ARM

U.S. DEPARTMENT OF ENERGY

# 2020 ANNUAL REPORT

ATMOSPHERIC RADIATION MEASUREMENT

**On the covers:**

**Front –** The icebreaker *R/V Polarstern* carried more than 50 ARM instruments for the 2019–2020 Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. ARM data contributed to the comprehensive study of the atmosphere, ice, ocean, and ecosystem in the central Arctic.

**Inside –** Working on the MOSAiC expedition, ARM technician Tercio Silva stands in front of the *R/V Polarstern*.

## From the Technical Director

# Persevering Through the Pandemic

For the Atmospheric Radiation Measurement (ARM) user facility, fiscal year 2020 (FY2020) had a significant arctic focus. As usual, however, there was a lot going on around the facility, and ARM is looking at how it can best serve the research community in the future.

For most of FY2020, ARM staff monitored more than 50 instruments during the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. ARM gathered data that will help researchers learn more about how ice, atmosphere, and ocean systems are dynamically linked in the remote central Arctic.

MOSAiC involved a German research vessel frozen into the sea ice and more than 500 people and 70-plus research institutions from 20 nations. It was an incredibly challenging campaign to execute, and it got more complicated when the COVID-19 pandemic led to travel and logistical changes during the second half of MOSAiC. Thanks to a flexible team and thoughtful planning, the expedition continued until October 2020 as originally scheduled.

ARM also had a presence in northern Norway from December 2019 through May 2020 for the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE). ARM operated instruments at two locations to observe the effects of frigid arctic air flowing equatorward over relatively warmer open ocean. The air-sea temperature contrast in these outbreaks leads to widespread complex clouds. ARM's observations of these cold-air outbreak events over 100 days will prove valuable for studying this important phenomenon.

COMBLE and MOSAiC data—along with data from our North Slope of Alaska atmospheric observatory—will be hugely important for scientists to understand earth system processes in the under-measured Arctic. These observations support a broad international focus on the Arctic with an emphasis on improving weather and environmental prediction in that region.

In addition to COVID-19's impact on MOSAiC plans, the pandemic presented other tests for ARM. The Southern Great Plains observatory briefly reduced operations, and ARM postponed a number of field campaigns because of travel and visitor restrictions at our sites.

Although it was frustrating to delay some of the research efforts planned for FY2020, ARM found ways to maintain user engagement as meetings and workshops shifted to a virtual environment.

The 2020 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting took place online in June. With attendance no longer restricted by physical capacity or institutional rules on travel, more people could attend virtually. Over 400 people signed on for the plenary sessions on the opening day.

Several virtual workshops were also held for upcoming ARM campaigns and deployments.

One workshop discussed the future move of the third ARM Mobile Facility from Alaska to the Southeastern United States. A site science team led by Brookhaven National Laboratory in New York is tasked with developing the science plan for the deployment. The team is collecting feedback from the ARM/ASR and broader scientific communities to help inform decisions about the deployment.

The Southeastern U.S. deployment will provide a great opportunity for interdisciplinary work with strong science goals related to aerosol processes, cloud processes, and land-atmosphere interactions.

There were also workshops to share science and logistics plans for two upcoming mobile facility campaigns, the 2021–2022 TRacking Aerosol Convection interactions ExpeRiment (TRACER) and the 2021–2023 Surface Atmosphere Integrated Field Laboratory (SAIL).

The TRACER campaign in the Houston, Texas, area, emphasizes convective cloud and aerosol processes and is attracting a lot of interest in terms of guest measurements and modeling activities.

SAIL, which will take place in the Colorado Rockies, engages multiple science disciplines, including cloud and aerosol processes, land-atmosphere interactions, and hydrological processes.

As we prepare for future campaigns, ARM users continue to make good use of past campaign data. In this report, you will learn about recent studies leveraging observations from long-term ARM observatories. You will also read about new papers from two aerial facility campaigns, the 2013 Biomass Burning Observation Project (BBOP) and the 2017/2018 Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) campaign.

To continue meeting the needs of the research community, ARM looks to improve or expand on services that it provides. In FY2020, a great deal of behind-the-scenes work went into modernizing software tools and underlying databases related to activities ranging from tracking data quality to user preferences. More visible changes included the release of a major update of the Data Discovery portal and the initiation of the next phase of the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity.

ARM is also preparing for future changes and, in FY2020, drafted an update to its Decadal Vision as part of preparations for its Triennial Review. As with the Decadal Vision, ARM drew on community input, including workshops in FY2020 organized by ARM constituent groups and aerial measurement teams. Input from these workshops as well as other input from the user community will be represented in the new Decadal Vision that will help to guide ARM priorities in the coming years.

FY2020 will go down as a year of unprecedented challenges for ARM, but it also showed that we could adapt and persevere as a facility. I hope you enjoy reading about ARM's accomplishments in FY2020.

**Jim Mather**
ARM Technical Director

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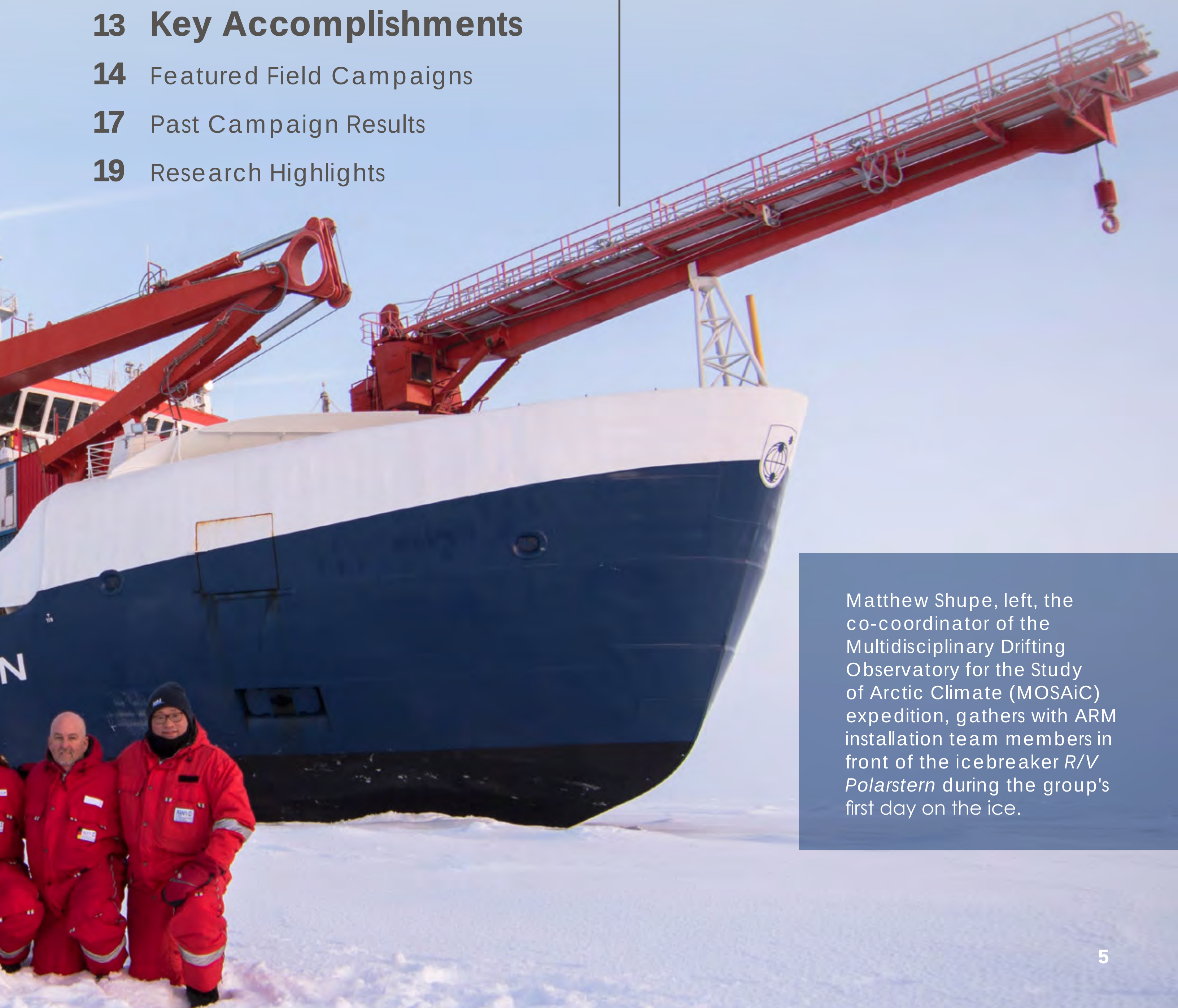


Matthew Shupe, left, the co-coordinator of the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition, gathers with ARM installation team members in front of the icebreaker *R/V Polarstern* during the group's first day on the ice.

# 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 2020 (FY2020).

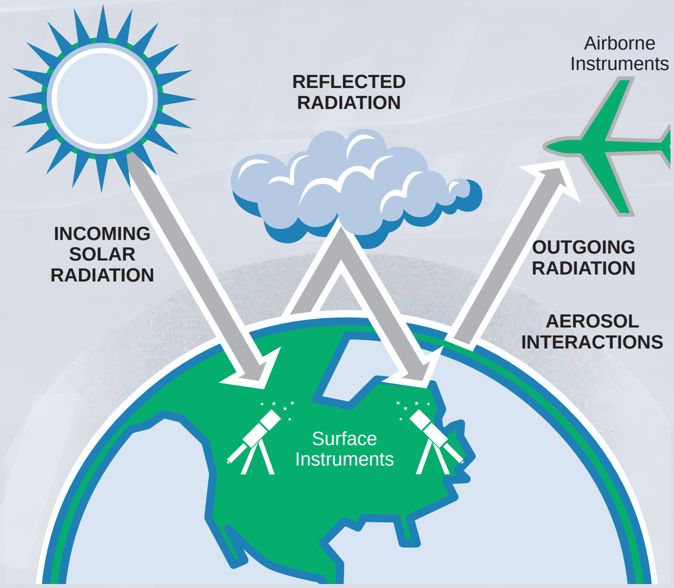
ARM is a multi-laboratory, U.S. Department of Energy (DOE) scientific user facility and a key contributor to national and international atmospheric and climate research efforts. ARM offers scientists cutting-edge, ground-based observatories, manned and unmanned aerial capabilities, and almost 30 years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

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

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

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

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




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

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

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

# 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.

### Scientists Provide Expertise and Direction for ARM Aerial Measurements

In early March 2020, atmospheric scientists gathered at Pacific Northwest National Laboratory in Washington state for the ARM Aerial Instrumentation Workshop. This event brought together the ARM Aerial Facility (AAF), managed by Pacific Northwest National Laboratory, and ARM's tethered balloon system (TBS) operations, managed by Sandia National Laboratories in New Mexico.

"We wanted to tap the expertise of attendees on aerial instrumentation, learn what technologies are available now or in the near future, and measure the capabilities of instrumentation against the science goals of the researchers," said AAF Manager Beat Schmid.

White papers submitted by instrument experts spurred and informed discussion at the invitation-based workshop organized by Schmid, AAF Science Manager Fan Mei, and TBS Facility Manager Dari Dexheimer.

In addition to its focus on aerial instrumentation, said Schmid, the workshop provided a wide-ranging update of ARM's manned aircraft, TBS, and unmanned aerial system operations. Importantly, it gave AAF and TBS managers a chance to hear from researchers.

The 59 attendees discussed how users can get the best data on atmospheric components that are important for understanding Earth's energy balance and improving the representation of atmospheric processes in earth system models. The group also talked about the present and future of ARM aerial measurement activities.


**ARM Aerial Facility Operations Manager Jason Tomlinson presents during the ARM Aerial Instrumentation Workshop.**

Presentations and findings from the workshop will contribute to ARM's strategic plan for the next decade. A workshop report published in July 2020 detailed what was learned and the technologies and instruments proposed.

# 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 Mobile Facility to Leave Alaska for Southeastern United States

By the end of FY2021, ARM plans to move the third ARM Mobile Facility (AMF3) out of Oliktok Point, Alaska. Its next destination will be the Southeastern United States, identified during a 2018 ARM workshop as a region of interest for further study.

To maximize the scientific value of the new site, DOE's Biological and Environmental Research program selected a site science team to help guide the AMF3 move.

ARM and Atmospheric System Research (ASR) are sponsoring the multi-institutional site science team, led by Brookhaven National Laboratory in New York. The team is responsible for developing a science plan and an initial research project for the new deployment, which is scheduled to start operations in FY2023. With feedback from the scientific community in mind, the group will help pinpoint potential destinations for AMF3 and collaborators in the Southeast.

The deployment "presents an exciting opportunity for collaborative, interdisciplinary, and transformational science across aerosol, convective, and land-atmosphere interaction topics," said site science team lead Chongai Kuang, an aerosol scientist at Brookhaven National Laboratory.

In 2020, the AMF3 team held a three-day kickoff workshop, and Kuang moderated a virtual breakout session during the Joint ARM User Facility/ASR Principal Investigators Meeting. Kuang also presented to the DOE Environmental System Science community on the upcoming deployment.


The third ARM Mobile Facility will end operations in Alaska in 2021 ahead of its move to the Southeastern United States.

AMF3 began operations at Oliktok Point in 2013. ARM will continue to support observations in Alaska at its fixed site at Utqiaġvik (formerly Barrow), which has collected atmospheric data since 1997.

# 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 Atmospheric System Research (ASR) to meet the objectives of DOE's Earth and Environmental Systems 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.

### User Executive Committee Provides Invaluable Feedback to ARM Management

The ARM User Executive Committee (UEC), as the official voice of the user community to ARM management, demonstrated its worth again during FY2020.

Members shared their insights from scientific conferences and workshops to help keep ARM at the forefront of atmospheric science. UEC member Paquita Zuidema participated in a data "hackathon" for the French-German EUREC4A field campaign—an approach that may be tried for future ARM campaigns.

In early March, UEC Chair Sébastien Biraud and member Art Sedlacek attended the ARM Aerial Instrumentation Workshop in Washington state. Not long after the workshop, COVID-19 forced events such as the 2020 Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting to go virtual. UEC members connected with other current and potential ARM users during the joint meeting and other online events.

