation for millimeter-wavelength radars, passive microwave remote sensing, 5G/6G commercial links, and space-Earth telecommunications. However, the authors also pointed to a need for more comprehensive studies of melting-layer properties.

Reference

Li H and D Moisseev. 2019. "Melting layer attenuation at Ka- and W-bands as derived from multifrequency radar Doppler spectra observations." *Journal of Geophysical Research: Atmospheres,* 124(16):9520-9533, https://doi.org/10.1029/2019JD030316.



The gray shading identifies regions of spectra where liquid or solid water particles are scattering light without changing the wavelength. (Copyrighted image from the journal.)

Scanning ARM cloud radar data from the BAECC field campaign in Finland helped researchers derive melting-layer attenuation at Ka and W bands.

Scaling Relationships of Raindrop Size Distributions

A Journal of Applied Meteorology and Climatology study from February 2019 reports a new method for describing the variability of raindrop sizes in precipitation. Setting aside many structural assumptions in existing methods, the new approach uses general mathematical relationships to describe the scaling behavior of the relative proportions of small and large drops.

The authors applied these relationships to long-term disdrometer data from ARM's Southern Great Plains, Eastern North Atlantic, and (now-closed) Tropical Western Pacific atmospheric observatories. Further data came from ARM field campaigns in the Indian Ocean and Finland. The researchers also used a detailed rain microphysics model. Both data and model confirmed the applicability of the scaling relationships.

Hugh Morrison of the National Center for Atmospheric Research led the multi-institutional study.

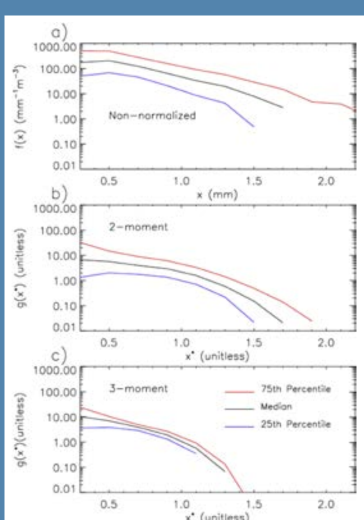
Raindrop size distribution is critical for understanding bulk microphysical process rates such as evaporation. The authors said that their scaling expressions can be used to improve the representation of these processes and to develop retrievals from a set of directly measured bulk quantities. The mathematical method proposed in this study is said to provide the best estimates of the retrieved unknown quantities. It also delivers rigorous estimates of uncertainty, which existing approaches typically lack.

In contrast to previous studies, the researchers derived general scaling expressions for raindrop size distributions from basic mathematical principles. Any "moment" of the distribution, which is a weighted integral of the distribution over drop size, was related to a set of reference moments using generalized power expressions.

The authors said that, unlike previous studies, these scaling expressions are applicable to any number and combination of reference moments.

Reference

Morrison H, MR Kumjian, CP Martinkus, OP Prat, and M van Lier-Walqui. 2019. "A general *N*-moment normalization method for deriving raindrop size distribution scaling relationships." *Journal of Applied Meteorology and Climatology*, 58(2):247-267, https://doi.org/10.1175/JAMC-D-18-0060.1.



Panels show the median (black) and 25th (blue) and 75th (red) percentiles of a) the disdrometer-observed raindrop size distributions, and the normalized distributions applying the new method using b) two and c) three reference moments. (Copyrighted image from the journal.)

Paul Ortega, operations manager for ARM's Eastern North Atlantic atmospheric observatory, points to a two-dimensional video disdrometer as site technician Carlos Sousa observes.

Modeling Rain in Large Storms: Closing the Gaps

A long-standing problem in atmospheric models is underestimating a common form of precipitation: widespread, light-to-moderate stratiform rainfall within large convective storms. (Stratiform rainfall happens when air masses collide and move over each other diagonally or when deep convection humidifies the free troposphere.)

A *Journal of Geophysical Research: Atmospheres* study from January 2019 took on the factors that contribute to these underestimations, which are not well understood. To characterize the underlying bias—offsets from observations—and variability in models, researchers at Pacific Northwest National Laboratory in Washington state led a paper comparing model results with real-world data. They used simulated stratiform precipitation from a convective system formed along a narrow band of high winds and storms called a squall line.

Observational data came from the Midlatitude Continental Convective Clouds Experiment (MC3E), a 2011 ARM-NASA field campaign at ARM's Southern Great Plains atmospheric observatory.

The authors simulated their own squall-line convective system by employing a cloud-resolving model with eight different cloud microphysics schemes. In most of the microphysics schemes, simulations underestimated the total stratiform precipitation. All the schemes underestimated the frequency of moderate stratiform rain rates.

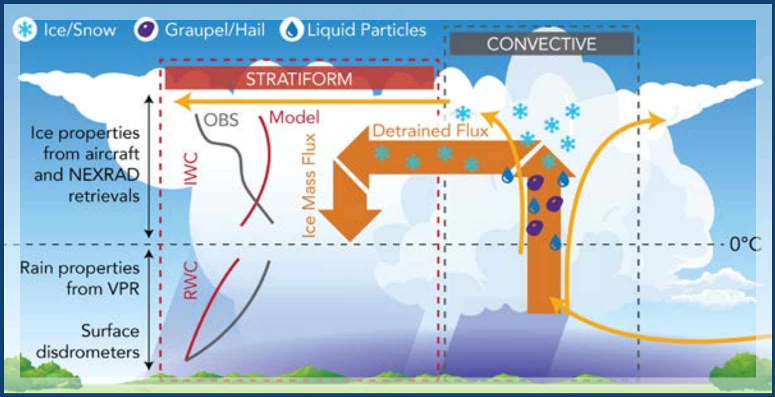
Results showed that, contrary to observations, simulated ice water content decreased as it fell toward the melting level. The authors speculate this is the primary cause of the simulations underestimating the stratiform rainfall rate.

Researchers also found that variability across simulations was primarily caused by different condensate properties detrained—pushed out—from the convective area of the squall-line system.

The authors said that the study illustrates the key role of convective microphysics in determining stratiform properties. It also highlights the need for more measurements of convective motions and microphysics to improve model parameterizations and reduce model biases.

Reference

Han B, J Fan, A Varble, H Morrison, CR Williams, B Chen, X Dong, SE Giangrande, A Khain, E Mansell, JA Milbrandt, J Shpund, and G Thompson. 2019. "Cloud-resolving model intercomparison of an MC3E squall line case: part II. Stratiform precipitation properties." *Journal of Geophysical Research: Atmospheres*, 124(2):1090-1117, https://doi.org/10.1029/2018JD029596.



In a paper comparing modeled and observed precipitation from the MC3E field campaign, simulations (in red) overestimated ice water content (IWC) above 7 kilometers (about 23,000 feet), but they showed a decreasing trend approaching the melting level—the opposite of observations.

Researchers simulated convective clouds observed during an ARM-NASA field campaign in Oklahoma to examine model biases and variability.

Aerosol Seasonal Variations and Key Processes in the Marine Boundary Layer

A December 2018 paper in *Atmospheric Chemistry and Physics* outlines key processes that control the distribution of aerosol sizes in the marine boundary layer. The low clouds there are the dominant type covering the Earth's surface and are sensitive to changes in aerosol conditions.

A team led by researchers at Brookhaven National Laboratory in New York and Washington University in St. Louis also established governing equations for three modes of aerosol concentration and verified them with ARM data. They found that ocean ecosystems had a substantial influence on the supply of aerosols that grew clouds.

Aerosols are small liquid or solid particles that have profound effects on the Earth's energy budget by scattering and absorbing sunlight and by influencing cloud properties. Specifically, the researchers looked at cloud condensation nuclei (CCN), aerosols on which water vapor condenses to form cloud droplets.

CCN concentration influences the number and size of cloud droplets. In turn, the way CCN are distributed influences cloud coverage, cloud albedo (reflectivity), and precipitation.

The paper adds to knowledge of how low clouds respond to changes in aerosol concentration, which is one of the largest uncertainties in earth system simulations.

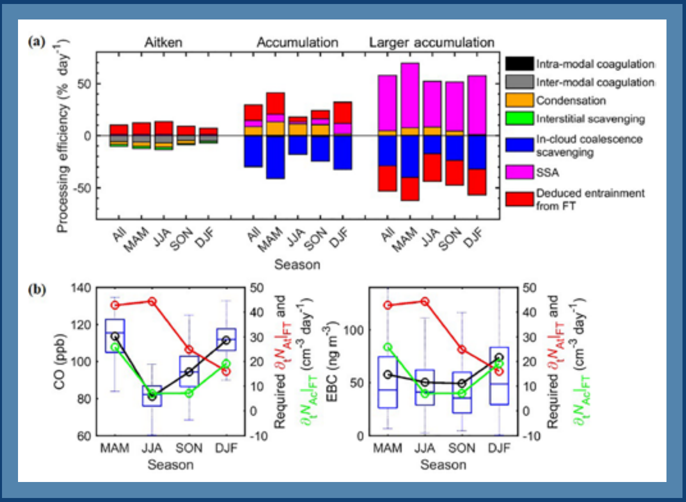
The authors used long-term (2015–2017) measurements from ARM's Eastern North Atlantic atmospheric observatory, which sits in a region of persistent marine boundary-layer clouds. These observations helped the authors verify their proposed governing equations of aerosol number.

