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U.S. DEPARTMENT OF
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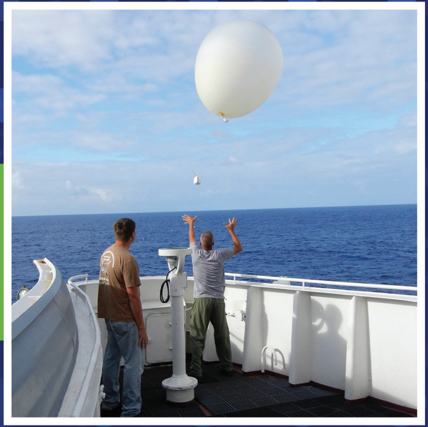
Office of
Science

Accomplishments in ATMOSPHERIC SCIENCE



2008-2013

Accomplishments in Atmospheric Science

The U.S. Department of Energy's (DOE) Office of Science is the single largest supporter of basic research in the physical sciences in the United States. Within this research portfolio, its Climate and Environmental Sciences Division sponsors atmospheric research to understand the physics, chemistry, and dynamics governing clouds, aerosols, and precipitation. The goal: to advance the predictive understanding of Earth's climate system, and inform the development of sustainable solutions to the Nation's energy and environmental challenges.

Toward this goal, two tightly linked DOE entities work cooperatively, connecting observations and studies of Earth's atmospheric system with the computer models that open a window to Earth's future climate.

Atmospheric Radiation Measurement (ARM) Climate Research Facility. For two decades, ARM has been recognized as the world leader for providing atmospheric measurements of cloud, aerosol, radiation, and precipitation properties. Continuous observations from heavily instrumented sites at strategic locations around the world are augmented with data from periodic field campaigns at specific locations or from aircraft. As a scientific user facility, the global research community has full access to the ARM Facility observational network and data.

Atmospheric System Research (ASR) program. University and national laboratory scientists funded by ASR use long-term data from the ARM Facility, targeted field campaigns, laboratory studies, and process models to explore cloud, aerosol, and precipitation processes. ASR has made significant advances in these areas, which are critical to improving the regional and global models used to simulate Earth's future climate. The ASR community is a key ARM user group and provides targeted scientific feedback to ensure that ARM measurement strategies are scientifically responsive and cutting edge.

The following pages describe key scientific accomplishments and activities from ARM and ASR during the past five years, and a vision for the future that builds on these accomplishments.

Improvements to Global Climate Models

Computer models—not crystal balls—are the only tool scientists have to peer into the future. More accurate data and better analysis techniques increase the confidence in model predictions. In the past five years, ARM data and associated ASR research have contributed to improvements in several global climate models, including the joint DOE and National Center for Atmospheric Research (NCAR) Community Atmosphere Model, or CAM5.

New Techniques Improve Model Efficiency and Accuracy

The largest uncertainty in future climate predictions is how changes in aerosol and cloud properties will interact with the Earth's energy balance to either amplify or reduce warming. In order to develop improved predictions of these climate 'feedbacks', researchers have developed more efficient and accurate treatments of aerosol, cloud, and radiative transfer processes in global models. In climate models, the term 'radiative transfer' refers to the movement of energy in and out of Earth's atmosphere. Because this complex process involves interactions with both clouds and aerosols, *radiative transfer* models consume a lot of computer time. Building on previous advances in this area, researchers developed a new radiative transfer model designed specifically to run more efficiently and accurately in global models. It includes novel techniques for capturing the interaction of radiation with clouds.

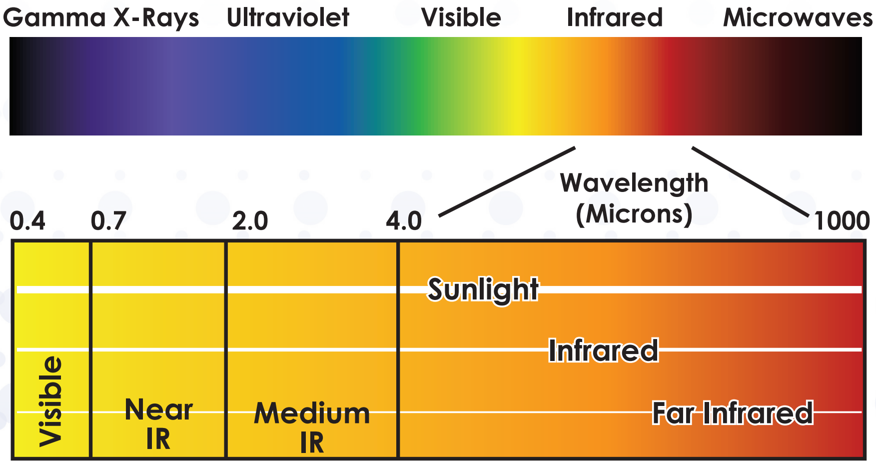
Researchers also used ARM data to develop new techniques that better predict how aerosol and cloud particles form and grow in the atmosphere. The new aerosol model includes the diversity of aerosols in three size ranges, better capturing the details of aerosol particles. The new cloud formulation describes cloud droplets in terms of water mass per unit volume, as well as the number of cloud droplets in that volume, whereas previous techniques only determined water mass. These improvements resulted in far more realistic portrayals of these processes in the CAM5 model and are expected to improve accuracy in other model simulations.