Other UEC efforts during FY2020 included:

- contributing crucial input about the way forward to ARM's updated Decadal Vision and Triennial Review documents.
- providing feedback to the ARM Data Center on early versions of the redesigned Data Discovery, ARM's portal to more than 2 petabytes of data.
- advising on how to enhance ARM's impact at the American Geophysical Union (AGU) Fall Meeting and stepping up as volunteers at the ARM booth.

Elections for UEC members occur every two years. In August, ARM sought nominations for six positions opening in January 2021.

### ARM/ASR Joint Meeting a Virtual Success

In 2020, the Joint ARM User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting went virtual.

Because the Zoom video conferencing platform has a broader reach than a typical hotel meeting room, more people got to attend the 2020 joint meeting, which took place from June 23 to 26. About 400 people, including DOE leadership, national laboratory staff, and university researchers, signed on for the opening plenary sessions. DOE ARM Program Manager Sally McFarlane talked about COVID-19 impacts on ARM, changes to ARM's Infrastructure Management Board, and plans for ARM's new research aircraft.

Eight two-hour breakout sessions—focused on ARM/ASR research and projects—each attracted more than 100 attendees. ASR working groups also reported larger-than-usual attendance at their sessions.


**DOE ARM Program Managers Sally McFarlane and Rickey Petty and DOE Atmospheric System Research (ASR) Program Managers Shaima Nasiri and Jeff Stehr are on screen during the 2020 joint meeting.**

## Longtime ARM Aerial Facility Program Manager Retires

In June 2020, ARM Aerial Facility (AAF) Program Manager Rickey Petty bowed out of his professional work life—ready, he said, "to cross the finish line of retirement."

Petty spent 26 years as a program manager and meteorologist with DOE. He was the program manager of the AAF since its inception in 2006.

"My 26 years have gone by in a zip," said Petty. "I couldn't have asked for a more rewarding career. I'm proud to have been part of the science that has been done."

As AAF program manager, Petty consulted on budgetary matters, flight operations, and safety issues with DOE ARM Program Manager Sally McFarlane.

"I will miss working with Rick," said McFarlane before Petty's retirement. "His positive attitude and inside knowledge of how DOE works have made him a great colleague."

**ARM Aerial Facility Program Manager Rickey Petty, seen here in his Germantown, Maryland, office, retired in June 2020 after a 26-year career with DOE.**

## Constituent Groups Help Shape ARM's Long-Term View

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

In particular, the Aerosol Measurement Science Group (AMSG) and Cloud and Precipitation Measurements and Science Group (CPMSG) offer assessments and recommendations to increase the scientific impact of ARM investments in mission-critical data sets.

The AMSG and CPMSG held strategic planning workshops in FY2020 that were key sources of input for ARM in updating its Decadal Vision document. Increasing emphasis on spatial sampling and the coordinated use of intensive operational periods are key topics in the document that emerged from conversations within the AMSG and CPMSG.

**Microwave radiometers, which provide data to help modelers represent clouds, precipitation, aerosols, and radiation, emerged as an investment theme during a constituent group workshop.**

From their workshops, the groups are preparing reports to help ARM optimize current instrument operations, determine instrument needs, improve data products, and identify measurement gaps.

## Newly Funded ASR Projects Come With Big TRACER Focus

In July 2020, DOE announced funding of $19 million for 31 projects through Atmospheric System Research (ASR). These university-based projects are designed to expand the fundamental understanding of atmospheric processes in the earth system, particularly processes that limit the predictability of earth system models.

Notably, 10 of the projects will help maximize the scientific impact of ARM's 2021–2022 TRacking Aerosol Convection interactions ExpeRiment (TRACER) in the Houston, Texas, area.

The TRACER ASR projects include studies of ultrafine aerosol formation, convective cloud properties, coastal urban boundary-layer interactions with convection, and impacts of convective storms on aerosol processing and atmospheric composition and chemistry.

**The TRACER campaign will study convective clouds that commonly appear over the Houston, Texas, area.**

"Atmospheric processes leading to cloud formation and precipitation are notoriously complex and difficult to model accurately," said Chris Fall, Director of DOE's Office of Science. "These studies, which combine observation and modeling, will be important steps toward more precise and predictive models on both regional and global scales."

### International Workshop Explores ARM Data From Argentina

The Sierras de Córdoba mountain range in central Argentina is home to some of the world's largest and tallest thunderstorms. Two recent field campaigns in the region teamed up to collect intensive measurements that would help improve understanding of convective clouds, including these storms.

ARM's Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign took place from October 2018 through April 2019. The other campaign—Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations (RELAMPAGO)—received most of its funding from the National Science Foundation. RELAMPAGO and CACTI crossed over in late 2018 during a seven-week intensive operational period.

**Attendees of the RELAMPAGO-CACTI Data Analysis Workshop gather for a group picture.**

In November 2019, 81 researchers met in Buenos Aires, Argentina, for the RELAMPAGO-CACTI Data Analysis Workshop. Participants from the United States, Argentina, and Brazil discussed data and research from both campaigns. Adam Varble, CACTI principal investigator from Pacific Northwest National Laboratory in Washington state, was on the organizing committee of the four-day workshop.

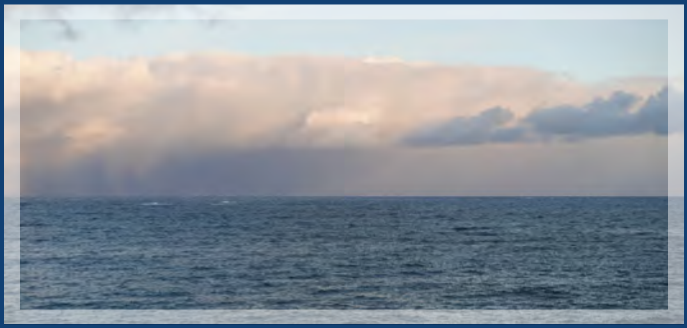
Day One focused on describing data sets collected, including their quality control and availability. The second and third days highlighted ongoing and planned research, and the final day featured a satellite workshop and multi-Doppler radar retrieval course.

At the end of the workshop, participants discussed next steps for research using the data, including areas of possible collaboration. The CACTI campaign is a windfall of data for cloud researchers—over 6½ months, cumulus or stratocumulus clouds were observed on 173 days, deep convection on 79 days, and rainfall on 92 days over the ARM Mobile Facility site.

### A Guide to Representing Small-Scale Atmospheric Processes in Models

Small-scale processes affecting clouds and precipitation are problematic for weather forecasts and earth system models. Because cloud particles are so numerous and tiny, atmospheric models must represent the evolution of particle populations statistically, which opens them up to errors.

A paper first published in May 2020 by the *Journal of Advances in Modeling Earth Systems* contends that current approaches to representing small-scale processes are not making the grade. The international group of authors, many of whom are long-term ARM users, advocates for new approaches that build upon observational, modeling, and statistical advances.



**A new paper advocates for new approaches to improve model representation of small-scale processes that influence how cloud and precipitation particles form and change.**

This paper makes a case for a "particle-based" approach to improve the representation of cloud and precipitation particle populations in models. The authors, led by Hugh Morrison at the National Center for Atmospheric Research, say this approach helps address some limitations of traditional approaches.

The paper also asserts that ground-based and aerial measurements of clouds and precipitation (such as those conducted by ARM), laboratory studies, and satellite remote-sensing observations are critical to filling in knowledge gaps of small-scale processes. Authors suggest increased emphasis on evaluation of model performance using field observations, including development of new frameworks to facilitate rigorous model evaluation and constraint by observations; and leveraging of new statistical modeling tools, such as machine learning.

**Reference**

Morrison H, M van Lier-Walqui, AM Fridlind, WW Grabowski, JY Harrington, C Hoose, A Korolev, MR Kumjian, JA Milbrandt, H Pawlowska, DJ Posselt, OP Prat, KJ Reimel, S-I Shima, B van Diedenhoven, and L Xue. 2020. "Confronting the challenge of modeling cloud and precipitation microphysics." *Journal of Advances in Modeling Earth Systems*, 12(8):e2019ms001689, https://doi.org/10.1029/2019MS001689.

# 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 FY2020.*


## ARM and International Partners Support Major Arctic Expedition

In FY2020, ARM participated in the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition—a massive mission to document the atmosphere, sea ice, ocean, biogeochemistry, and ecosystem of the central Arctic.

More than 500 people and 70-plus institutions from 20 countries were active in the German-led MOSAiC expedition from September 2019 to October 2020. DOE was the first funder to commit to MOSAiC, and ARM provided the most atmospheric instruments to the expedition—more than 50.

MOSAiC's central observatory was the German icebreaker *R/V Polarstern*, which froze into and then drifted with the arctic sea ice for most of the year. In spring 2020, because of travel and logistical challenges related to COVID-19, the *Polarstern* briefly left the ice to complete a crew rotation off the Norwegian island of Svalbard. ARM instruments continued to operate on the ship during that time.

ARM staff supported the deployment, making sure instruments ran well in extreme conditions, including several blizzards, and moving equipment away from cracking ice in the spring. Some technicians deployed during the monthslong polar night, when the sun does not rise above the horizon.

**Aboard the icebreaker *R/V Polarstern*, ARM instruments withstood the elements to collect atmospheric data during the MOSAiC expedition.**

"The people who ARM brings to the field are such an important reflection of the ARM facility, and this team has done a fantastic job," said Matthew Shupe, MOSAiC co-coordinator from the Cooperative Institute for Research in Environmental Sciences.

From MOSAiC, ARM collected at least 8 terabytes of data that are freely available to users for future arctic research.

## Research Team Hunts Cold-Air Outbreaks in the Arctic

After six months of collecting data in northern Norway, ARM's Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) ended in May 2020.

COMBLE's science plan, formulated with 20 international collaborators, focused on studying cold-air outbreaks (CAOs) in the marine boundary layer to examine important but little-understood atmospheric processes. The field campaign's outdoor laboratory was a vast stretch of open water in the Norwegian Sea.

"We wanted to sample the arctic airmass, modified by this relatively warm sea, on the downwind shore as far north as we could go in Scandinavia," said Bart Geerts, COMBLE principal investigator from the University of Wyoming.

A CAO happens when a mass of cold air from an edge of polar ice sweeps across an open area of warm water. Among other things, CAOs prompt the formation of shallow convective clouds, which then grow and evolve into a characteristic cloud regime that plays a key role in the Earth's energy balance.

Shallow low clouds over the oceans have been extensively studied, but little is known about the properties of such clouds formed during CAOs or about related processes within the boundary layer. Key questions include: What controls the macrostructure of this cloud regime? What is the liquid/ice phase distribution in these clouds? And what is the role of cloud-active aerosols?

COMBLE will narrow those knowledge gaps.

"We're very pleased to have the (CAO) data set," said Geerts. "This is the first time such a high-quality, comprehensive data set has been collected."

**"The people who ARM brings to the field are such an important reflection of the ARM facility, and this team has done a fantastic job."**

*—Matthew Shupe, MOSAiC co-coordinator from the Cooperative Institute for Research in Environmental Sciences*

The first ARM Mobile Facility, the chief instrument platform during COMBLE, was sited on the Norwegian Sea. Farther north, a smaller ARM instrument suite collected measurements on Norway's Bear Island

## Cracking the Mysteries of Atmospheric Ice

Two campaigns in late 2019 at ARM's Southern Great Plains atmospheric observatory targeted ice-nucleating particles (INPs). INPs are particles that can act as the nucleus for the formation of ice clouds in the atmosphere. However, the conditions under which these particles occur and the frequency with which they form ice clouds are poorly understood.

For three weeks in October, atmospheric chemist Daniel Knopf of Stony Brook University in New York led the field portion of a pilot study to improve INP representation in earth system models. Researchers sought to close gaps between observations and predicted rates of ice formation by particle species.

At the same time, Naruki Hiranuma (aka Seonggi Moon) from West Texas A&M University led a campaign that he said provided the first automated and continuous measurements of ambient INP concentrations. Measurements occurred for 45 days straight and at intervals of roughly every six minutes.

Hiranuma's work, supplemented by ARM data, involved the first official field deployment of a new device that makes artificial clouds and uses particle detectors to monitor the abundance and characteristics of INPs.

ARM's Southern Great Plains atmospheric observatory proved to be a fruitful location for studying ice-nucleating particles.

## Countdown Begins for Convective Cloud Campaign in Texas

ARM will soon embark on a field campaign to capture data on deep convective clouds. During the TRacking Aerosol Convection interactions ExpeRiment (TRACER), an ARM Mobile Facility (AMF) will collect measurements in 2021 and 2022 in the Houston, Texas, area. The second-generation C-Band Scanning ARM Precipitation Radar (CSAPR2) will track convective cells within a four-month summertime intensive operational period.

In January 2020, a team of TRACER researchers, ARM staff, and local scientists visited potential locations around Houston for the AMF, CSAPR2, and an ancillary instrument site. The AMF will be sited at La Porte Municipal Airport southeast of Houston, while the CSAPR2 and ancillary site will be located south and southwest of downtown.

A two-day virtual science and logistics meeting in April 2020 brought together TRACER science team members, interagency collaborators, ARM staff, DOE program managers, and interested researchers. Topics included ARM operations and emerging partnerships and research opportunities with other agencies and institutions.

Taken from the Moody Tower Observatory in Houston, Texas, this photo shows the University of Houston, foreground, and the downtown skyline.

# Past Campaign Results

## Biomass Burning Campaign Gives Rise to Studies and Inspiration

In the summer and fall of 2013, ARM's Biomass Burning Observation Project (BBOP) took to the skies in search of microphysical data on wildfires and controlled agricultural burns. Such events are important sources of trace gases and carbon-containing aerosols entering the atmosphere.

What exactly happens, scientists asked, as these earth system-altering components are emitted, transported, and processed miles above the Earth? What is the fate of light-scattering brown carbon particles and of light-absorbing black carbon particles?

Larry Kleinman and Art Sedlacek, atmospheric chemists at Brookhaven National Laboratory in New York, led BBOP's research team. They recognized the merit of laboratory studies, but also saw the need for measurements from smoke plumes close to large wildfires.