Researchers also reported on the importance of small particles from the free troposphere, the area of the atmosphere just above the planetary boundary layer. Results showed that the free troposphere contributed CCN directly, but it also supplied particles that grew into CCN, especially during the summer and fall seasons.

Scientists linked the particle growth to a common chemical signature of ocean ecosystems: the oxidation of dimethyl sulfide, an abundant marine sulfur compound produced from phytoplankton.

Reference

Zheng G, Y Wang, AC Aiken, F Gallo, MP Jensen, P Kollias, C Kuang, E Luke, S Springston, J Uin, R Wood, and J Wang. 2018. "Marine boundary layer aerosol in the eastern North Atlantic: seasonal variations and key controlling processes." *Atmospheric Chemistry and Physics,* 18(23):17615-17635, https://doi.org/10.5194/acp-18-17615-2018.



The graphs show key controlling processes of marine boundary-layer aerosol number concentrations in the Eastern North Atlantic. (Copyrighted image from the journal.)

Marine boundary-layer clouds loom offshore at ARM's Eastern North Atlantic atmospheric observatory.

How Low-Cloud Reflectivity Responds to Warming

As the world warms, how will clouds respond? In particular, how will the reflectivity of low-level clouds, the most predominant in the world, respond to changes in temperature?

Exactly how the optical properties of clouds, including reflectivity, will respond to warming and whether those changes will enhance or counteract warming remain great sources of uncertainty in predicting future warming. In a *Journal of Geophysical Research: Atmospheres* study from February 2019, ARM ground-based observations reinforce previous model and satellite findings—namely that cloud reflectivity increases at colder temperatures and decreases at warmer temperatures.

An analysis of the physical mechanisms driving this behavior, the authors said, provides a basis to assess model performance. It also highlights the importance of competing factors that contribute to the overall change in cloud properties with warming.

To quantify how low-cloud reflectivity responds to changes in temperature, scientists at Lawrence Livermore National Laboratory in California joined colleagues from Colorado State University and the State University of New York at Albany to analyze retrievals of cloud properties from ARM sites in Alaska, Oklahoma, and the Azores.

They also tested whether the observations supported any of the mechanisms in the literature that propose an explanation of what drives the reflectivity response.

Many earth system models predict that the reflectivity of low-level clouds increases with warming in the middle and high latitudes. Specifically, models predict an increase in reflectivity with warming for clouds at colder temperatures (those below freezing) and a decrease in reflectivity with warming for clouds at warmer temperatures. Analyses of satellite retrievals have also found a similar relationship.

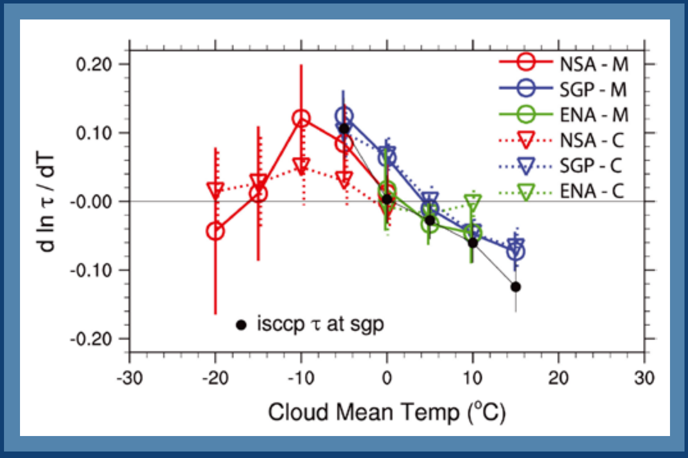
Can the same relationship also be seen in ground-based observations of low-level stratiform clouds? The authors—backed by ARM data—said, “Yes.”

The study’s findings and methods, they said, provide an observational means to constrain model processes behind the cloud response to future warming.

Reference

Terai CR, Y Zhang, SA Klein, MD Zelinka, JC Chiu, and Q Min. 2019. “Mechanisms behind the extratropical stratiform low-cloud optical depth response to temperature in ARM site observations.” *Journal of Geophysical Research: Atmospheres*, 124(4):2127-2147, https://doi.org/10.1029/2018JD029359.

The paper used data on low clouds from ARM sites in Alaska (pictured), the Azores, and Oklahoma.



This figure shows the cloud optical thickness-temperature relationship at multiple ARM sites. (Copyrighted image from the journal.)

Measurements Over Ocean and Land Yield Cloud Edge Insights

The cloud edge is an atmospheric transition zone between cloudy and cloudless skies. This region can be just a few hundred meters or several kilometers wide. It is important for understanding the mechanisms of cloud mixing processes and has strong effects on Earth's energy balance.

Cloud edges are packed with water vapor, cloud droplets, and aerosols that are full of moisture. Scientists need to better understand the variability of cloud and aerosol properties in these transition zones to improve estimates of their impacts on the energy balance and to reduce uncertainties in models related to entrainment and mixing processes.

In a *Journal of Geophysical Research: Atmospheres* paper from July 2019, three NASA researchers advanced the understanding of such radiative forcing by studying the variability of cloud optical thickness and droplet effective radius in cloud edge transition zones. Their observational data came from the ARM shortwave spectroradiometer, which measures visible and near-infrared spectral radiance.

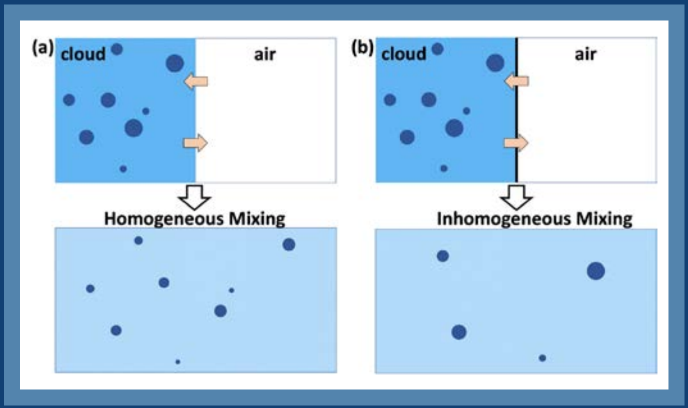
The researchers used 22 cloud edge cases from ARM's Southern Great Plains atmospheric observatory and the 2012–2013 Marine ARM GPCI Investigation of Clouds (MAGIC) field campaign. MAGIC collected cloud data on a ship traveling back and forth across the Pacific Ocean between Hawaii and California.

They employed a method that approximates transition-zone spectra as a linear combination of definitely clear and definitely cloudy spectra. The slope and intercept of the linear relations characterize cloud optical thickness and droplet effective radius in the transition region.

In both observational settings, the researchers found a significant decrease of cloud optical thickness toward cloud edges. However, they also found that the decrease in cloud droplet size was much more significant for clouds over land compared with those over the ocean.

Reference

Yang W, A Marshak, and G Wen. 2019. "Cloud edge properties measured by the ARM shortwave spectrometer over ocean and land." *Journal of Geophysical Research: Atmospheres,* 124(15):8707-8721, https://doi.org/10.1029/2019JD030622.



This schematic illustration shows two limiting scenarios of the air entrainment and mixing processes. (Copyrighted image from the journal.)

The study of cloud edge properties in part relied on data from shipboard instruments used in the MAGIC field campaign.

The Formation of Tarball Particles in Wildfires

Biomass burning events such as wildfires emit enormous amounts of aerosol particles and gases into the atmosphere, significantly influencing regional air quality and earth systems. Moreover, biomass burning emissions are expected to increase as a result of climate change.

Meanwhile, it is becoming increasingly clear that spherical organic aerosol particles called tarballs are a common particle type generated by wildfires and similar events. A September 2019 study in the *Proceedings of the National Academy of Sciences* shows that tarballs form through a combination of chemical and physical changes to primary organic aerosols—a class of volatile species emitted from the biosphere.

The study built on earlier research reported by a group at Brookhaven National Laboratory in New York. That work demonstrated that tarballs are a major component of biomass burning aerosols and are formed through processing primary organic aerosols.