BBOP relied on measurements aboard ARM's now-retired Gulfstream-159 (G-1) research aircraft. Equipped with chemical and optical sensors, the G-1 flew through wildfire plumes in the Pacific Northwest and through controlled-burn plumes in Arkansas, where rice straw was being burned after harvest.

Since 2013, BBOP has inspired more than a dozen studies. One of the most recent, from February 2020, was led by Katherine Junghenn Noyes at the University of Maryland, College Park.

With BBOP as an observational baseline, the paper assessed a research aerosol retrieval algorithm used for the NASA Earth Observing System's multi-angle imaging spectroradiometer. The authors found that the algorithm, once properly validated by BBOP data, appropriately mapped qualitative changes in effective particle size, light absorption, spectral dependence, and other factors when compared with in situ observations.

Another 2020 study, led by Cary Presser of the National Institute of Standards and Technology, compared new and traditional techniques used to measure light transmission and absorption characteristics. Using particles collected on filters from nine BBOP flights, the authors showed that absorptivity results from the two techniques generally agreed. But they noted differences in transmissivity measurements, attributed to possible changes in the filters over time.

BBOP's impact is felt in other ways. A report from a March 2020 ARM aerial instrumentation workshop included a white paper by Sedlacek on a compact, extended-range version of the single-particle soot photometer used during BBOP. The original, heavier BBOP model measured the mass, number, and size distribution of soot. It is "the only instrument," wrote Sedlacek, "that can directly detect and characterize individual (black carbon)-containing particles."

The new version "has a lot of potential, a lot of legs" aboard tethered balloon systems, said Sedlacek at the workshop. Such a deployment would provide the first vertical profiles of black carbon concentrations.

**During the 2013 BBOP field campaign to study biomass burning, a funnel-shaped wildfire smoke plume, center, jutted into the sky over the Cascade Mountains of Washington state.**

**For a 2020 ARM aerial instrumentation workshop, Brookhaven National Laboratory scientist Art Sedlacek contributed a white paper on a new version of the single-particle soot photometer used during BBOP.**

## Early Results Emerge From ARM West Antarctic Radiation Experiment

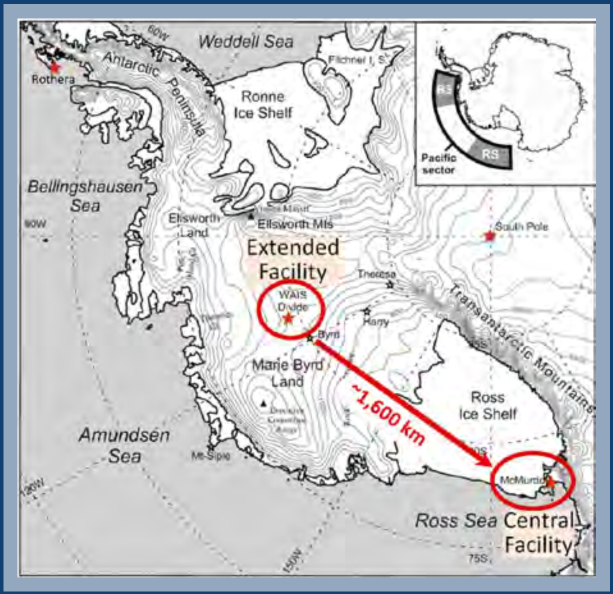
A July 2020 article in the *Bulletin of the American Meteorological Society (BAMS)* highlighted early outcomes from the ARM West Antarctic Radiation Experiment (AWARE).

From November 2015 to January 2017, this joint field campaign between DOE and the U.S. Antarctic Program collected atmospheric and remote-sensing data that contrast significantly with comparable arctic data.

During AWARE, ARM deployed a mobile facility to McMurdo Station on Ross Island and a smaller instrument suite to the West Antarctic Ice Sheet (WAIS).

The McMurdo data are invaluable, especially when compared with data from ARM's North Slope of Alaska sites, because they represent regions where high mountainous terrain influences meteorology and cloud physics.

At WAIS Divide, AWARE coincided with the start of a major melt event in a rapidly warming region with at-risk glaciers. These data on surface melt and mass loss are critical to understanding local atmospheric forcing and improving predictions of sea-level rise.




**This map shows the AWARE locations at McMurdo Station and the WAIS Divide ice camp.** *(Copyrighted image from the journal.)*

**Reference**

Lubin D, D Zhang, I Silber, RC Scott, P Kalogeras, A Battaglia, DH Bromwich, M Cadeddu, E Eloranta, A Fridlind, A Frossard, KM Hines, S Kneifel, WR Leaitch, W Lin, J Nicolas, H Powers, PK Quinn, P Rowe, LM Russell, S Sharma, J Verlinde, and AM Vogelmann. 2020. "AWARE: The Atmospheric Radiation Measurement (ARM) West Antarctic Radiation Experiment." *Bulletin of the American Meteorological Society*, 101(7):E1069-E1091, https://doi.org/10.1175/BAMS-D-18-0278.1.

## Special Journal Issues Include ARM Campaign Findings

Two recent ARM field campaigns are featured in joint special issues of the journals *Atmospheric Chemistry and Physics* and *Atmospheric Measurement Techniques*.

One issue, looking at marine aerosols, trace gases, and clouds over the North Atlantic, includes findings from ARM's Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) campaign.

Jian Wang of Washington University in St. Louis is co-organizing the issue. In summer 2017 and winter 2018, Wang led ACE-ENA, using ARM ground and aerial data to study marine aerosols and low clouds.

The first paper published in the issue used ACE-ENA data to help determine a regional aerosol baseline.

**Papers using data from ARM's Eastern North Atlantic atmospheric observatory are included in a joint special issue on marine aerosols, trace gases, and clouds over the North Atlantic.**

The other joint special issue covers new observations and related modeling studies of the aerosol-cloud-climate system in the southeast Atlantic and southern Africa. It includes ARM's 2016–2017 Layered Atlantic Smoke Interactions with Clouds (LASIC) field campaign on Ascension Island. LASIC focused on smoke aerosols from African biomass fires and their interaction with clouds while moving over the Atlantic.

Paquita Zuidema, LASIC principal investigator from the University of Miami, helped lead a May 2020 virtual workshop to discuss findings from LASIC and related campaigns in the region. Many collaborations discussed during the workshop have been—or will be—published in the joint special issue.

## Do Flying Fragments of Fungi Seed Clouds?

Fungi are organisms that dissolve plant matter and lead largely cryptic lives hidden away in soil. It now appears that nanoscale fragments of fungi episodically pulse from the Earth's surface, revealing a large, little-studied source of cloud-forming ice nuclei. These fungal nanoparticles, when present, can outnumber other biological particles by orders of magnitude.

These observations and conjectures are part of a January 2020 *Science Advances* paper by Michael Lawler, Danielle Draper, and James Smith at the University of California, Irvine. The team gathered guest instrument data during the 2016 Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) field campaign at ARM's Southern Great Plains atmospheric observatory.

With ARM measurements of rain rate, relative humidity, and aerosol size distribution as context, the authors identified fragments of fungal cells—likely bits of water-swollen spores that burst—in numbers greater than previously known.

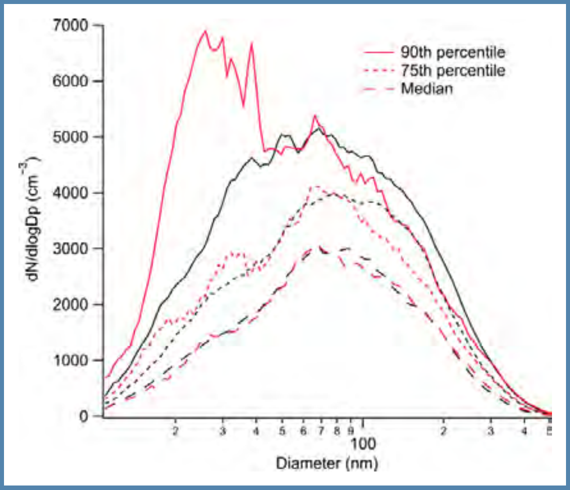
Pieces of fungal shrapnel are very small—about 30 nanometers wide, on average. Because they can be so numerous, and because biological particles can be effective ice nuclei, fungal nanoparticles may also play an important role in ice-cloud formation. This is counter to the commonly held view that atmospheric concentrations of biological particles are too low to be a significant source of ice nuclei. However, this speculation depends on the ice-nucleating ability of fungal species that burst, which is unknown.

To identify fungal fragments at the Southern Great Plains, researchers used a mass spectrometry technique. An inlet drew in ambient air and size-selected particles of 20 to 60 nanometers in diameter for sampling. Those particles accumulated on a platinum filament for 30 minutes, then were vaporized into gases suitable for analysis.

These results, taken together with previous observations of larger burst fungal fragments in the Amazon, suggest that such events are widespread geographically.

### Reference

Lawler MJ, DC Draper, and JN Smith. 2020. "Atmospheric fungal nanoparticle bursts." *Science Advances*, 6(3):eaax9051, https://doi.org/10.1126/sciadv.aax9051.




**Chitin, a structural constituent of fungi cell walls, revealed the episodic presence of fungi in the analyzed air samples. Plotted here is the statistical distribution of chitin (in red) and non-chitin particles (in black).** *(Copyrighted image from the journal.)*

**Clouds stream over ARM's Southern Great Plains Central Facility. The Guest Instrument Facility, pictured, is where researchers gathered data on airborne fragments of fungi.**

## Paper Clarifies Advection in the Marine Boundary Layer

Abundant low-lying decks of stratocumulus clouds over the world's oceans play a huge role in Earth's radiation budget, hydrologic cycle, and climate. Contributing to this influence are the horizontal extent and thickness of such clouds and their shifting rates of precipitation.

The life span of such clouds is partly controlled by how strongly they are coupled with surface energy fluxes. However, the thermodynamics of such marine boundary-layer clouds are not well understood and remain a big source of uncertainty in predictive earth system models.

Scientists at the University of Maryland, College Park, investigated two sides of a phenomenon that informs such models: advection, the horizontal and vertical transport of heat, moisture, mass, and other properties.

Cloud-topped boundary-layer advection over warm subtropical waters can cause "deepening-warming" decoupling. Colleagues Youtong Zheng and Zhanqing Li looked at a thermodynamically opposite phenomenon called low-level warm-air advection, which happens as warm air advects into a cloud-topped boundary layer over cold water.

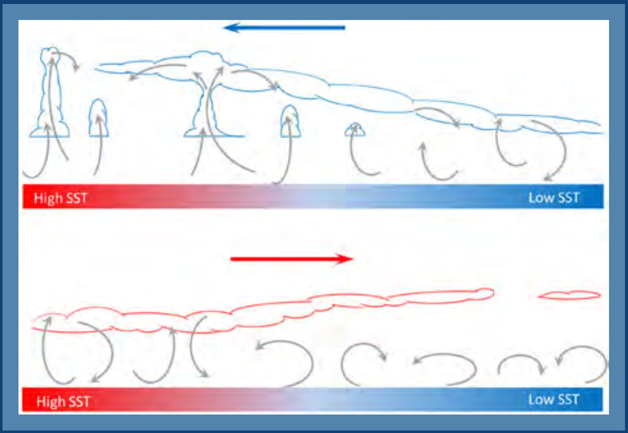
The duo synthesized satellite imagery, reanalysis, and three case studies of ship-based data. The data came from voyages between Australia and Antarctica during ARM's 2017–2018 Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) field campaign.

In a *Journal of Geophysical Research: Atmospheres* paper published online in October 2019, Zheng and Li demonstrated that cloud-surface decoupling is stronger in the colder setting such that cumulus penetration above the main boundary-layer temperature inversion does not occur. In addition, they found that boundary-layer clouds over the frigid Southern Ocean have longer life spans than previously believed—in the range of several tens of hours. This finding alone may correct present underestimates derived from satellite data.

The study also suggests that under conditions of strong decoupling, surface-generated aerosols such as sea spray and biogenic particles may not reach cloud bases easily from cold waters. That opens inroads into nascent investigations of cold-ocean aerosols.

### Reference

Zheng Y and Z Li. 2019. "Episodes of warm-air advection causing cloud-surface decoupling during the MARCUS." *Journal of Geophysical Research: Atmospheres,* 124(22):12227-12243, https://doi.org/10.1029/2019JD030835.




**Cold thermal advection over warmer sea water, top, allows marine boundary-layer clouds to remain unstable and convective—that is, precipitating. Low-level warm-air advection over colder sea surfaces, bottom, is unfavorable for the vertical development of cumulus clouds.** *(Copyrighted image from the journal.)*

**A cloud-filled horizon appears during ARM's shipborne MARCUS field campaign across the Southern Ocean.**

## The Use of Clouds to Represent Rain in Large-Scale Models

The formation of rain within clouds is a complex interplay of processes across a range of scales, making it difficult to represent in global earth system models.

A research team led by Katia Lamer at Brookhaven National Laboratory in New York tackled the issue of rain representation in models by gazing up at the shallow clouds above ARM's Eastern North Atlantic atmospheric observatory. The team's *Journal of Geophysical Research: Atmospheres* paper appeared online in March 2020.

Lamer and her co-authors searched for relationships between the properties of rain and of the large-scale environment, while also accounting for the character of the clouds. The team hypothesized that such relationships, if they exist, could help approximate the behavior of rain in large-scale models.

The authors analyzed thousands of hours characterized by large-scale subsidence, an atmospheric condition frequently associated with shallow clouds. They used radar and lidar measurements to quantify key rain properties, including rain rate, virga base height (the lowest extent of rain not reaching the surface), and rain-to-cloud fraction. The researchers used the same measurements to quantify key cloud properties, such as cloud-base height, cloud thickness, and cloud phase—that is, the predominance of liquid water or ice.

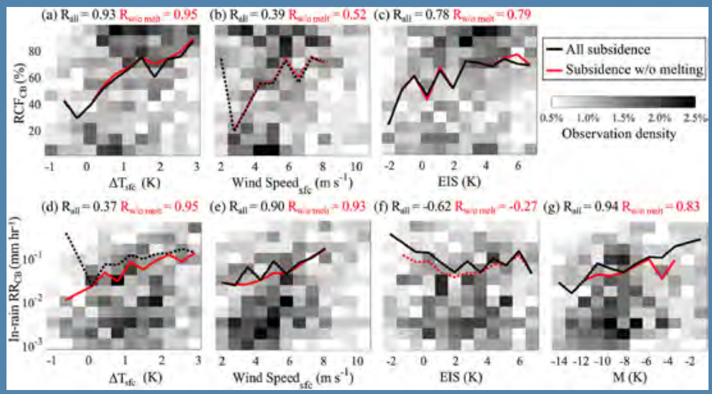
Finally, to derive large-scale environmental properties, the team combined reanalysis with observations from meteorological stations and radiosondes.

The study confirmed the existence of robust relationships between rain properties and cloud thickness, even in ice-topped shallow clouds. According to Lamer, the team's statistical analysis also revealed that "relationships between the large-scale environment and rain exist but seem indirect and could likely result from the large-scale environment's influence on clouds."

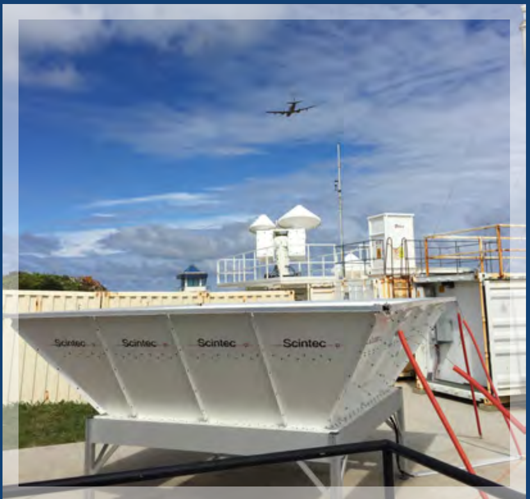
Ultimately, the study suggests that it is important to base the representation of precipitation in global models on cloud properties and the characteristics of the large-scale environment.

### Reference

Lamer K, CM Naud, and JF Booth. 2020. "Relationships between precipitation properties and large-scale conditions during subsidence at the Eastern North Atlantic observatory." *Journal of Geophysical Research: Atmospheres,* 125(7):e2019JD031848, https://doi.org/10.1029/2019JD031848.




**Solid lines denote statistically significant relationships between rain properties (y-axis) and measures of surface forcing and environmental stability (x-axis).** *(Copyrighted image from the journal.)*




**Sensors installed at ARM's Eastern North Atlantic atmospheric observatory collect measurements of the marine environment, the shallow clouds above, and the rainfall they support.**

## Supercooled Clouds Deliver a Nonturbulent Arctic Surprise

Polar regions are dominated by ice-bearing supercooled stratiform clouds within turbulently mixed layers. However, nonturbulent liquid-bearing clouds are also present—and in greater numbers than previously thought, according to a *Geophysical Research Letters* paper anchored by ARM data.

Liquid-bearing clouds are important for exerting a stronger radiative influence on polar surfaces. They are typically denser than ice clouds and scatter, absorb, and emit radiant energy more effectively.

The problem is that mixed-phase conditions without turbulent mixing does not fit neatly into long-standing conceptual models of polar stratiform clouds. Nonturbulent liquid-bearing clouds have been widely overlooked and poorly represented in models.

Published online in April 2020, the paper—led by Israel Silber at Pennsylvania State University—reports that nonturbulent conditions are present in around 25% of liquid-bearing polar clouds. The finding that nonturbulent liquid-bearing clouds are so common has implications for the representation of polar aerosol-cloud interactions in large-scale models.

The researchers designed large-eddy simulations based on cloud measurements from ARM's North Slope of Alaska atmospheric observatory and from Antarctica's McMurdo Station, the main site of the 2015–2017 ARM West Antarctic Radiation Experiment (AWARE).

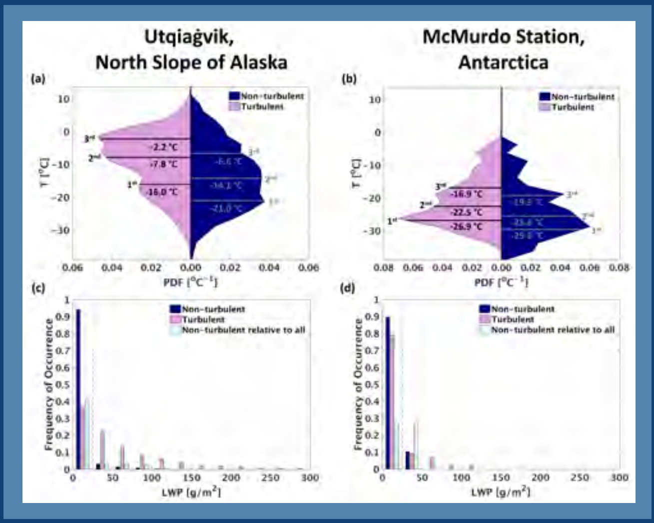
Importantly, their findings indicate an under-appreciated influence of gravity waves, a form of oscillating vertical winds that occur under stable atmospheric conditions. These waves may hasten turbulence formation and—under certain conditions—enhance cloud droplet formation and growth.

The study comes at a time when the role of liquid-bearing polar clouds in predicting the evolution of sea ice in the Arctic and polar temperatures is of great concern. Nonturbulent liquid-bearing clouds may rapidly become turbulent in a warming environment. That aerosol-modulated cloud-climate feedback mechanism can potentially accelerate warming of sea-ice surfaces, but until now has not appeared in the literature.

These conclusions indicate that regional and global models of polar conditions may require faithful representations of aerosols and the effect of gravity waves on cloud evolution.

### Reference

Silber I, AM Fridlind, J Verlinde, LM Russell, and AS Ackerman. 2020. "Nonturbulent liquid-bearing polar clouds: Observed frequency of occurrence and simulated sensitivity to gravity waves." *Geophysical Research Letters,* 47(10):e2020GL087099,https://doi.org/10.1029/2020GL087099.




**Cloud statistics are presented from ARM's North Slope of Alaska atmospheric observatory, left, and from Antarctica's McMurdo Station, right, during the AWARE field campaign.** *(Copyrighted image from the journal.)*

**An ARM Mobile Facility collected measurements at McMurdo Station in Antarctica during the AWARE field campaign.**

## Cloud Simulations Could Benefit From New Land Model Framework

Over land, convective clouds are influenced by variations in soil and vegetation. For instance, such clouds tend to gather over areas bounded by rivers or marked by discontinuities in types of vegetation, such as summertime patchworks of grasses and wheat.

The heterogeneity—variety—of a land surface can force air circulations with low-level convergence, like a sea breeze, that help shallow clouds transition to the deep cumulus kind that produce rain.

With current advances in numerically modeling clouds, there is an increasing need for regional-scale land model predictions at the spatial scale of convective storms. To date, simplified vegetation categories in models fail to capture the heterogeneity of agricultural areas.

A *Journal of Geophysical Research: Atmospheres* paper published online in April 2020 presents a new framework for modeling land surface characteristics.

To obtain parameters characterizing vegetation in models, the authors used a combination of satellite remote-sensing data and observations from ARM's Southern Great Plains atmospheric observatory. They combined the parameters with land model experiments to improve how vegetation is represented in the latest version of the Community Land Model (CLM4.0), a common platform.

The result is a new data set and classification scheme for two traditional measures of vegetation—plant functional type and leaf area index.

"We used ARM observations to improve the vegetation input data set for land models and to inform uncertain land model parameters," said lead author Ian Williams, now at Iowa State University.

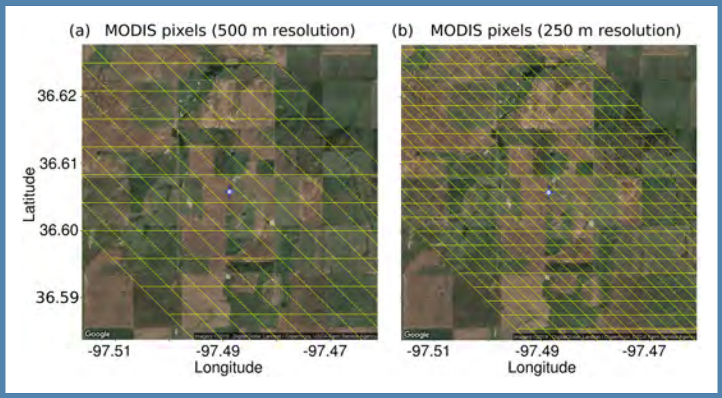
The new framework enables consistent comparisons between models and ground-based measurements of surface turbulent heat flux. It also improves predictions of spatial heterogeneity, including crop distributions in the winter-wheat belt spanning central Oklahoma and parts of Kansas.

"The new data set gives a more accurate and detailed depiction of vegetation properties and surface fluxes," said Williams.

It will be useful, he added, in cloud-resolving models and large-eddy simulations at the ARM site.

### Reference

Williams IN, JM Lee, J Tadić, Y Zhang, and H Chu. 2020. "Modeling spatial heterogeneity in surface turbulent heat flux in the U.S. southern Great Plains." *Journal of Geophysical Research: Atmospheres,* 125(13):e2019JD032255, https://doi.org/10.1029/2019JD032255.




**Centered on ARM's Southern Great Plains Central Facility (blue crosshairs), true—color satellite imagery from July 2015 shows fields of winter wheat (brown) and grass (green).** *(Copyrighted image from the journal.)*

**Dramatic cloud cover looms over a patch of ARM's Southern Great Plains atmospheric observatory.**

## Scientists Chase Modeled Air Motions Within Storms

Mesoscale convective systems (MCSs) bring severe weather, affect economies, and regulate the global water cycle and general circulation—all characteristics making them important to model correctly.

Researchers struggle to measure and model one fundamental MCS property: convective vertical air motions, the updrafts and downdrafts that embody the kinematic character of thunderstorms. Ideally, specialized observational aircraft would penetrate storm systems often, sweeping up data. But such forays are costly, hazardous, and infrequent. The consequent shortage of direct observations inhibits model improvements.

A *Journal of Geophysical Research: Atmospheres* study of updraft and downdraft core size and intensity, published online in May 2020, documents the structure of MCSs by using radar wind profilers. It illustrates how these observations can be used—and shows the importance of observing and modeling these structures at relatively high spatial resolution.

Led by Dié Wang at Brookhaven National Laboratory in New York, researchers summarized mature-storm convective draft properties, including core width, shape, intensity, and mass flux (the volume of air moved by wind). They used ARM data from radar wind profilers, radiosondes, and surface sensors in Oklahoma and the Amazon Basin.

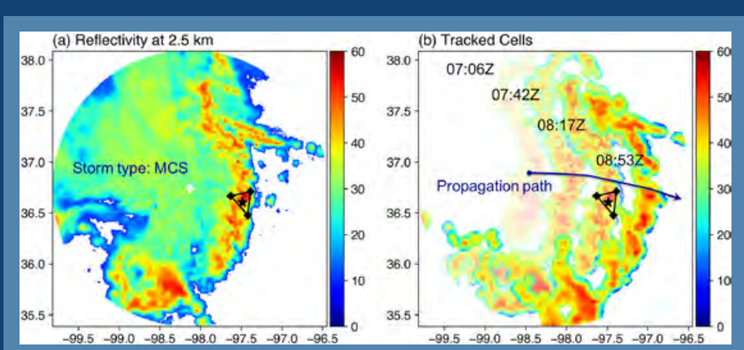
The researchers compared their observational statistics to idealized simulations from the Weather Research and Forecasting model at a range of resolutions—grid spacings of 4 kilometers (2.5 miles) to 250 meters (820 feet). They aimed to understand and quantify model performance and biases in simulating the behaviors and processes of convective draft cores.

Unsurprisingly, the best match with observations came from parameter performances modeled at a grid scale of 250 meters. But 250-meter grid spacing is still not enough to resolve—accurately simulate—some draft properties, especially downdraft intensity and mass flux.

“Downdrafts are particularly under-resolved,” said co-author Andreas Prein of the National Center for Atmospheric Research. “Future work will focus on going to even higher grid spacing to understand whether the model can simulate realistic draft characteristics.”

### Reference

Wang D, SE Giangrande, Z Feng, JC Hardin, and AF Prein. 2020. “Updraft and downdraft core size and intensity as revealed by radar wind profilers: MCS observations and idealized model comparisons.” *Journal of Geophysical Research: Atmospheres,* 125(11):e2019JD031774, https://doi.org/10.1029/2019JD031774.




**Two Next-Generation Radar (NEXRAD) views show a June 5, 2013, mesoscale convective system (MCS) event over ARM’s Southern Great Plains atmospheric observatory. The star represents the Central Facility. Triangles denote three extended facility sites.** *(Copyrighted image from the journal.)*

**Researchers used radar wind profiler data from ARM’s Southern Great Plains atmospheric observatory to study mesoscale convective system draft properties.**

## Studies Unite ARM Data and DOE High-Resolution Model Simulations

In FY2020, a few studies combined the power of ARM data and DOE's Energy Exascale Earth System Model (E3SM). The E3SM library includes ARM cases for validating or improving simplified representations to be used in E3SM, including its single-column model (SCM). An SCM encompasses a vertical column over one grid cell in a model extending from the surface to the top of the atmosphere.

Xue Zheng of Lawrence Livermore National Laboratory in California led a study assessing how well the single-column mode in version 1 of E3SM simulates the transition of precipitating marine stratocumulus clouds to cumulus. It featured a case study from the 2012–2013 Marine ARM GPCI Investigation of Clouds (MAGIC), which involved an instrumented cargo ship traversing the Pacific Ocean.

The authors compared the model with observations and a large-eddy simulation of the same case. They found that E3SM accurately captured the stratocumulus-to-cumulus transition but exhibited some problems with precipitation, such as drizzle evaporating too close to the surface. The authors identified some underlying causes for these problems, including the length of the model time step.

Models do not always accurately simulate diurnal precipitation changes. Yi-Chi Wang of Academia Sinica in Taiwan and Shaocheng Xie of Lawrence Livermore National Laboratory led a study to evaluate a recent change to the representation of convection initiation in E3SM that is expected to improve the timing of convection.