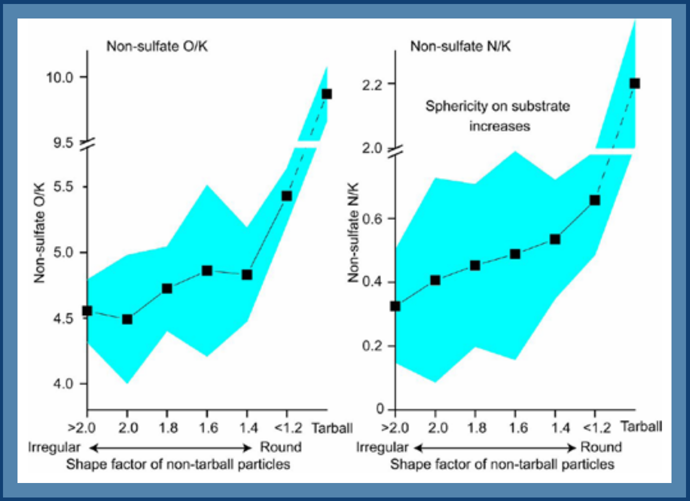
The 2019 study showed that increases in nitrogen and oxygen in aerosols relative to a conserved tracer (elemental potassium) correlated with particle shape, and that this transformation occurred during the first hours after biomass burning aerosol emissions. This correlation suggests that chemical reactions involving nitrogen and oxygen with primary organic aerosols change the particle viscosity and surface tension, resulting in tarballs.

The study used transmission electron microscopy of organic aerosols collected in a 2013 ARM field campaign called the Biomass Burning Observation Project (BBOP). Results showed that the presence of tarballs increased with distance from a wildfire and that this increase in distance was tied to a change in composition.

The authors said that the abundance of tarballs generated by wildfires dictates that scientists should quantify the chemical, microphysical, and optical properties of these particles better. If so, the contributions of tarballs to aerosol energy balance can be better understood and constrained in earth system models.

Reference

Adachi K, AJ Sedlacek III, L Kleinman, SR Springston, J Wang, D Chand, JM Hubbe, JE Shilling, TB Onasch, T Kinase, K Sakata, Y Takahashi, and PR Buseck. 2019. "Spherical tarball particles form through rapid chemical and physical changes of organic matter in biomass-burning smoke." *Proceedings of the National Academy of Sciences,* 116(39):19336-19341, https://doi.org/10.1073/pnas.1900129116.



The graphs show increases of nonsulfate ratios of oxygen and nitrogen relative to potassium (O/K and N/K) as particle shapes become more spherical. (Copyrighted image from the journal.)

During ARM's Biomass Burning Observation Project (BBOP) in 2013, the G-1 research aircraft flew over the Cascade Mountains in Washington state, approaching a wildfire on the horizon.

A 4-Dimensional View of Clouds Produces Unique Data

The speeds at which clouds rise through the atmosphere are hard to pin down, but they are critical to determining cloud behavior. These so-called updraft speeds affect precipitation, aerosol mixing, and even how often lightning strikes.

A new variation on an established measurement technology called stereophotogrammetry may help solve the updraft-speed puzzle.

Researchers at Lawrence Berkeley National Laboratory and the University of California, Berkeley, tested a multiview technique that captures novel images of shallow clouds from all sides. Details appeared in the December 2018 *Bulletin of the American Meteorological Society* (BAMS).

The dynamics of clouds, such as those seen at ARM's Southern Great Plains atmospheric observatory, are hard to measure. A new technique will help.

At ARM's Southern Great Plains atmospheric observatory, researchers set up three pairs of cameras in a triangular array, spaced at 500 meters (about 1,600 feet). Together, the cameras provided a four-dimensional (4D) gridded stereoscopic view of shallow clouds. This information was processed into a unique data set on the sizes, lifetimes, and life cycles of those clouds.

Reference

Romps DM and R Öktem. 2018. "Observing clouds in 4D with multiview stereogrammetry." *Bulletin of the American Meteorological Society*, 99(12):2575-2586, https://doi.org/10.1175/BAMS-D-18-0029.1.

Research Team Solves Old Puzzle About Rain and Agriculture

University of Arizona researcher Xubin Zeng co-wrote a paper in *Geophysical Research Letters* that he said demonstrated "the substantial scientific value" of data from ARM's Southern Great Plains atmospheric observatory.

Zeng and lead author Joshua Welty, a doctoral student at Arizona, quantified the relationship between soil moisture and how precipitation amplifies over the Central Great Plains. They tapped Southern Great Plains data from 2002 to 2011 to link morning soil moisture to afternoon rainfall accumulations.

Both dry and wet morning soils can signal heavier afternoon rain during summer months, but dry morning soils will do that only on days when regional moisture is limited. Moist morning soils signal afternoon rain only on days with a strong regional convergence of atmospheric water vapor.

A summer storm begins to gather at ARM's Southern Great Plains atmospheric observatory.

Methods developed in the paper could be applied to other types of data that might someday inform large-scale earth system models. "There is exciting potential for global analysis," said Welty.

Reference

Welty J and X Zeng. 2018. "Does soil moisture affect warm season precipitation over the Southern Great Plains?" *Geophysical Research Letters*, 45(15):7866-7873, https://doi.org/10.1029/2018GL078598.

New Directions in Cloud Modeling With the LASSO Workflow

The Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) workflow is an ARM simulation library that complements observational data and provides insight into cumulus cloud distribution. LASSO combines supercomputing resources with measurements from area-covering and vertically pointing instruments at ARM's Southern Great Plains atmospheric observatory.

LASSO's 78 case dates so far, with an LES ensemble for each date, focus on shallow convective clouds. They are the visual manifestation of vertical updrafts that bring heat and moisture from Earth's surface into the cooler atmosphere.

In FY2019, William Gustafson, LASSO principal investigator from Pacific Northwest National Laboratory in Washington state, and Andrew Vogelmann, co-principal investigator from Brookhaven National Laboratory in New York, led a workshop considering four other cloud regimes for inclusion in LASSO. The workshop report was published in September.

In FY2019, the LASSO team considered proposed scenarios for expanding LASSO beyond shallow convection at ARM's Southern Great Plains atmospheric observatory.

Meanwhile, three new examples of LASSO-related research emerged.

In late 2018, Vogelmann and others reported on work to improve the representation of vertical velocity at the cloud base. To shrink the gap between observations and models, the team uses routine simulations from LASSO and data from Doppler lidars, which can "see" winds when there are no clouds.

In January 2019, Cleveland State University's Thijs Heus and others reported using LASSO to make a model that reproduces cloud-size distributions close to those found in nature. Heus said that LASSO provides "a big database of cumulus clouds, for statistical power."

In May 2019, Heus published a *Journal of Atmospheric Sciences* study with Roel A.J. Neggers and Philipp J. Griewank from the University of Cologne in Germany. The paper used five LASSO cases to investigate the spatial structure of cumulus cloud populations. (A sixth case, from elsewhere, looked at more slowly organizing marine precipitating clouds.) The study provided a new way to estimate the degree of organization in simulated or observed cumulus cloud populations.

References

Gustafson WI, AM Vogelmann, and JH Mather. 2019. *Science Drivers and Proposed Modeling Approaches for Future LASSO Scenarios*. DOE Atmospheric Radiation Measurement (ARM) user facility. DOE/SC-ARM-19-023.

Neggers RAJ, PJ Griewank, and T Heus. 2019. "Power-law scaling in the internal variability of cumulus cloud size distributions due to subsampling and spatial organization." *Journal of the Atmospheric Sciences*, 76(6):1489-1503, https://doi.org/10.1175/JAS-D-18-0194.1.

Advancing **Capabilities**

Infrastructure Achievements

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

ARM Retires Long-Serving Aircraft, Lands New Laboratory in the Sky

In late 2018, the ARM Aerial Facility retired its Grumman Gulfstream-159 (G-1) turboprop aircraft, which, for three decades, helped advance atmospheric research in field campaigns across the world. ARM then purchased its replacement, a Bombardier Challenger 850 regional jet.

Despite entering service in 1998, the Challenger 850 is "virtually new," having logged less than 5,500 airframe/engine hours and less than 2,600 takeoffs and landings, said ARM Aerial Facility Manager Beat Schmid. This larger airplane "means we will have the ability to carry more instruments and more researchers," he added.

"This is a big step forward in ARM's data collection capabilities."

—Beat Schmid, ARM Aerial Facility Manager from Pacific Northwest National Laboratory, about ARM's new plane

The new jet also has a much greater geographic range and improved flight performance. The plane's maximum altitude is 41,000 feet, doubling previous heights reached by the G-1.

"This is a big step forward in ARM's data collection capabilities," said Schmid. "It will allow us to offer the science community additional types of aerial sampling, the power to climb and descend more quickly within desired areas of interest, and the ability to fly much higher. For example, we will now be able to sample high cirrus clouds."