The authors used ARM data from Brazil and the Southern Great Plains to understand the underlying physics of the new convection trigger. Numerical tests with the E3SM SCM indicate that the new trigger could effectively suppress overactive daytime convection and capture the nighttime precipitation often missed by most earth system models.

Meng Zhang of Texas A&M University led a paper on understanding model processes responsible for simulating arctic mixed-phase clouds, which contain ice crystals and supercooled liquid cloud droplets. E3SM produces too little ice in these clouds, and this study seeks to evaluate the contribution of three model components to this issue.

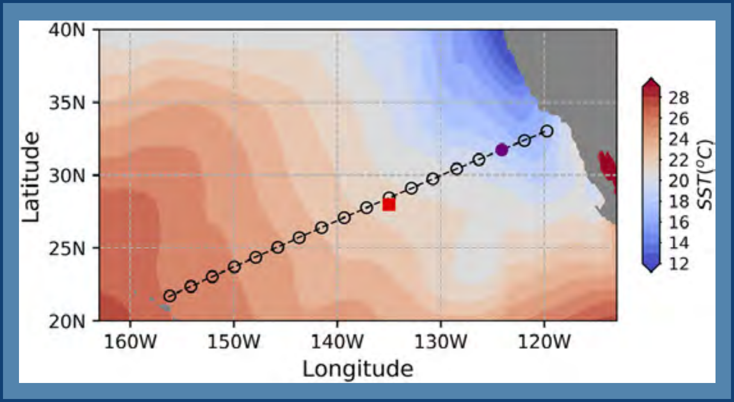
Through comparisons with ARM's 2004 Alaska-based Mixed-Phase Arctic Cloud Experiment (M-PACE), the authors determined that each component played a role in the underrepresentation of ice and the relative contribution of each component to this issue.

### References

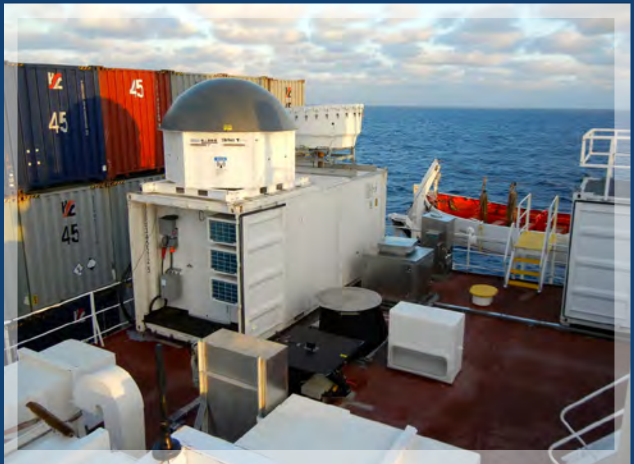

Zheng X, SA Klein, VP Ghate, S Santos, J McGibbon, P Caldwell, P Bogenschutz, W Lin, and MP Cadeddu. 2020. "Assessment of precipitating marine stratocumulus clouds in the E3SMv1 Atmosphere Model: A case study from the ARM MAGIC field campaign." *Monthly Weather Review,* 148(8):3341-3359, https://doi.org/10.1175/MWR-D-19-0349.1.

Wang Y-C, S Xie, S Tang, and W Lin. 2020. "Evaluation of an improved convective triggering function: Observational evidence and SCM tests." *Journal of Geophysical Research: Atmospheres*, 125(11):e2019JD031651, https://doi.org/10.1029/2019JD031651.

Zhang M, S Xie, X Liu, W Lin, K Zhang, H-Y Ma, X Zheng, and Y Zhang. 2020. "Toward understanding the simulated phase partitioning of arctic single-layer mixed-phase clouds in E3SM." *Earth and Space Science,* 7(7):e2020EA001125, https://doi.org/10.1029/2020EA001125.


**Sea surface temperature gradients are mapped for a transit leg during MAGIC. The black dashed line is the ship track. The purple circle is the location of the sounding used as an initial condition. The black open circles show the sounding locations. The red square shows the latitude and longitude of single-column mode simulations for the study.** *(Copyrighted image from the journal.)*



**A 2020 paper featured a case study from the MAGIC field campaign, during which an instrumented cargo ship made trips between Los Angeles, California, and Honolulu, Hawaii.**

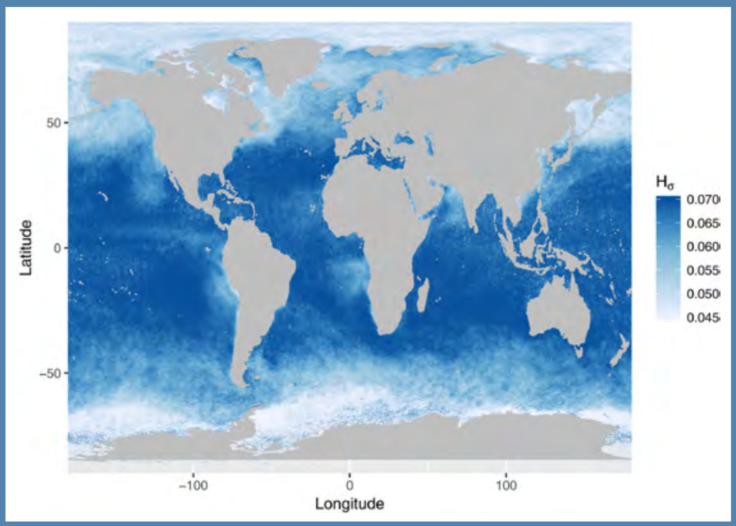
## An Exploration of Droplet Number Concentration in Warm Clouds

Cloud droplet number concentration is an important factor in understanding aerosol-cloud interactions. In the case of warm (liquid water) clouds, aerosol impacts are closely related to the droplet number concentration, which is most commonly measured by airborne instruments.

A 2018 *Reviews of Geophysics* study, noted in early 2020 by the Web of Science Group as a highly cited paper, reviews uncertainties associated with current satellite retrievals of droplet number concentration. The paper assesses assumptions used within satellite retrievals—a task for which ARM data proved useful.

For example, simulations of mixed-phase clouds (containing ice and liquid) constrained by airborne ARM measurements over the Arctic had nearly identical droplet number concentration profiles, with or without ice included.

The paper also looks at retrieval techniques using ground-based remote-sensing observations, including work pioneered using ARM observations over the Eastern North Atlantic.




**One way to estimate the quality of satellite retrievals is the heterogeneity index, as pictured in the bar graph above, next to a compilation of 2008 data on single-layer liquid clouds from the satellite-based MODerate Imaging Spectroradiometer (MODIS). Such satellite retrievals imperfectly infer cloud properties such as droplet number concentration.** *(Copyrighted image from the journal.)*

The authors conclude that combining ground- and satellite-based measurements of droplet number concentration and related cloud properties "might have the potential to enhance both types of retrievals and to characterize errors given the relative advantages of each."

**Reference**


Grosvenor DP, O Sourdeval, P Zuidema, A Ackerman, MD Alexandrov, R Bennartz, et al. 2018. "Remote sensing of droplet number concentration in warm clouds: A review of the current state of knowledge and perspectives." *Reviews of Geophysics*, 56(2):409-453, https://doi.org/10.1029/2017RG000593.


## Researchers Crack Open Shells Around Shallow Clouds

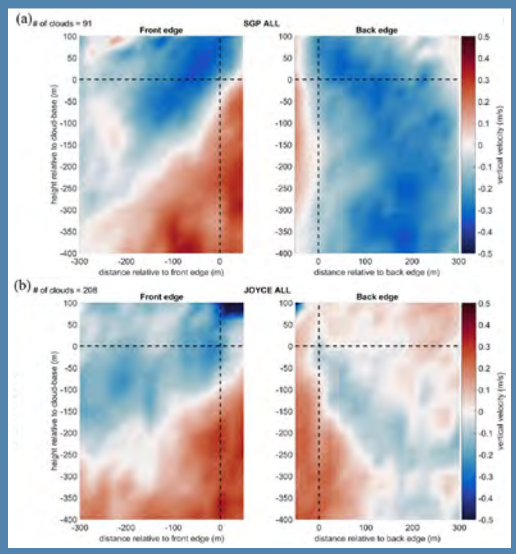
Earth system models separate shallow cumulus clouds from their surrounding environment, but they struggle to account for subsiding shells—moist regions of sinking air around the clouds. A *Geophysical Research Letters* paper published online in August 2020 explored how the shells behave.

Doppler lidar data from ARM's Southern Great Plains atmospheric observatory and a German cloud observatory showed vertical asymmetry between shells at the front and back edges of the cloud. Using large-eddy simulations, researchers found that this difference resulted from fundamental cloud structures, not how the lidars sampled the clouds.

This study started as a group project during the July 2018 ARM Summer Training and Science Applications event in Oklahoma. Lead author Lucas McMichael at the University of Kansas was one of 24 graduate students and early career scientists to participate in the event. The weeklong program, taught by veteran atmospheric scientists, focused on applications of ground-based remote-sensing observations.

**Reference**


McMichael LA, F Yang, T Marke, U Löhnert, DB Mechem, AM Vogelmann, K Sanchez, M Tuononen, and JH Schween. 2020. "Characterizing subsiding shells in shallow cumulus using Doppler lidar and large-eddy simulation." *Geophysical Research Letters*, 47(18):e2020GL089699, https://doi.org/10.1029/2020GL089699.


**These vertical velocity composites are for all clouds observed at (a) the Southern Great Plains atmospheric observatory and (b) the JOYCE observatory in Germany. Wind blows from right to left (the back edge is upwind). Cloud resides in the first quadrant for the front-edge plots and in the second quadrant for the back-edge plots.** *(Copyrighted image from the journal.)*

### ARM Images Help University Team Home In on Ice Halos

In the atmosphere, ice crystals make up thin, layered cirrostratus clouds starting at about 5,000 meters (16,400 feet). The crystals bend light that passes through them, forming a halo. The most common halo is a 22-degree halo, which occurs when smooth-faced hexagonal ice crystals exist within a cloud. Its name represents the halo's 22-degree radius around the sun or moon.

To learn more about cirrostratus cloud composition, several students at the University of Minnesota, Morris, made computer image analysis of halos the focus of their undergraduate research project. Advised by Sylke Boyd, an associate professor of physics, they wrote and refined an algorithm to detect 22-degree halos in all-sky camera images, including ones from ARM.

A paper summarizing the project appeared in *Atmospheric Measurement Techniques* in 2019. The ARM total sky images used to help train the algorithm came from the Southern Great Plains.


**A 22-degree halo—named for its radius around the sun or moon—appears in an all-sky camera image over the University of Minnesota, Morris, campus.**

**Reference**

Boyd S, S Sorenson, S Richard, M King, and M Greenslit. 2019. "Analysis algorithm for sky type and ice halo recognition in all-sky images." *Atmospheric Measurement Techniques*, 12(8):4241-4259, https://doi.org/10.5194/amt-12-4241-2019.

### ARM Modeling Activity Closes Book for Now on Shallow Convection

The Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity began to enter a new phase in FY2020.

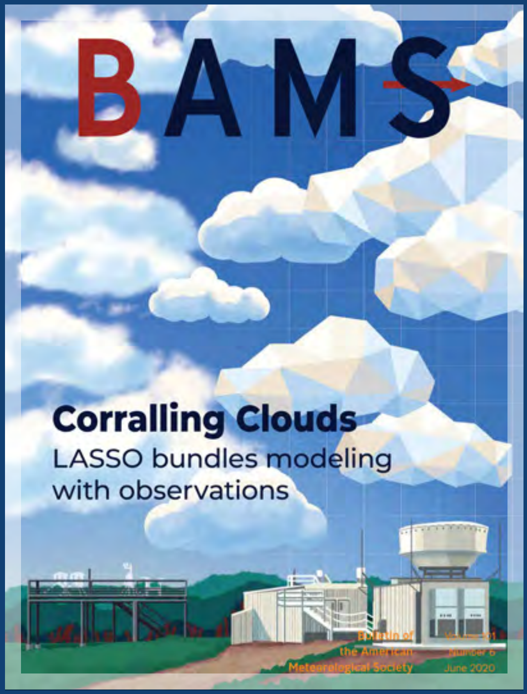
Since 2015, LASSO focused on continental shallow convection over ARM's Southern Great Plains (SGP) atmospheric observatory. By combining ARM observations with LES modeling, LASSO "data bundles" allow researchers to compare routine, high-resolution simulations with what happened over the SGP on a given date.

After five seasons of shallow convection work, the LASSO team announced in January 2020 that it would start turning its attention toward deep convection. Initially, the deep convection case will focus on ARM's 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in Argentina.

The LASSO team used FY2020 to prepare more SGP data bundles and make additional enhancements to the LASSO shallow convection product before putting the SGP scenario on hiatus.

The June 2020 issue of the *Bulletin of the American Meteorological Society (BAMS)* featured LASSO on its cover and an abridged version of a paper documenting the SGP shallow convection scenario.

William Gustafson, LASSO principal investigator from Pacific Northwest National Laboratory in Washington state, was the paper's lead author. He said that the *BAMS* cover image—an illustration of clouds over the SGP—"encapsulates two viewpoints of clouds from the perspectives of real-world observations and discretized modeling." LASSO, he added, "blends these two viewpoints to advance the science of clouds."




**The June 2020 *BAMS* cover featured the LASSO activity at ARM's Southern Great Plains atmospheric observatory.**

In September, the LASSO team announced the release of data bundles from the 2019 SGP shallow convection season. Those data bundles included a new addition requested by users: the high-time-resolution data used to generate skill scores in the bundles and inform the LES simulations.

With the release of the 17 new case dates from 2019, the LASSO library contains 95 shallow convection cases.

**Reference**

Gustafson WI, AM Vogelmann, Z Li, X Cheng, KK Dumas, S Endo, KL Johnson, B Krishna, T Toto, and H Xiao. 2020. "The Large-Eddy Simulation (LES) Atmospheric Radiation Measurement (ARM) Symbiotic Simulation and Observation (LASSO) activity for continental shallow convection." *Bulletin of the American Meteorological Society*, 101(4):E462-E479, https://doi.org/10.1175/BAMS-D-19-0065.1.