The Challenger 850 will be modified from its business jet configuration to accommodate ARM instrumentation. During that time, pilots and maintenance staff will be trained. The jet is expected to be ready for its first ARM campaign by the end of 2022.

The ARM Aerial Facility's new Bombardier Challenger 850 will expand scientific data collection capabilities.

ARM Data Center Moves Forward on FY2019 Priorities

The ARM Data Center remained busy in FY2019, archiving and delivering about 20 terabytes of data per month. Staff also worked on projects to improve the ARM data user experience, including a new version of ARM's Data Discovery browser that will be available in FY2020.

Giri Prakash, ARM Data Services manager at Oak Ridge National Laboratory in Tennessee, said that feedback from users and the 2017 Triennial Review spurred the Data Discovery overhaul.

"All this led us to go back to the drawing board," said Prakash, "and we wanted to start fresh to ensure we give the best experience to the users."

Meanwhile, the ARM Data Center enhanced usage of its high-performance computing clusters, Stratus and Cumulus.

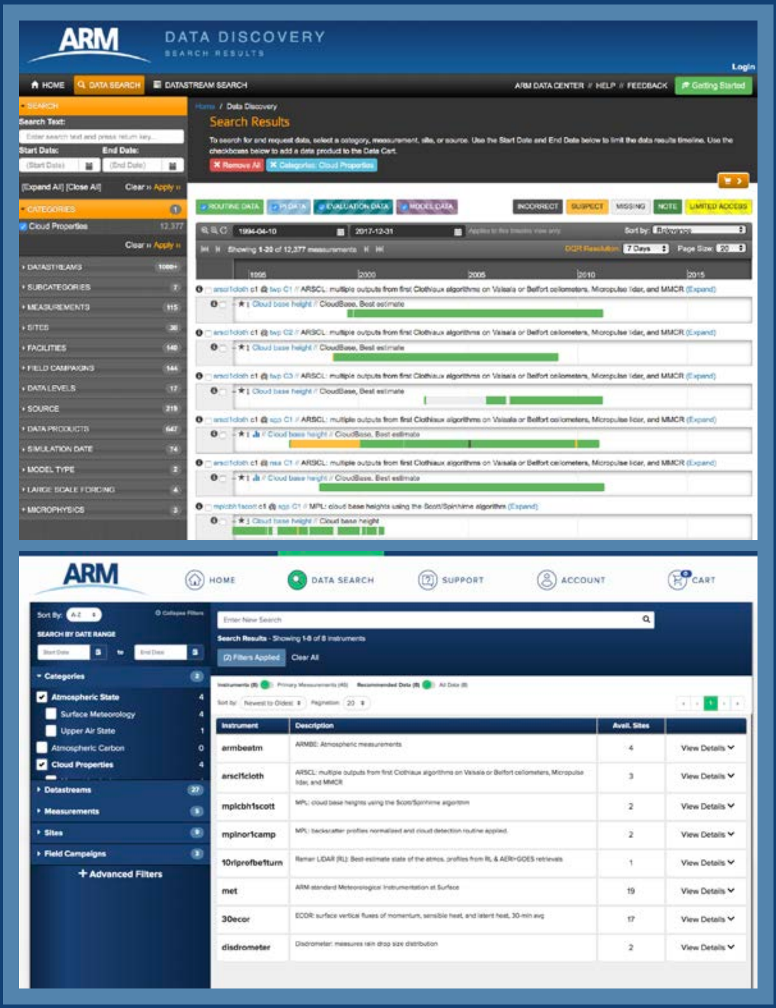
"We wanted to start fresh to ensure we give the best experience to the users."

—Giri Prakash, ARM Data Services Manager from Oak Ridge National Laboratory, sharing the debut of the new Data Discovery browser

Users can remotely access, develop, and run code on a cluster via Jupyter notebook, an open-source application.

Also, the new Atmospheric Emitted Radiance Interferometer Optimal Estimation (AERIOE) value-added product (VAP) is now running on Stratus. AERIOE is the first VAP to run in routine operational mode on a cluster.

Stratus allows the VAP to finish runs in six hours versus 3,888 on a traditional system, said Jitu Kumar, ARM Data Center high-performance computing lead.



Search results are shown in the current version of Data Discovery (top) and the new version.

A Team Effort: ARM Contributes to Science on Ice

In September 2019 in Tromsø, Norway, ARM staff installed advanced atmospheric instruments on the German icebreaker *R/V Polarstern* for the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition.

Through October 2020, scientists from 20 countries are investigating the causes and consequences of diminished ice cover in the Arctic. The *Polarstern*, frozen into pack ice and drifting past the North Pole, is the main observatory for logging atmospheric, ice, oceanic, and ecosystem conditions.

DOE, the first U.S. funding agency to support MOSAiC, supports the deployed ARM instruments and is funding researchers through Atmospheric System Research (ASR) and the Early Career Research Program.

ARM will likely collect "far more data than any other MOSAiC participant."

—Matthew Shupe, ARM's MOSAiC lead scientist from University of Colorado

In April 2019, an ARM team beta-tested MOSAiC instruments at Los Alamos National Laboratory in New Mexico. The instruments are operating on the *Polarstern* as part of "an unprecedented cloud observatory" for arctic science, said Matthew Shupe, a co-coordinating scientist for MOSAiC. ARM instruments include a precipitation suite, three radiation suites, meteorological instruments, and the first scanning cloud radar deployed in the arctic ice pack.

By campaign's end, said Shupe, ARM will likely collect "far more data than any other MOSAiC participant."

ARM technicians and others made sure ARM instruments were safely installed and functioning on the *R/V Polarstern* before the MOSAiC field campaign.

A New ARM Pilot Signs Up

In November 2018, Jennifer Armstrong co-piloted ARM's Gulfstream-159 (G-1) research aircraft on its final campaign.

Armstrong, a 12-year pilot, was the first woman to fly the G-1 for ARM. The aircraft was retired after the Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in Argentina.

Armstrong has flown for more than a decade with the Alaska Air National Guard, including combat deployments.

In 2014, Armstrong started working with ARM, testing one of its unmanned aerial system platforms. Of piloting the G-1 during CACTI, she said: "It's a good fit for me—not just flying, but flying for a greater cause."

Jennifer Armstrong made ARM history as the first woman to pilot its G-1 research aircraft.

New Data Products

Precipitation Value-Added Product Rolled Out for Laser Disdrometers

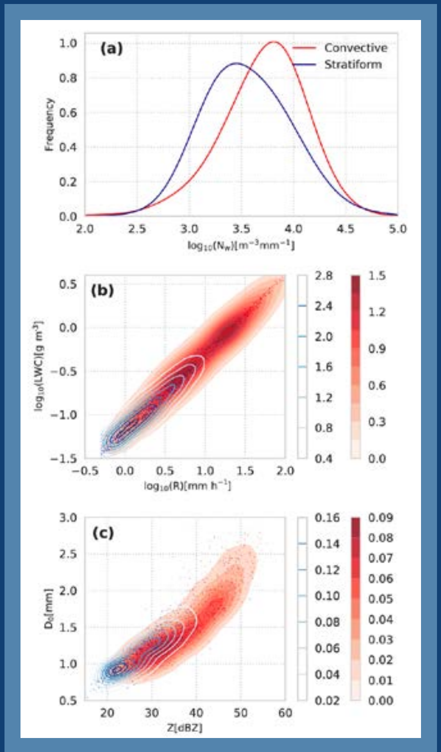
In FY2019, ARM released a precipitation value-added product (VAP), the Laser Disdrometer VAP for Quality-Controlled Measurements, using PyDSD (LDQUANTS). This VAP provides quality-controlled disdrometer measurements of drop size distributions (DSDs), rain rates, and polarimetric radar-equivalent quantities.

Implementations of the algorithms are from PyDisdrometer (PyDSD), an open-source Python library for working with disdrometer data.

DSD measurements from laser disdrometers can be used to estimate key precipitation properties, including the rainfall rate, number concentration of drops, and mean raindrop size information. For these quantities to be useful in model evaluation, radar monitoring, or other activities, disdrometer data sets require careful quality control and processing. LDQUANTS uses standard methods adapted from existing literature to filter spurious drops and extract important microphysical quantities of parameterized DSDs.

In support of radar-based research interests and monitoring, this VAP also estimates radar-equivalent dual-polarization quantities (e.g., Reflectivity Factor Z, Differential Reflectivity ZDR). LDQUANTS computes these quantities by using the T-matrix scattering technique and several wavelength, temperature, and drop shape assumptions.

LDQUANTS is available for the Green Ocean Amazon (GoAmazon2014/15) and Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaigns, and routine laser disdrometer data collection at ARM's Southern Great Plains and Eastern North Atlantic atmospheric observatories.



Histograms of quantities associated with convective (red) and stratiform (blue) drop size distributions (DSDs) in terms of normalized DSD intercept parameter N_w (a), liquid water content LWC versus rainfall rate R (b), and median drop size D_0 versus S-band Reflectivity Factor Z (c). Density is shown on the color scale.

Reference: Wang D, SE Giangrande, MJ Bartholomew, J Hardin, Z Feng, R Thalman, and LAT Machado. 2018. "The Green Ocean: precipitation insights from the GoAmazon2014/5 experiment." *Atmospheric Chemistry and Physics*, 18(12):9121-9145, https://doi.org/10.5194/acp-18-9121-2018.

New Value-Added Product Available for Atmospheric Emitted Radiance Interferometer

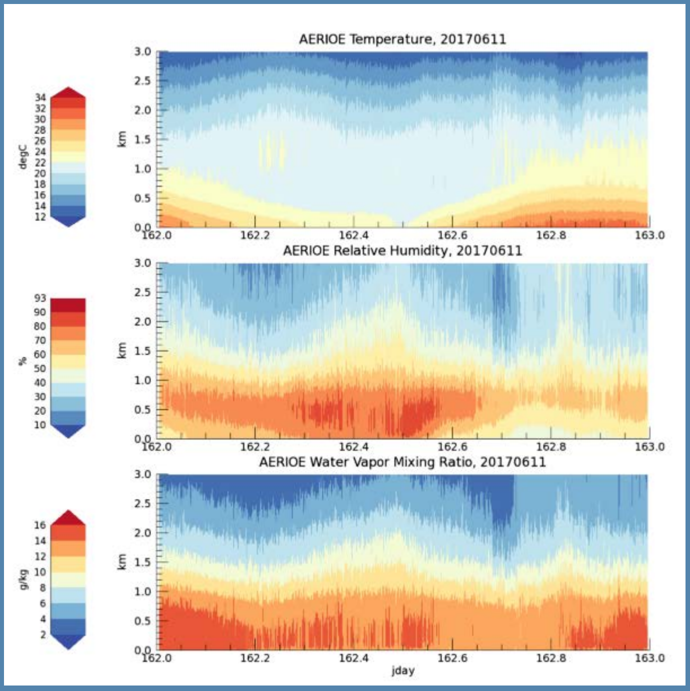
Providing boundary-layer profiles of temperature and water vapor mixing ratio and liquid cloud retrievals, the Atmospheric Emitted Radiance Interferometer Optimal Estimation (AERIOE) value-added product (VAP) debuted in FY2019.

AERIOE helps retrieve profiles in both clear and cloudy conditions so users can better understand the processes taking place in the boundary layer. The high-time-resolution retrievals of boundary-layer thermodynamic profiles provide new information about the evolution of the boundary layer that is difficult to measure. Improved liquid water path retrievals in optically thin clouds allow users to better quantify microphysical properties in clouds such as shallow cumulus.

The AERIOE retrieval algorithm uses an optimal estimation framework to derive cloud and thermodynamic profiles using AERI radiances and additional inputs. The current version of the AERIOE VAP, which has produced data starting from April 2019 at ARM's Southern Great Plains atmospheric observatory, includes:

- microwave radiometer brightness temperatures to better constrain liquid water path and precipitable water vapor
- surface meteorological measurements to constrain thermodynamic profiles
- Rapid Refresh model output to constrain thermodynamic profiles in the upper atmosphere.

The retrieval delivers boundary-layer profiles of temperature and humidity at the native temporal resolution of the AERI, or approximately every 20 seconds.



The figure shows a time series of temperature, relative humidity, and water vapor mixing ratios retrieved from AERIOE. Retrievals are from ARM's Southern Great Plains Central Facility on June 11, 2017.

VAP to Detect Shallow Cumulus Cloud Events Announced

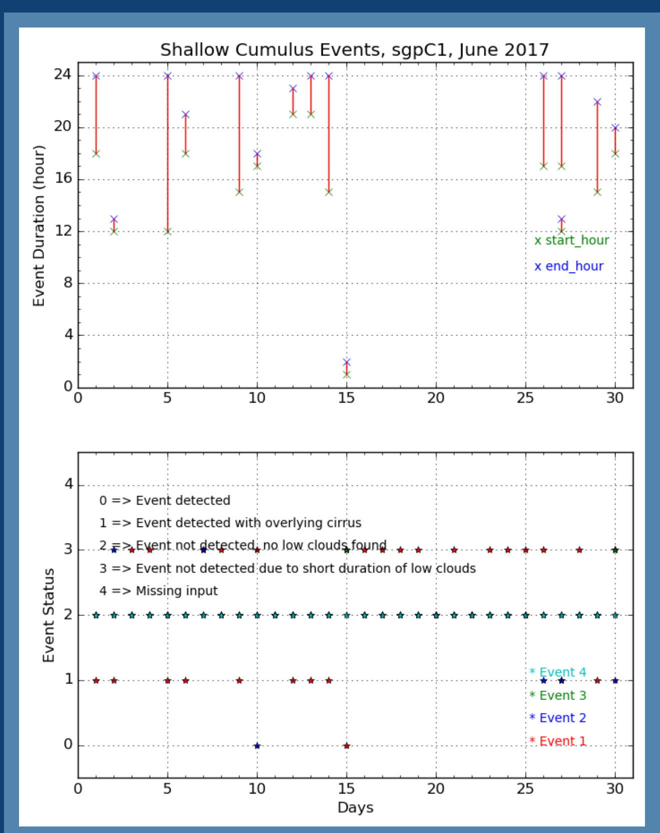
Announced in FY2019, the Shallow Cumulus value-added product (VAP) was developed to identify potential cases of interest for the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) workflow. This VAP automatically detects periods of shallow cumulus clouds using information from vertically pointing active sensors and the total sky imager, which measures the fraction of sky covered by clouds.

Data are available for ARM's Southern Great Plains atmospheric observatory from 2000 to 2019.

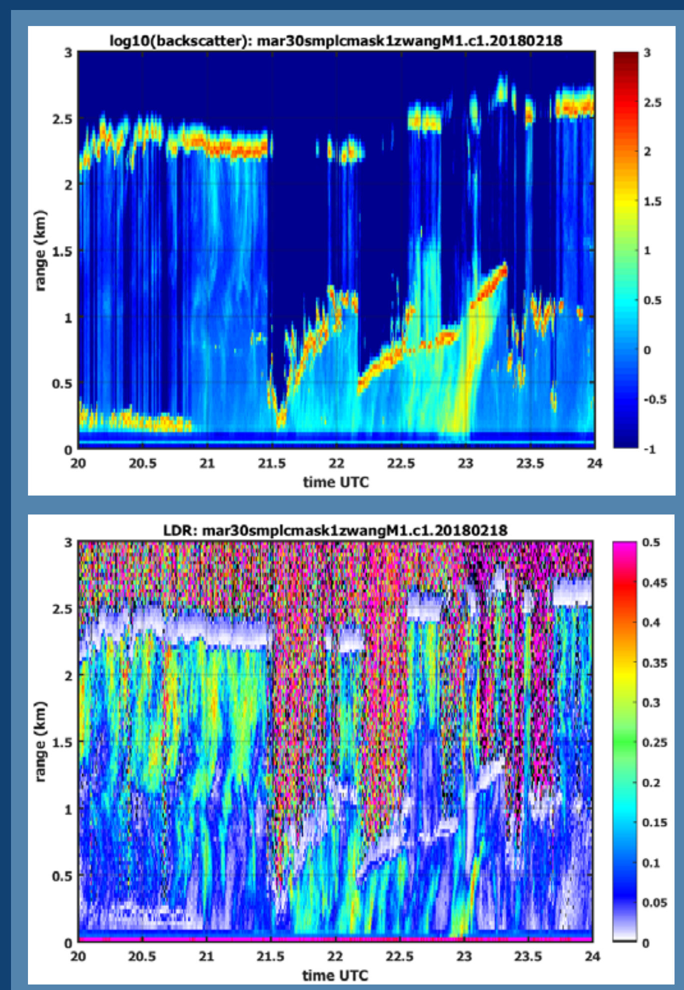
This VAP classifies events as shallow cumulus when low clouds are detected for at least 1.5 hours and meet specified criteria for cloud occurrence and cloud fraction. It also identifies cases with overlying cirrus or transitions to and from different cloud types.

The Shallow Cumulus VAP produces two kinds of files. Daily files detail which criteria a time period failed or passed to be identified as a shallow cumulus event. Monthly summary files provide a view of what hours contained shallow cumulus events during the month.

Inputs for the Shallow Cumulus VAP include the Cloud Type Classification (CLDTYPE) VAP, which classifies clouds using cloud boundaries from the Active Remote Sensing of Clouds (ARSCL) VAP, and cloud fraction from the total sky imager and ceilometer.



These plots provide data about shallow cumulus events at ARM's Southern Great Plains Central Facility in June 2017. The top panel shows days with shallow cumulus events. The bottom panel gives more information for up to four events.