# 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's Future Research Aircraft Moves to Modification Phase

A team led by FMS Aerospace of Huntsville, Alabama, was selected to lead the modification of ARM's recently purchased Bombardier Challenger 850 aircraft. Voyageur Aviation Corp. of North Bay, Ontario, Canada, started the hands-on work to convert the former business jet into a configuration suited for aerial research.

When the aircraft modification is complete, a no-frills interior will feature comfortably spaced instrument racks from front to back—all with neatly routed electrical and vacuum tubing.

"We're looking forward to a more open cabin that will allow more instrumentation and flexibility to meet the needs of the ARM research community," said ARM Aerial Facility Operations Manager Jason Tomlinson, noting that key cost drivers are external modifications, including three pylons under each wing. "The pylon location is exciting. It will really satisfy the needs of our PIs when it comes to cloud sampling and other measurements."

The front service door area—typically used as a galley for passenger jets—will house a variety of external instruments. Different instruments will go in place of the front two windows. Other areas of modification include large ports on the fuselage and belly of the aircraft that will either look up or down to accommodate instrumentation.

**"We're looking forward to a more open cabin that will allow more instrumentation and flexibility to meet the needs of the ARM research community."**

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

**The complex work of modifying the Challenger 850 to its new life in science will take about 18 months.**

## New ARM Data Discovery Browser Officially Launches

Finding ARM data got easier in May 2020, when the ARM Data Center officially switched to a new version of its Data Discovery browser. Here, users can search for and order data from ARM's archive, which crossed the 2-petabyte mark in FY2020.

Based on feedback from users and stakeholders, the ARM Data Center began developing the new Data Discovery in FY2019.

"In the past, users experienced a bit of a challenge finding the data that better suit their needs, especially with our vast collection of data," said Giri Prakash, who manages ARM's data services.

On the Data Discovery home page, users can look for data by typing in specific terms or employing a guided search. By default, Data Discovery filters search results to list recommended ARM data products based on criteria such as data quality, accuracy, and completeness.

Accessible from the search results screen, a new pop-up page provides data details and allows users to add data to the order cart.

"With Data Discovery, we have completely rethought how we do development," said Kyle Dumas, the browser's lead developer. "We have employed new technologies and practices that reduce the total code written while improving quality and reusability."

**"With Data Discovery, we have completely rethought how we do development." We have employed new technologies and practices that reduce the total code written while improving quality and reusability."**

*— Kyle Dumas, the browser's lead developer*

### ARM Data Quality Office Celebrates 20 Years of Service

For those close to ARM, an unofficial slogan might be, "It's all about the data." But users who integrate ARM data in their research may say, "It's all about the quality of the data."

The ARM Data Quality (DQ) Office, which celebrated its 20th anniversary in 2020, is the gatekeeper of ARM data collected around the world. The DQ Office is based at the University of Oklahoma Cooperative Institute for Mesoscale Meteorological Studies.

According to ARM DQ Office Manager Randy Peppler, the DQ team's principal mission is to identify data anomalies based on quality control procedures and tools.

"Two decades ago, ARM had the foresight not only to understand the importance of data quality, but the need to produce data in a coordinated way across the organization," said Peppler. "Today, ARM's data program is strong, and ARM users can feel very confident about the data they're using in their research."

**From left to right are ARM Data Quality Office staff members Ken Kehoe, Randy Peppler, Corey Godine, Alyssa Sockol, and Austin King.**

## Development Work Stays Front and Center in FY2020

ARM development activities in FY2020 focused on acquiring, installing, and phasing out instruments, upgrading facilities, and releasing new science products.

Among its instrument efforts, ARM upgraded one of its high-spectral-resolution lidars and tested it at the Southern Great Plains atmospheric observatory by running it with the Raman lidar. In a follow-on to a previous campaign at the site, ARM combined the lidars for testing multiwavelength aerosol retrievals to provide vertical profiles of aerosol properties.

The ARM Aerial Facility got a new hangar to house its Bombardier Challenger 850 regional jet, which is being modified for scientific missions. ARM also replaced two aging containers for the first ARM Mobile Facility, which in FY2020 marked the 15th anniversary of its field campaign debut.

The ARM Data Center rolled out a new version of Data Discovery, where users can find and order ARM data, and implemented a new system for reporting preventive and corrective instrument maintenance.

ARM data product activities included steps to harmonize—or standardize—aerosol size distribution and trace gas data from different instruments for improved usability. ARM also released a new group of products from the 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in Argentina. CACTI deep convection is the next scenario of focus for the Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) activity.

### Follow the History of ARM Aerosol Observing Systems

A paper published by the *Journal of Atmospheric and Oceanic Technology* in December 2019 details the history and capabilities of ARM's Aerosol Observing Systems (AOS).

The system, first developed in 1996, fulfills ARM's mission to provide the research community with in-place measurements that improve understanding and model representations of aerosols and clouds. AOS provide continuous observations required to reduce uncertainties in earth system models.

Brookhaven National Laboratory in New York upgraded the AOS design in 2009, and today five standardized ARM AOS are found around the world. Some of these systems are designed specifically to withstand extreme conditions, such as marine environments on ship deployments or prolonged exposure to cold.

**Two Aerosol Observing Systems—one old, left, and the other upgraded—are co-located at ARM's Southern Great Plains atmospheric observatory.**

This paper, written by several AOS and aerosol instrument experts, provides a valuable and comprehensive guide to the AOS infrastructure, instrument suite, and data processing steps. Janek Uin, an AOS instrument mentor at Brookhaven National Laboratory, was the lead author.

**Reference**

Uin J, AC Aiken, MK Dubey, C Kuang, M Pekour, C Salwen, AJ Sedlacek, G Senum, S Smith, J Wang, TB Watson, and SR Springston. 2019. "Atmospheric Radiation Measurement (ARM) Aerosol Observing Systems (AOS) for surface-based in-situ atmospheric aerosol and trace gas measurements." *Journal of Atmospheric and Oceanic Technology*, 36(12):2429-2447, https://doi.org/10.1175/JTECH-D-19-0077.1.

# New Data Products

## ARM Beefs Up Data Sets for Driving and Evaluating Models

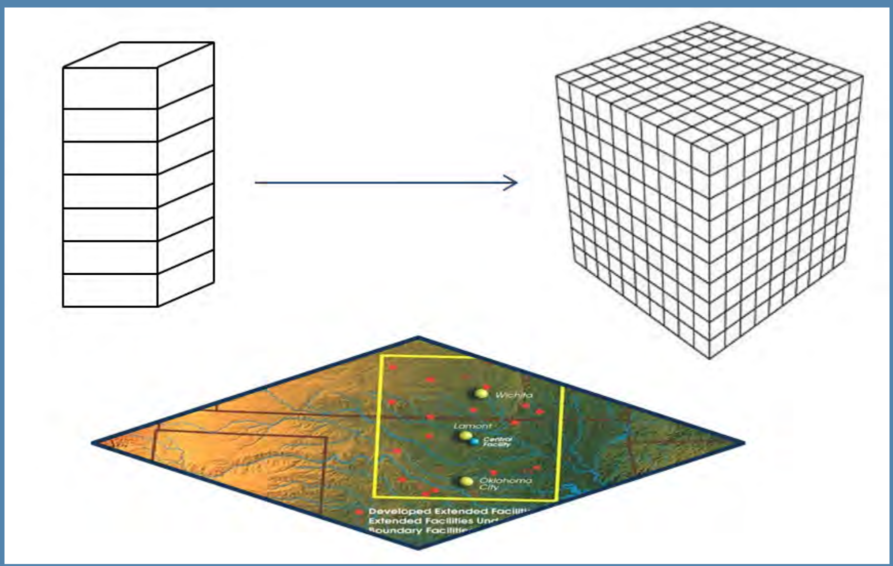
In FY2020, ARM served up more data products to aid modelers.

ARM Best Estimate (ARMBE) data sets for atmospheric measurements and cloud and radiation quantities were released for the Eastern North Atlantic (ENA) atmospheric observatory and mobile facility campaigns in Brazil, Niger, and Antarctica. ARMBE products contain best estimates of several quantities often used in model evaluation.

From the ENA, ARM released continuous large-scale forcing data using a constrained variational analysis approach, known as VARANAL. The period of data—June 2017 through February 2018—covers the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) campaign. These data allow scientists to drive and evaluate single-column models, cloud-resolving models, and large-eddy simulations for cloud and convective systems.

ARM also released its first three-dimensional large-scale forcing data product, VARANAL3D—an extension of the one-dimensional VARANAL. Initially, VARANAL3D evaluation data are available from ARM's Southern Great Plains observatory.

Meanwhile, a new metrics and diagnostics package aims to enable ARM data usage in earth system model evaluations. The package, called ARM-DIAGS, covers multiple ARM sites. ARM-DIAGS includes ARM data sets, compiled from multiple ARM data products, and a Python-based analysis toolkit for computation and visualization. ARM-DIAGS is housed on the GitHub development platform.




This schematic showing ARM's Southern Great Plains atmospheric observatory illustrates the difference between VARANAL, left, and VARANAL3D.

## New Value-Added Products Key In on Cloud Properties

ARM made available several new value-added products (VAPs) in FY2020 to help users answer questions about cloud properties.

The Point Cloud of Cloud Points (PCCP) VAP provides three-dimensional (3D) positions of clouds captured by stereo cameras at ARM's Southern Great Plains atmospheric observatory. PCCP enables 3D representations of macrophysical cloud features such as the cloud-base and cloud-top heights, structure of cloud boundaries, and cloud-level horizontal velocities.

ARM also released an evaluation VAP for cloud microphysical properties that builds upon the historical Continuous Baseline Microphysical Retrieval (MICROBASE) product.

The Improved MICROBASE Product with Uncertainties (MICROBASEKAPLUS) provides continuous, high-time-resolution profiles of cloud properties such as liquid/ice water content and liquid/ice effective radius.

In FY2020, ARM announced an updated version of its Microwave Radiometer Retrievals (MWRRET) VAP for 3-channel microwave radiometers.

The first MWRRET retrieves liquid water path (LWP) and precipitable water vapor (PWV) from ARM's original standard 2-channel microwave radiometers. LWP and precipitable water vapor are important variables in understanding radiative transfer in the atmosphere and clouds.

MWRRETv2 is initially available for 3-channel microwave radiometers at ARM's fixed observatories. The third channel provides additional sensitivity to liquid water, especially at low LWPs.

**In a field at ARM's Southern Great Plains atmospheric observatory, just south of Lamont, Oklahoma, a stereo camera aims at a precise point in the sky.** *Photo is courtesy of the Bulletin of the American Meteorological Society (BAMS).*

## Radar Releases Focus on Argentine Campaign, Scanning Radars

New ARM radar data products from the 2018–2019 Cloud, Aerosol, and Complex Terrain Interactions (CACTI) field campaign in Argentina made a splash in FY2020.

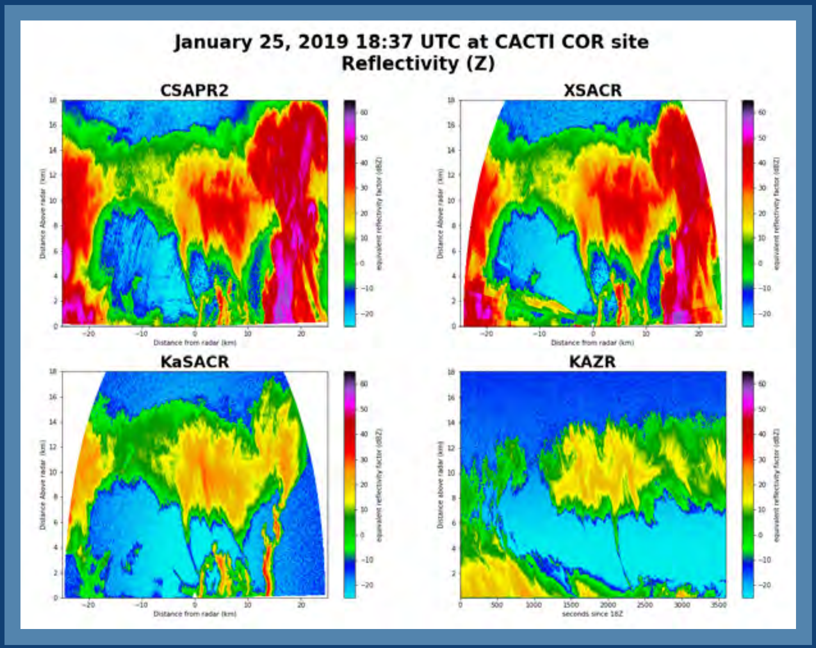
Leading the way was the release of CACTI radar data that underwent calibration, correction, and quality control processes beyond ARM's standard quality checks and corrections. These data—collectively known as a data epoch—can lessen uncertainty in retrievals such as particle phase or size distribution.

Other cloud radar value-added products (VAPs) released from CACTI include Scanning ARM Cloud Radar Grid (SACRGRID), providing radar moments from range-height indicator scans on a Cartesian grid. The Ka-Band ARM Zenith Radar Active Remote Sensing of CLouds (KAZRARSCL) VAP provides cloud boundaries and best-estimate time-height fields of radar moments. ARM also reprocessed CACTI cloud radar spectra.

In FY2020, ARM announced three evaluation VAPs for scanning ARM precipitation radars (SAPRs) at the Southern Great Plains atmospheric observatory.

SAPR Quasi-Vertical Profiles (SAPRQVP) and SAPR Velocity Azimuth Display (SAPRVAD) are derived from the Corrected Moments in Antenna Coordinates Version 2 (CMAC2) VAP. CMAC2 corrects raw radar data and retrieves precipitation quantities from the measurements.

Another new evaluation VAP, Mapped Moments to a Cartesian Grid (MMCG), allows users to analyze CMAC2 data in Cartesian coordinates instead of antenna coordinates.