Sample MPLCMASK plots from the MARCUS deployment show the backscatter (top) and the linear depolarization ratio (LDR, bottom) for a selected range and Coordinated Universal Time (UTC) on February 18, 2018.

Making Mobile Data Products a Priority

In FY2019, ARM prioritized the processing of data from research campaigns using ARM Mobile Facilities to produce value-added products (VAPs). ARM staff processed 10 data products for seven recent field campaign deployments.

- A pair of VAPs produced evaluation data for the Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS, 2017–2018) field campaign. The 95 GHz W-Band ARM Cloud Radar-Active Remote Sensing of Clouds (WACR-ARSCL) VAP provides cloud boundaries and best-estimate time-height fields of radar moments. The Micropulse Lidar Cloud Mask (MPLCMASK) VAP delivers cloud boundary data that are useful for identifying cloud base height and cloud thickness in optically thin clouds.
- Two VAPs were made available for both the ARM West Antarctic Radiation Experiment (AWARE, 2015–2017) and Layered Atlantic Smoke Interactions with Clouds (LASIC, 2016–2017) field campaigns. The Data Quality Assessment for ARM Radiation Data (QCRAD) VAP has long been ARM's recommended datastream for broadband surface irradiance measurements. The Microwave Radiometer Retrievals (MWRRET) VAP retrieves column precipitable water vapor and liquid water path—both important variables to understanding radiative transfer in the atmosphere and clouds—from ARM's 2-channel microwave radiometers.
- Large-scale forcing data using a constrained variational analysis approach (VARANAL) were updated for the ARM Madden-Julian Oscillation (MJO) Investigation Experiment on Gan Island (AMIE-Gan, 2011–2012) and Green Ocean Amazon (GoAmazon2014/15) field campaigns.
- The Scanning ARM Cloud Radar-Advanced-Velocity Azimuth Display (SACR-ADV-VAD) VAP moved into production for the Two-Column Aerosol Project (TCAP, 2012–2013) and Biogenic Aerosols – Effects on Clouds and Climate (BAECC, 2014) field campaigns. SACR-ADV-VAD provides profiles of horizontal wind estimates at cloud level.

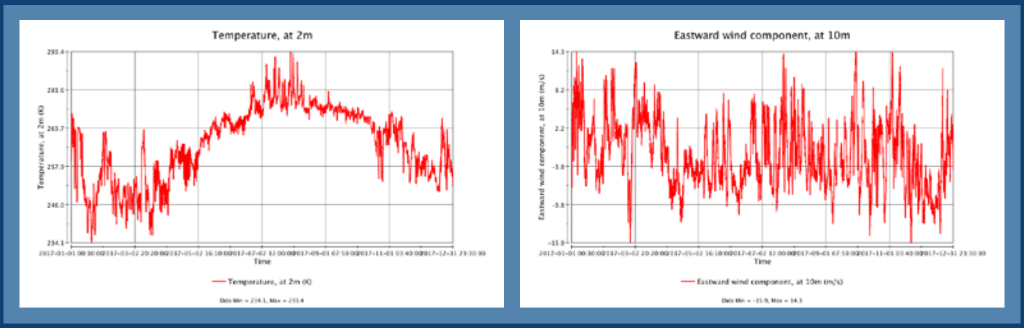
These data efforts were in response to recommendations from the 2017 ARM Triennial Review, a high-level review conducted by DOE with external reviewers every three years to ensure scientific and program management performance.

ARM Best Estimate Data Products Grow for North Slope of Alaska

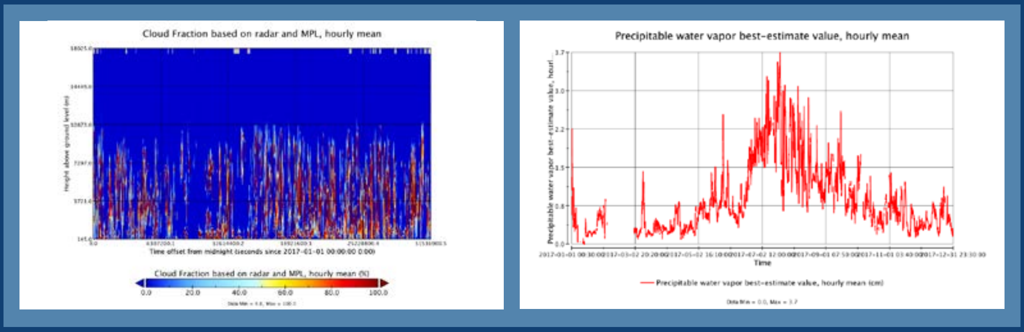
ARM provides tailored datastreams known as ARM Best Estimate (ARMBE) data products. ARMBE products contain best estimates of several cloud, radiation, and atmospheric quantities that are often used to evaluate global earth system models.

In FY2019, two ARMBE data sets expanded for the North Slope of Alaska atmospheric observatory. The ARM Best Estimate Atmospheric Measurements (ARMBEATM) product added data from 2013 to 2018, while the ARM Best Estimate Cloud Radiation (ARMBECLDRAD) data set grew to include the years 2004 to 2018.

Data are averaged over a one-hour time interval comparable to a typical resolution used in model output.



The images show ARMBEATM 2-meter temperature (left) and 10-meter zonal wind (right) for ARM's North Slope of Alaska atmospheric observatory in 2017.



The images show ARMBECLDRAD cloud fraction (left) and precipitable water (right, unit: cm) from 2017 at ARM's North Slope of Alaska atmospheric observatory.

Science Outreach

ARM Teams Up With DOE Partners for Aerosol Summer School

In July 2019, ARM co-sponsored the 2019 Aerosol Summer School with DOE's Environmental Molecular Sciences Laboratory (EMSL) and Atmospheric System Research (ASR) program.

Students attending the summer school at Pacific Northwest National Laboratory in Washington state ranged from a post-bachelor's research associate to postdoctoral researchers.

The curriculum focused on aerosols and their effects on earth systems. During lectures and lab demonstrations, students learned about aerosol composition, properties, theory, measurements, and modeling.

ARM and EMSL—both DOE scientific user facilities—served as co-hosts. ARM and EMSL staff and users, including several ASR-funded principal investigators, prepared and taught the material.

"There's definitely this new element of training a next generation in the science, but also training them in how to engage with these facilities to do the science."

—Jim Mather, ARM Technical Director from Pacific Northwest National Laboratory

The class consisted of 25 students from the United States, Canada, Germany, and India. Selected out of 126 applicants, the students came from diverse research areas and courses of study, including atmospheric science, physics, chemistry, and engineering.

The aerosol school took place a year after ARM's second Summer Training and Science Applications event on observations and modeling of clouds and precipitation.

"With the ARM workshop and this one," said ARM Technical Director Jim Mather, "there's definitely this new element of training a next generation in the science, but also training them in how to engage with these facilities to do the science."

Jason Tomlinson, ARM Aerial Facility engineering manager, points out part of an aircraft probe to students during the 2019 Aerosol Summer School.

ARM Data Services Manager Represents ARM Around the World

During FY2019, ARM Data Services Manager Giri Prakash represented ARM at several international data and computing architecture working group meetings and conferences.

In November 2018, Prakash went to SciDataCon as part of International Data Week in Gaborone, Botswana, where he gave an invited talk, "A Modern Data Center Architecture to Enable Next Generation Data Science." He also co-chaired the session "A Survey on the Impact of Data Citation Practices in Research."

Later that month, he participated in international data system discussion at the Polar Data and Systems Architecture Workshop in Geneva, Switzerland.

Also, Prakash worked to make ARM data visible to the hundreds of researchers participating in the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) field campaign, which began in September 2019.

Working with Germany's Alfred Wegener Institute, which leads MOSAiC, and the campaign's central office, Prakash and ARM Data Center staff registered ARM MOSAiC metadata with the campaign's central data portal, SensorWeb. Using the portal, scientists can find ARM data and a link to download the data through ARM's Data Discovery browser.