**Radar images of a large storm system that passed by the CACTI ARM Mobile Facility site highlight how different frequencies and sampling showcase different aspects of the storm.**

## Value-Added Products for Raman, Micropulse Lidars Move Into Production

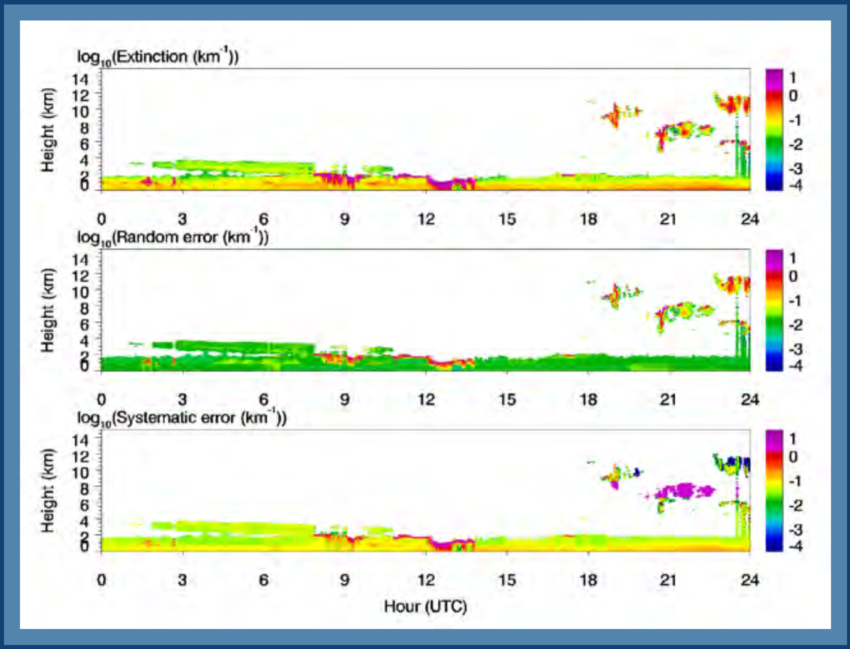
Gaps in our understanding of aerosols and their interactions and influence on clouds are among the main sources of energy balance uncertainties in models. To reduce these uncertainties, continuous height-resolved measurements of cloud and aerosol optical properties are needed.

ARM's Raman Lidar Profiles – Feature detection and Extinction (RLPROF-FEX) value-added product (VAP) provides height- and time-resolved estimates of aerosol and cloud extinction, backscatter, and vertical and horizontal depolarizations. In FY2020, RLPROF-FEX moved to production for ARM's Eastern North Atlantic and Southern Great Plains atmospheric observatories.

Scientists can use the output from RLPROF-FEX for process studies, climatology development, instrument intercomparison studies, and model validation.

ARM also put an updated version of its Micropulse Lidar Cloud Mask (MPLCMASK) VAP into production for sites operating fast-switching polarized micropulse lidars. MPLCMASK implements a cloud detection algorithm to provide cloud boundaries from ARM micropulse lidars. The cloud mask from MPLCMASK is the primary lidar cloud mask for input to the Active Remote Sensing of CLouds (ARSCL) VAP.

The updated MPLCMASK applies instrument corrections to the lidar measurements with modifications specific to a polarized fast-switch system. It also calculates the linear depolarization ratio, which provides information on particle shape.




This figure for RLPROF-FEX shows the aerosol extinction coefficient and its uncertainties at ARM's Eastern North Atlantic atmospheric observatory on July 21, 2019.

## Ship-Based Southern Ocean Campaign Spawns Value-Added Products

ARM released evaluation data for navigation and ship correction from the 2017–2018 Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) field campaign.

On shipboard deployments, some ARM Mobile Facility instruments collect Global Positioning System and inertial navigation system measurements. The Navigation Best Estimate (NAVBE) value-added product (VAP) consolidates multiple sources of these data into one continuous datastream to be used when information is required about ship location and orientation, and to provide an estimate that would not necessarily be available from any one instrument.

Complementing and making use of NAVBE, several ship-correction VAPs post-process ARM data to correct the effect of ship motion on measurements intended to be vertically pointing.

For MARCUS, the Marine W-Band (95 GHz) ARM Cloud Radar Ship Correction (MWACRSHIPCOR) VAP produces motion-corrected fields of reflectivity, mean Doppler velocity, spectral width, and signal-to-noise ratio. Additional corrections are made to mean Doppler velocity to reduce the effect of ship heave, or upward/downward motion. The Micropulse Lidar Ship Correction (MPLPOLFSSHIPCOR) VAP produces corrected signal return values.

These data are inputs to the ship-corrected MWACR Active Remote Sensing of CLouds (MWACRARSCL) product, which provides cloud boundaries and best-estimate time-height fields of radar moments.

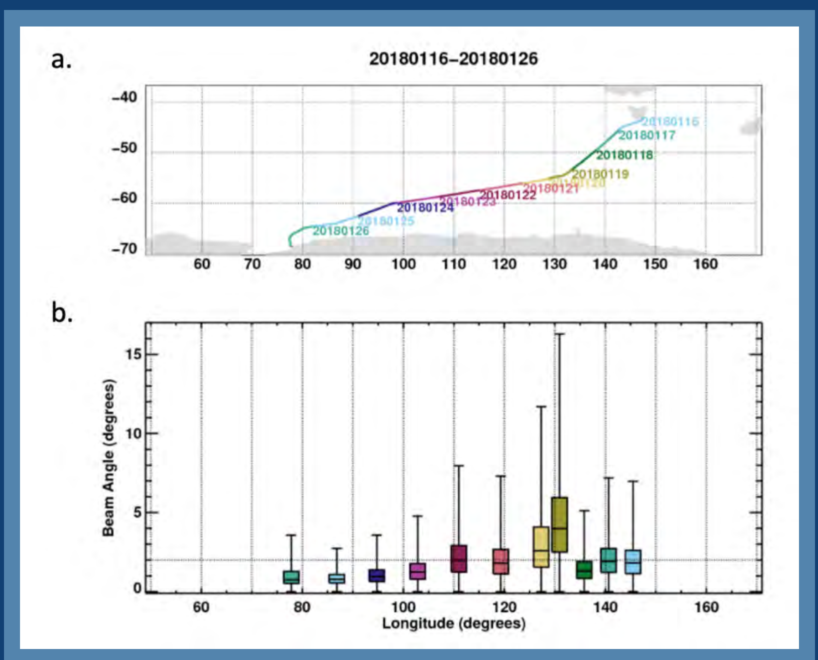



**Figure a shows the MARCUS ship's track—color-coded by day—from January 16 to 26, 2018. Beam angles are represented in figure b, and the colors of the boxes correspond to the days in figure a. Data in these figures come from NAVBE.**

### ARM Adds to Its Scientific Data Toolbox

To help users working with time-based atmospheric data sets, ARM supports the new open-source Atmospheric data Community Toolkit (ACT). This library provides code for the data processing life cycle—discovery, input/output, quality control, corrections, retrievals, visualization, and analysis—and anyone can use it or add to it.

ARM staff at Argonne National Laboratory in Illinois worked with the ARM Data Quality Office and ARM Data Center to develop ACT. The toolkit has already factored into important data revisions and streamlining of processes.

When a user noted that wind speed and wind direction data from ARM's Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) field campaign were not corrected for ship motion as the files indicated, the ACT team got to work. The team quickly put code into ACT, showing users how they could correct the wind for ship motion, and ARM updated metadata in the files.

## Boon of Aerosol Data Releases at Researchers’ Fingertips

In FY2020, ARM moved closer to harmonizing—or standardizing—aerosol size distribution data from different instruments.

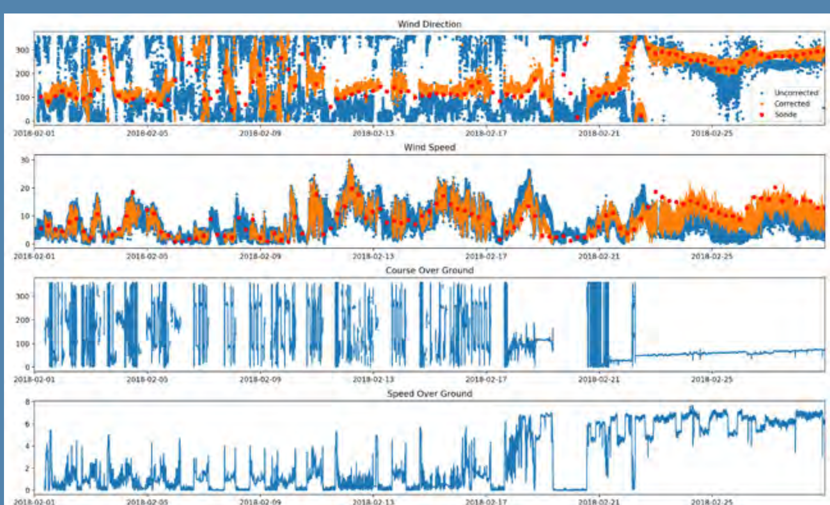
Quality-controlled b-level data became available for the ultra-high-sensitivity aerosol spectrometer, aerodynamic particle sizer, and regular and nanoparticle versions of the scanning mobility particle sizer. The b-level processing converts raw (a-level) counts from these four instruments to the same units and standardizes variable names. In future development, these data will be merged into a single, consistent size distribution that covers the entire measured size range.

Other b-level releases included calibrated ozone monitor data from the Eastern North Atlantic and Southern Great Plains (SGP) atmospheric observatories and from mobile deployments in Alaska, Norway, and the central Arctic.

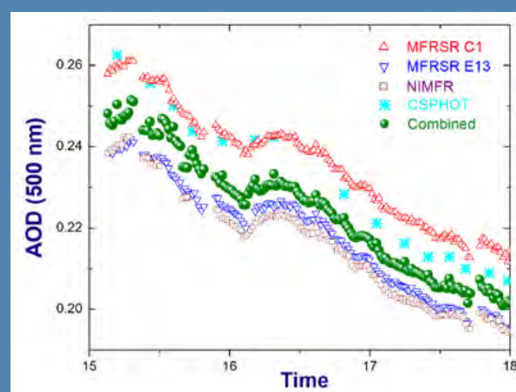
New aerosol chemical speciation monitor (ACSM) data, which provide information on aerosol composition, were also processed and released. Eastern North Atlantic and SGP b-level ACSM data are now available in near-real time. A new value-added product, which applies a composition-dependent collection efficiency correction to ACSM data, is available for evaluation.

Addressing differences in continuity, data quality, and time resolution among individual aerosol optical depth (AOD) products, ARM released the Quality Control Aerosol Optical Depth (QCAOD) value-added product. QCAOD is available for a 21-year period (1997–2018) at the SGP.

QCAOD merges individual AOD products from different radiometers to generate a combined AOD at two wavelengths with high-quality, enhanced continuity and 1-minute time resolution. In addition, QCAOD provides uncertainty assessment of the individual and combined AODs.




This plot shows, from the top: uncorrected, corrected, and sonde measurements of wind direction; wind speed (same comparisons as wind direction); the ship’s course over ground; and the ship’s speed over ground during the MARCUS field campaign. The Atmospheric data Community Toolkit team helped correct wind speed and wind direction data from the Aerosol Observing System meteorological sensor.




These time series show the combined aerosol optical depth (AOD, green) and its four individual components (red, blue, wine, and cyan) during a three-hour period at ARM’s Southern Great Plains atmospheric observatory.

# Science Outreach

## Back to Brazil: ARM Returns for Second Data Workshop

ARM's participation in a 2017 Brazilian data science workshop was such a success that ARM Data Center staff were invited back to the University of São Paulo for another workshop in 2020.

Representing ARM at the February 2020 event were Giri Prakash, Ranjeet Devarakonda, and Maggie Davis, all from Oak Ridge National Laboratory in Tennessee.

The workshop enabled knowledge sharing between the ARM Data Center and the Brazilian Atmospheric Data Science group. About 150 workshop participants discussed ideas around best practices in data management tools and techniques, including a hands-on session using ARM data.

On the first morning, Prakash, who manages ARM's data services, explained ARM's recent advances in data management and analysis, Devarakonda described data tools, and Davis discussed data visualization. In afternoon training sessions, ARM staff and Brazilian scientists viewed and analyzed ARM data from the Green Ocean Amazon (GoAmazon2014/15) campaign. During the second and third days, smaller groups focused on big-data issues.

Already, this group has planned journal articles and continued collaboration, while at least 35 Brazilian attendees have registered with ARM.

**ARM Metadata Flow Leader Maggie Davis, left, works with a data science workshop participant in Brazil.**

## ARM's Impact Showcased at 2019 AGU Fall Meeting

With about 25,000 attendees annually, the American Geophysical Union (AGU) Fall Meeting is the world's largest international earth and space science meeting. At the December 2019 AGU Fall Meeting in San Francisco, California—part of AGU's centennial celebration—ARM data were featured in more than 100 posters and presentations.

"AGU is a great place to showcase what ARM has accomplished and get valuable opinions on where we are going," said ARM Technical Director Jim Mather.

At least 12 posters and presentations used data from ARM's Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) field campaign, which ran in summer 2017 and winter 2018 in the Azores. Another heavily highlighted campaign was Green Ocean Amazon (GoAmazon2014/15), when scientists studied the atmosphere around Manaus, a Brazilian city of 2 million residents.

A media workshop focused on the yearlong Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition, which began in September 2019. ARM deployed more than 50 instruments for MOSAiC.

Two ARM-related town halls helped to solicit feedback from the scientific community. Mather led a town hall on updating ARM's Decadal Vision strategic plan, and the other looked at observations, platforms, and campaigns in the Alaskan Arctic.

**At the ARM AGU exhibit, Jonathan Gero from the University of Wisconsin shows the campaigns with which he has been involved.**


**Tom Watson, an ARM instrument mentor, lectures during the 2019 Aerosol Summer School.**

### ARM/EMSL Aerosol Summer School Appears in BAMS

In July 2019, ARM and two other DOE entities—the Environmental Molecular Sciences Laboratory (EMSL) and Atmospheric System Research (ASR)—co-sponsored a weeklong summer school on aerosols and their effects on earth systems. A year later, the *Bulletin of the American Meteorological Society (BAMS)* published a meeting summary of the 2019 Aerosol Summer School.

Two dozen university students and postdoctoral researchers attended the summer school at Pacific Northwest National Laboratory in Washington state. ARM and EMSL, both DOE national scientific user facilities, served as co-hosts. ARM and EMSL staff and users, including several ASR-funded principal investigators, taught the material.

The *BAMS* summary—led by ARM Technical Director Jim Mather and co-authored by a group of summer school organizers and instructors—describes the course organization and curriculum. The course introduced students to a range of aerosol topics and to ARM and EMSL. ARM hopes to conduct similar courses in the future.

# Budget Summary **and Facility Usage**

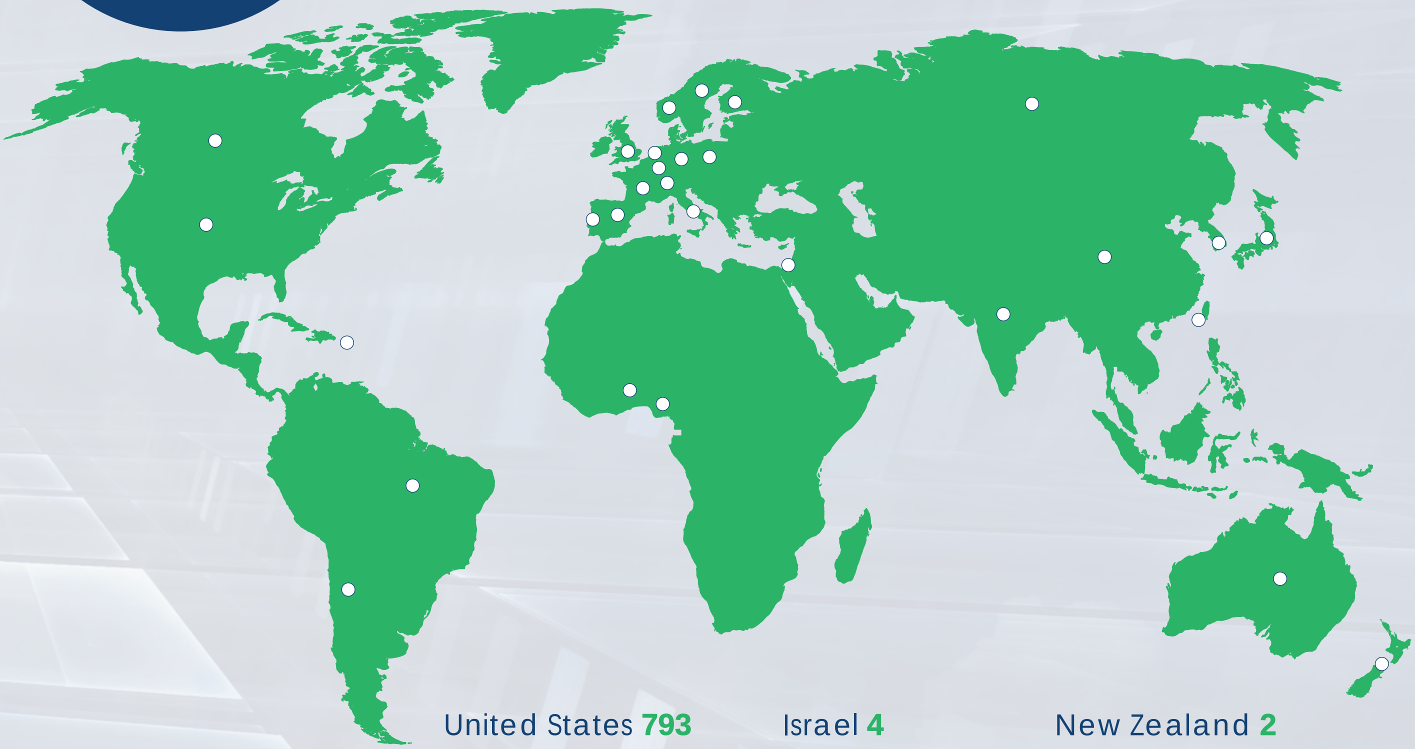
# Fiscal Year 2020 Statistical Overview

## INFRASTRUCTURE BUDGET

**$70,110K**

**1,001**
TOTAL SCIENTIFIC USERS

## USERS BY COUNTRY



United States **793**
China **37**
Germany **34**
United Kingdom **32**
Brazil **30**
Finland **8**
Australia **7**
Canada **7**
India **7**
Norway **5**
Israel **4**
Sweden **4**
Switzerland **4**
Italy **3**
Portugal **3**
South Korea **3**
Taiwan **3**
Argentina **2**
France **2**
Netherlands **2**
New Zealand **2**
Spain **2**
Cameroon **1**
Japan **1**
Luxembourg **1**
Nigeria **1**
Poland **1**
Puerto Rico **1**
Russia **1**

**29**
Countries

## USER STATISTICS

| | | |
|---|---|---|
| University | 512 | 51% |
| Foreign | 197 | 20% |
| DOE Labs | 170 | 17% |
| Other Gov | 73 | 7% |
| Industrial | 49 | 5% |

## FACILITY USAGE

| | | |
|---|---|---|
| Onsite | 57 | 6% |
| Remote | 203 | 20% |
| Data | 741 | 74% |

## PUBLICATIONS USING ARM*

**826** TOTAL

- ABSTRACTS OR PRESENTATIONS: 524
- TECHNICAL REPORTS: 59
- BOOK CHAPTER: 1
- JOURNAL ARTICLES: 223
- CONFERENCE PAPERS: 19

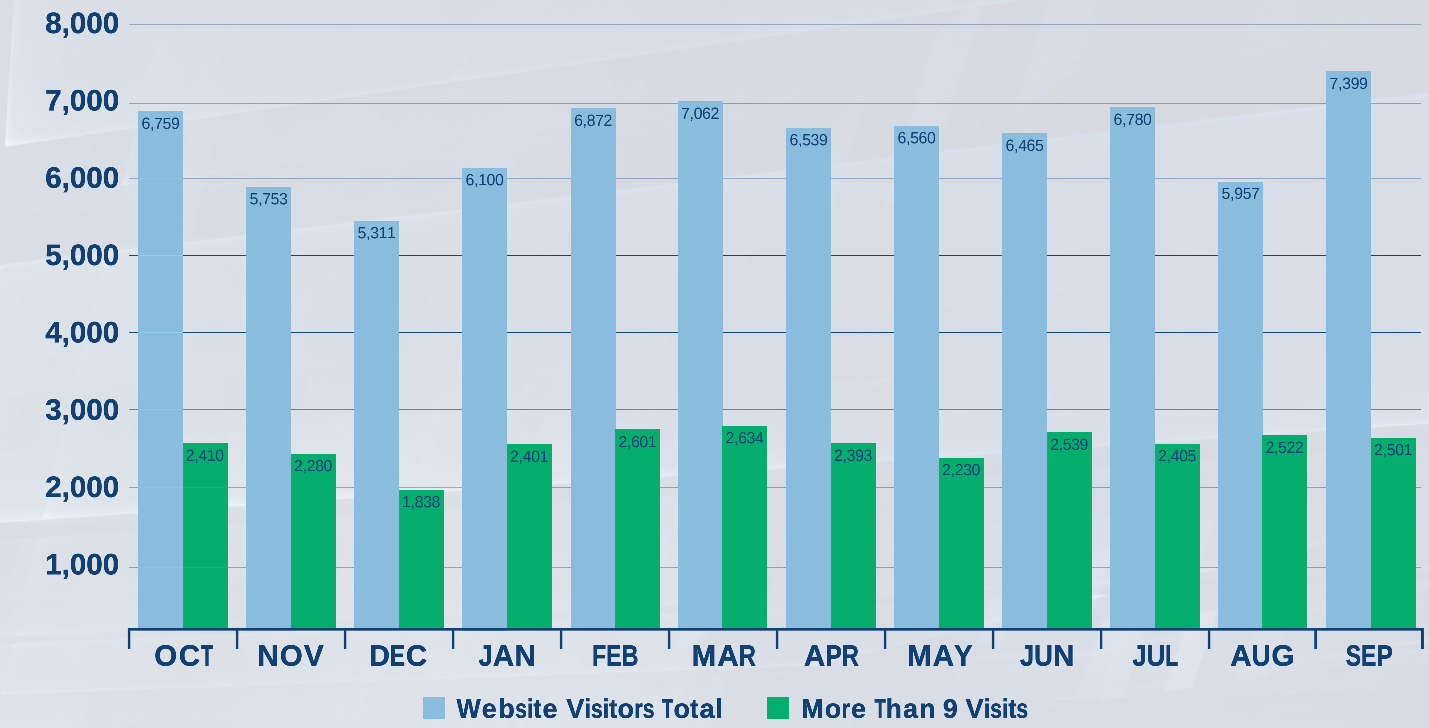
*Publication statistics were collected as of January 2021. Journal article numbers will continue to increase over time.

**450+** Instruments Collect Atmospheric Data

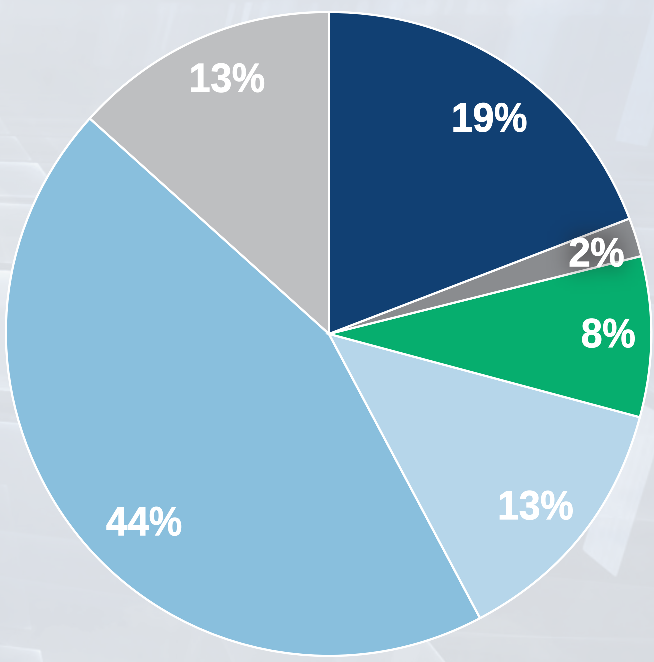
**~6,000** Publicly Available Datastreams

**~4,000** Journal Articles Since 1990

## WEBSITE VISITORS




## FIELD CAMPAIGNS




**52** Total

- AMF – 10
- AAF – 1
- ENA – 4
- NSA – 7
- SGP – 23
- OFFSITE – 7

## DATA PRODUCTS

**5** released to operations
- ADCME
- AOPAVG
- PCCP
- QCAOD
- RLPROF_FEX

**4** approved for development
- AOSACSMCDCE
- AOSCCNKAPPA
- PBLHT-DL
- CCN Profile

**6** released to evaluation
- AOSACSMCDCE
- MMCG
- PBLHT
- SAPRQVP
- SAPRVAD
- VARANAL3D

**7** existing VAPs updated
- CMAC2
- MFRSR AOD
- MPLCMASK
- MPLPOLFSSHIPCOR
- MWACRSHIPCOR
- MWRRETv2
- NAVBE

**6** b-level products implemented*
- APS
- nanoSMPS
- SMPS
- UHSAS
- Ozone
- CAPS

*Calibrations, corrections, and additional quality checks improved these data products.

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

# In Memoriam

## Charles "Chuck" Long
## (1953–2019)

ARM is saddened by the loss of friend and innovator Chuck Long, who died November 21, 2019, of cancer. Chuck was the ARM Tropical Western Pacific site scientist from 1999 until the sites closed in 2015. He retired at the end of 2018 from his senior research scientist position at the Cooperative Institute for Research in Environmental Sciences and NOAA Earth System Research Laboratory.

During his career, Chuck made lasting contributions to ARM and NOAA's radiation sciences programs. His work with radiometers included extensive study of the radiative impact of clouds, which led to the development of a technique to estimate clear-sky shortwave solar fluxes that is widely cited and used around the world. His fingerprints are on well-established ARM value-added products such as Radiative Flux Analysis (RADFLUXANAL) and Data Quality Assessment for ARM Radiation Data (QCRAD). Chuck also built the original prototype of the total sky imager, an instrument now in use at all ARM observatories.

Most of all, ARM misses Chuck's unique sense of humor and his willingness to tackle any problem, from logistics to science, with grit and a smile.

Members of the 2019–2020 Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition put down a sled to use as a footbridge over a crack in the ice floe.

**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 FY2020 and the pages on which their photos appear:*

**Matthew Shupe,** Cooperative Institute for Research in Environmental Sciences (Cover, Page 46)

**Hannes Griesche,** Leibniz Institute for Tropospheric Research (Page 2)

**Andrea Starr,** Pacific Northwest National Laboratory (Page 3, 8, 17, 39, 44)

**David Chu,** Los Alamos National Laboratory (Page 4)

**Nicki Hickmon,** Argonne National Laboratory (Page 6, 31)

**Alex Kotsakis,** University of Houston (now at the Universities Space Research Association; Page 11)

**Paola Salio,** Centro de Investigaciones del Mar y la Atmósfera/Universidad de Buenos Aires (Page 12)

**Stephen Springston,** Brookhaven National Laboratory (Page 12, 15)

**David Oaks,** ARM (Page 13)

**Tercio Silva,** Hamelmann Communications (Page 14)

**Scott Collis,** Argonne National Laboratory (Page 16)

**Michael Jensen,** Brookhaven National Laboratory (Page 16)

**Michael Lawler,** University of California, Irvine (Page 19)

**Katia Lamer,** Brookhaven National Laboratory (Page 21)

**Sylke Boyd,** University of Minnesota, Morris (Page 27)

**Jason Tomlinson,** Pacific Northwest National Laboratory (Page 28, 29)

**Emily Summars-Jeffries,** University of Oklahoma Cooperative Institute for Mesoscale Meteorological Studies (Page 30)

**Giri Prakash,** Oak Ridge National Laboratory (Page 38)

DOE/SC-ARM-20-020

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