ARM Technical Director Connects With University Community

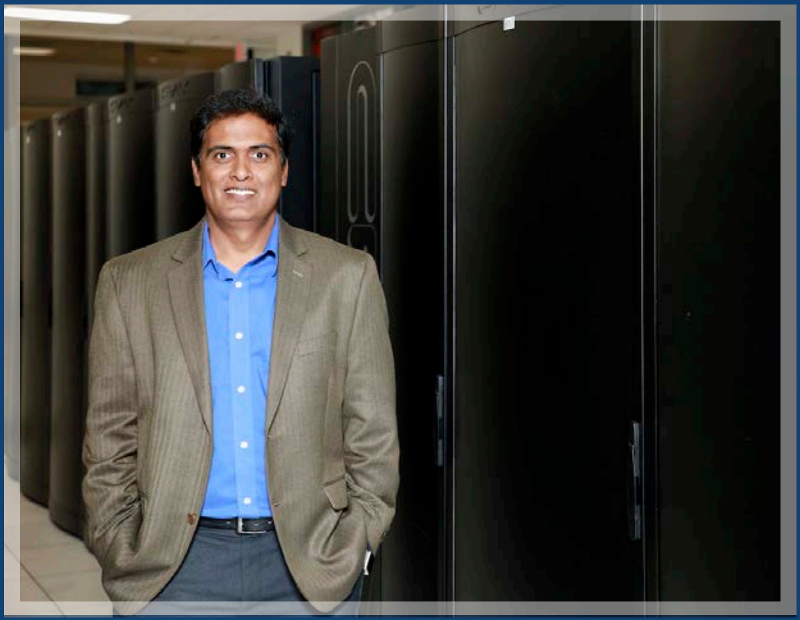
ARM Technical Director Jim Mather traveled to Boulder, Colorado, in October 2018 to be a breakout session presenter at the University Corporation for Atmospheric Research (UCAR) Annual Meeting. The breakout sessions highlighted federal organizations that help make science happen by providing resources to researchers.

The UCAR annual meeting brings together member representatives to discuss topics of importance to the university research and education community.

Attending his first UCAR annual meeting, Mather gave a tutorial on engaging with ARM to about 50 people representing atmospheric science departments around the country. His tutorial included information about ARM field campaigns, instruments, and data access.

Representatives from the National Science Foundation, NASA, and the National Oceanic and Atmospheric Administration also presented overviews of their organizations.

After Mather's tutorial, ARM was asked back for the October 2019 UCAR annual meeting.



ARM Data Services Manager Giri Prakash stands in front of Cumulus, one of the ARM Data Center's two high-performance computing clusters.

Budget Summary **and Facility Usage**

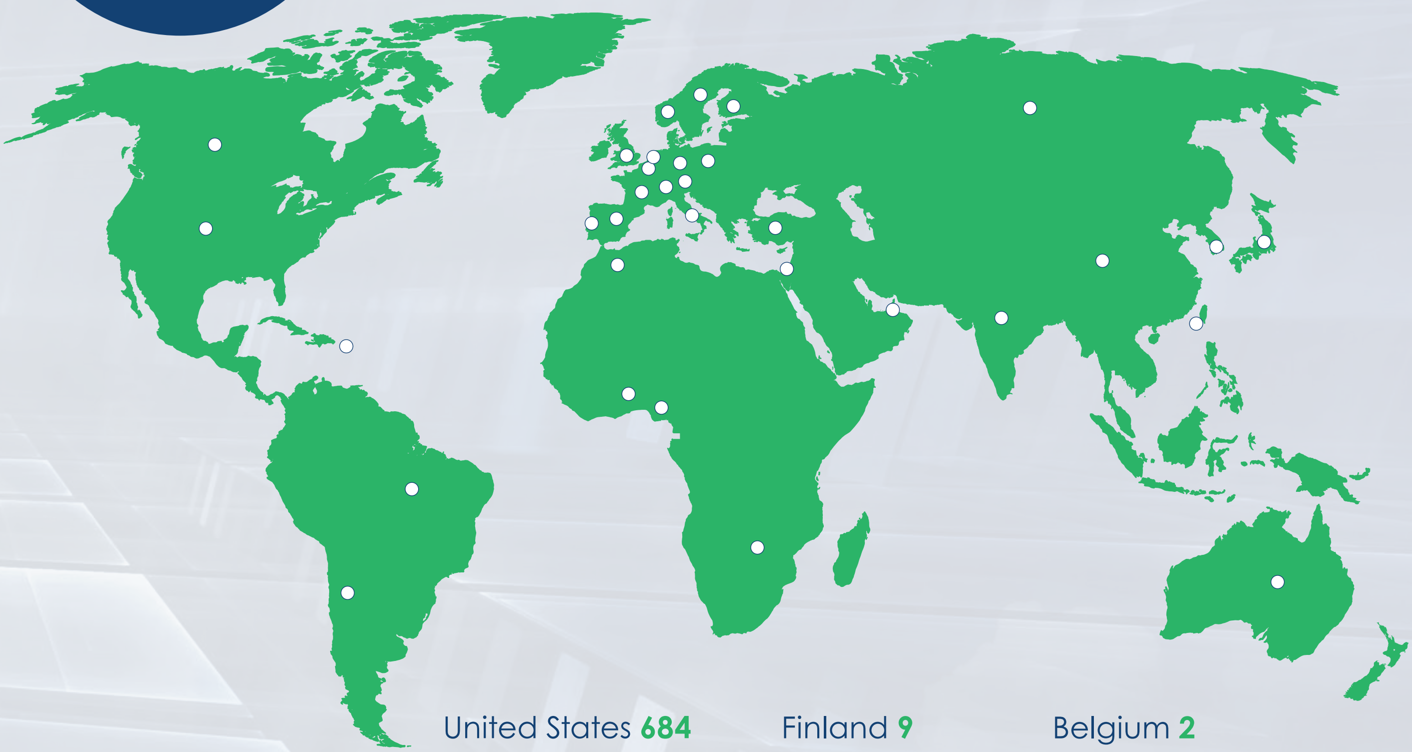
Fiscal Year 2019 Statistical Overview

INFRASTRUCTURE BUDGET

$67,499K

980
TOTAL SCIENTIFIC USERS

USERS BY COUNTRY



United States **684**
China **63**
United Kingdom **39**
Germany **29**
Brazil **29**
India **16**
Canada **13**
France **13**
Australia **12**
South Korea **12**
Nigeria **10**
Finland **9**
Portugal **7**
Argentina **6**
Israel **4**
Spain **4**
Taiwan **3**
Japan **3**
Poland **3**
Sweden **3**
Italy **2**
Netherlands **2**
Belgium **2**
Russia **2**
United Arab Emirates **2**
Switzerland **1**
Norway **1**
Algeria **1**
Austria **1**
Cameroon **1**
Zimbabwe **1**
Puerto Rico **1**
Turkey **1**

33
Countries

USER STATISTICS

University	410	42%
Foreign	266	27%
DOE Labs	164	17%
Other Fed	87	9%
Industrial	53	5%

FACILITY USAGE

Onsite	183	19%
Remote	52	5%
Data	745	76%

PUBLICATIONS USING ARM*

617 TOTAL

ABSTRACTS OR PRESENTATIONS	310
TECHNICAL REPORTS	48
BOOKS	3
BOOK CHAPTER	1
JOURNAL ARTICLES	218
CONFERENCE PAPERS	37

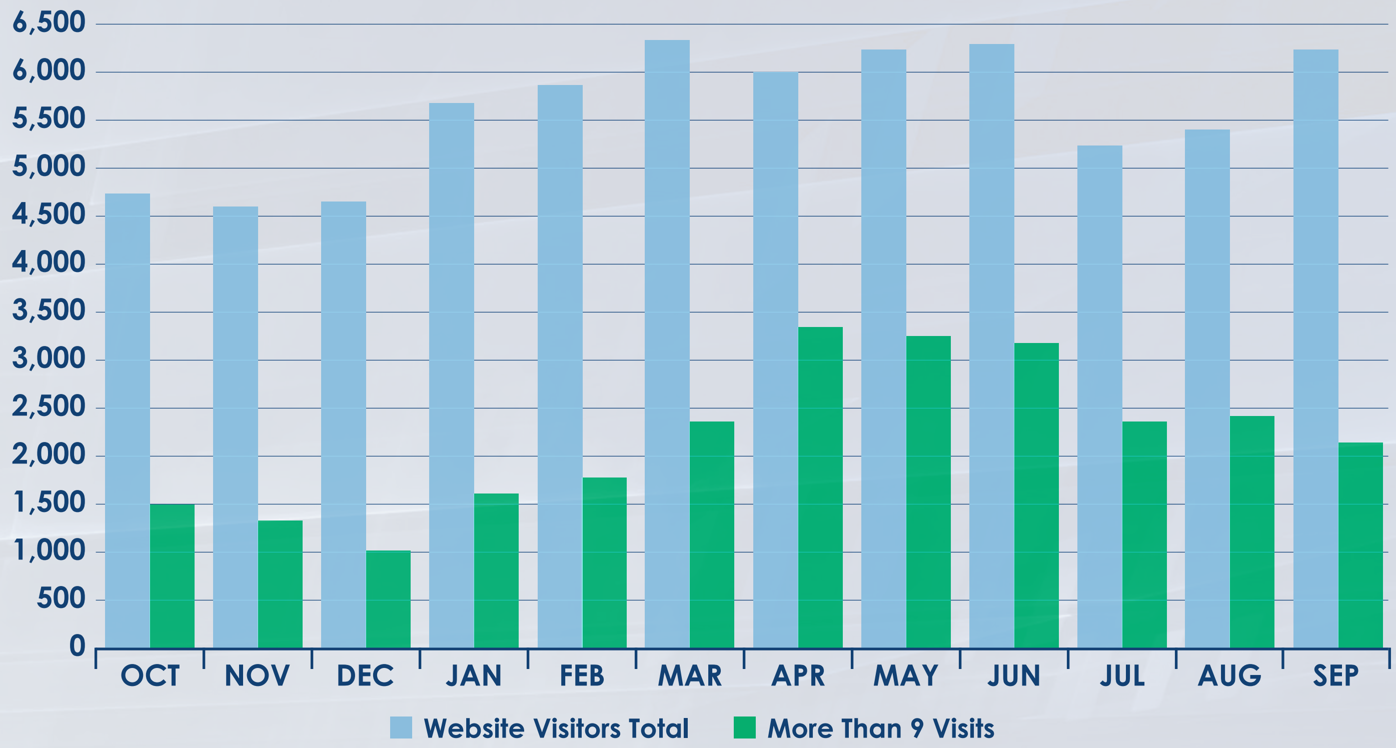
400+ Instruments Collect Atmospheric Data

6,000+ Publicly Available Datastreams

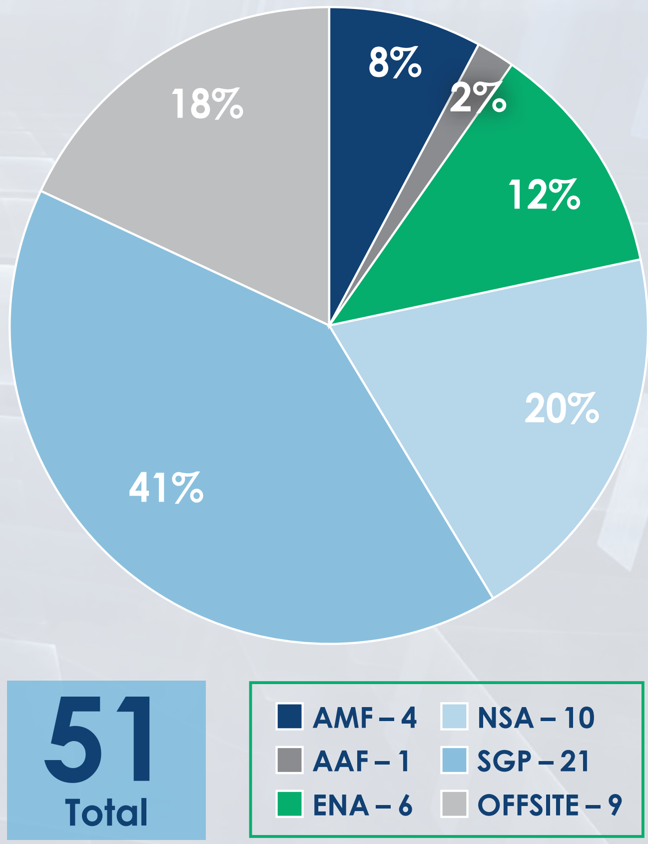
~4,000 Journal Articles Since 1990

*Publication statistics were collected as of January 2020. Journal article numbers will continue to increase over time.

WEBSITE VISITORS



FIELD CAMPAIGNS



VALUE-ADDED PRODUCTS

5 released to operations

- CMAC2
- LCL
- LDQUANTS
- OKMSOIL
- AERIOE

6 released to evaluation

- MWRRETv2
- WACRARSCL
- MPLCMASK
- ARMBECLDRAD
- ARMBEATM
- VARANAL

7 approved for development

- KAZRCOR
- KAZRARSCL
- CSPHOT
- LASSO-O
- New calibration product for ARSCL suite
- MPLCOR
- MPLCMASKML

13 existing VAPs updated

- MFRAOD
- QCRAD
- AERIOE
- DLPROF_WIND
- LANGLEY
- MWRRET
- SHALLOWCUMULUS
- RLPROFMR2
- RLPROFTEMP2
- QCECOR
- LASSOLCL
- RLPROF_CALIB
- MPLCMASK

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

From the Gulfstream-159 research aircraft, ARM staff caught an in-flight view of clouds and Argentina's Sierras de Córdoba mountain range during the 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign.

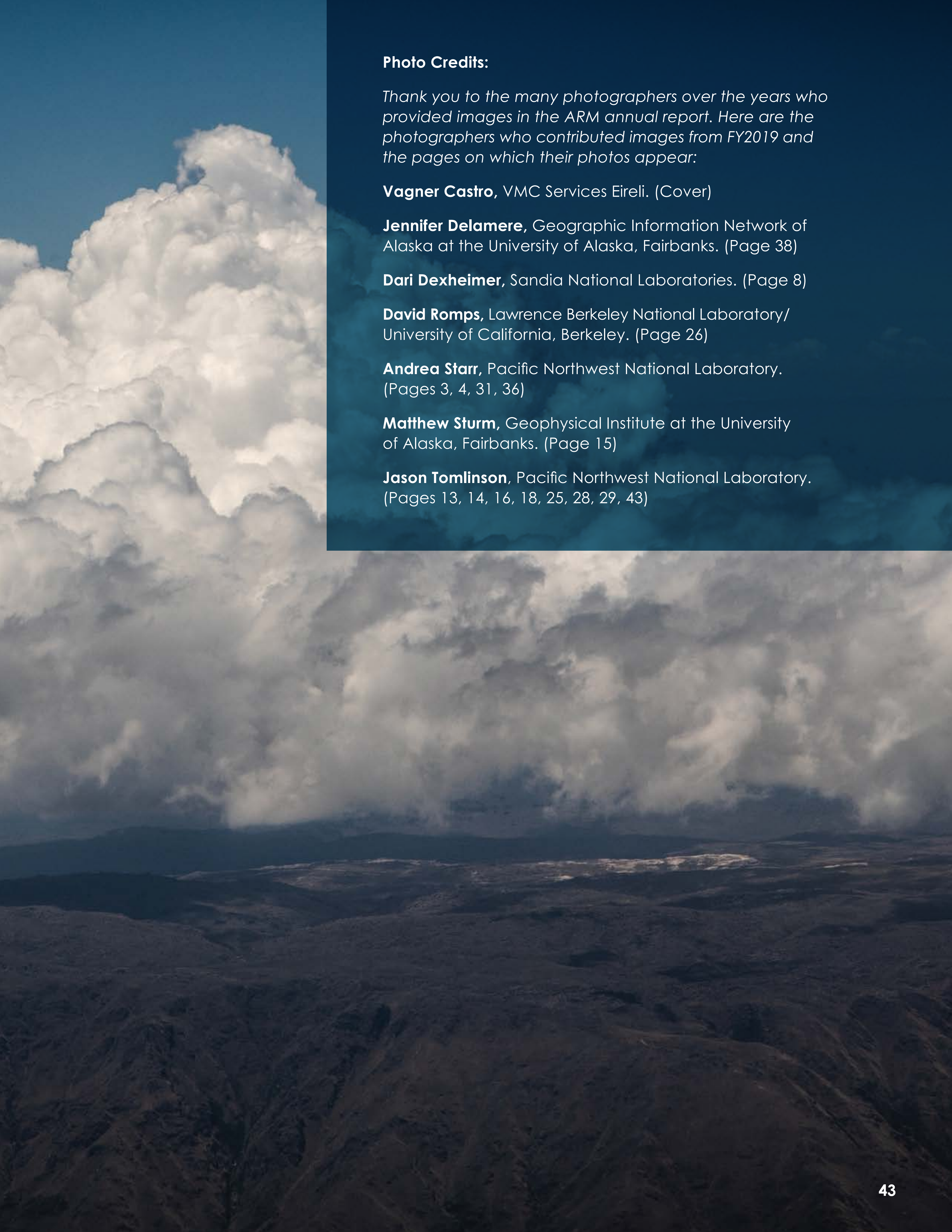


Photo Credits:

Thank you to the many photographers over the years who provided images in the ARM annual report. Here are the photographers who contributed images from FY2019 and the pages on which their photos appear:

Vagner Castro, VMC Services Eireli. (Cover)

Jennifer Delamere, Geographic Information Network of Alaska at the University of Alaska, Fairbanks. (Page 38)

Dari Dexheimer, Sandia National Laboratories. (Page 8)

David Romps, Lawrence Berkeley National Laboratory/ University of California, Berkeley. (Page 26)

Andrea Starr, Pacific Northwest National Laboratory. (Pages 3, 4, 31, 36)

Matthew Sturm, Geophysical Institute at the University of Alaska, Fairbanks. (Page 15)

Jason Tomlinson, Pacific Northwest National Laboratory. (Pages 13, 14, 16, 18, 25, 28, 29, 43)

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