Improved Measurements of Infrared Radiation

Atmospheric gases, such as water vapor and carbon dioxide, absorb infrared radiation to create a warming influence known as the greenhouse effect. Computer models that simulate this absorption are a critical part of climate models. Measurements in the mid-infrared are quite well known, but until recently, measurements in far-infrared region were nearly non-existent, even though absorption in that region is very important for heating in the upper atmosphere.

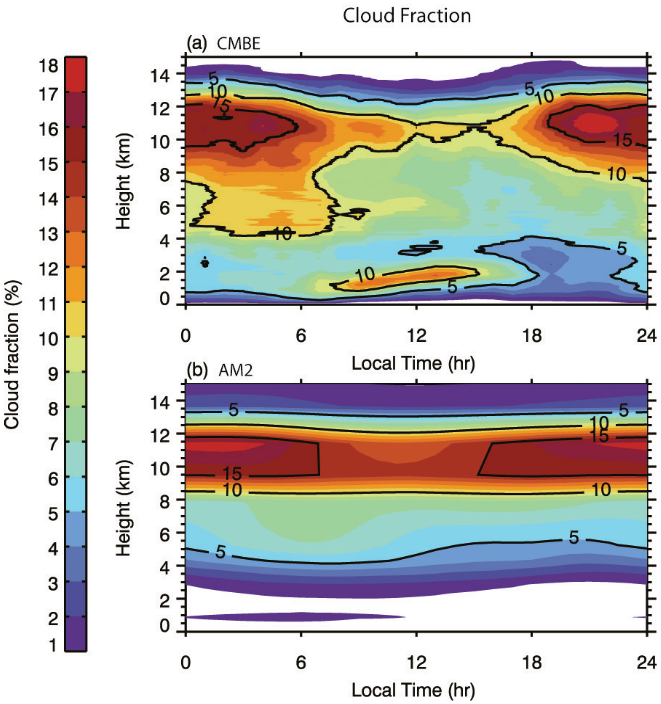
With advances in technology for measuring water vapor and far-infrared radiation, ARM conducted the Radiative Heating in Underexplored Bands Campaigns (RHUBC) in two phases, at arid locations where concentrations of water vapor were very low: the North Slope of Alaska (2007) and northern Chile (2009).

Using data from RHUBC, ASR scientists made substantial changes to model inputs of the strength of water vapor absorption in the far-infrared. When incorporated into the Community Earth System Model, improvements to a wide variety of atmospheric parameters included temperature and humidity profiles, as well as cloud amount in the middle and upper troposphere. These experiments and follow-on applications resulted in a substantial improvement to the representation of far-infrared radiation in radiative transfer models that will, in turn, improve the accuracy of climate model simulations.



New Products for Evaluating Models

Continuous observations from ARM sites are ideally suited to studying atmospheric processes, which indirectly leads to improvements in climate models. However, ARM data are also used to directly evaluate climate models through "data products" that make it easier for modelers to access and use ARM data. These products pull together data from multiple instruments and average them to time scales appropriate for climate models. This makes ARM data easier for climate modelers to use in comparison studies with model simulations.



For example, ARM Best Estimate products combine many measurements of cloud, radiation, and atmospheric quantities. These new products are part of the standard set of evaluation data products for the DOE/NCAR CAM5 and are also used to evaluate other models. For example, in the figure shown, the ARM Cloud Modeling Best Estimate (CMBE) shows significantly more detail about cloud fraction over a 24-hour period when compared against another model in the lower panel.

Understanding Atmospheric Processes

African Aerosols as Seeds for Hurricanes

In central Africa, the area known as the Sahel endures an annual monsoon cycle of dry winters and summers punctuated by active storm periods. The region is heavily influenced by natural aerosols in the form of both dust and smoke. As part of the ongoing African Monsoon Multidisciplinary Analysis (AMMA) focused on this region, the ARM Mobile Facility operated in Niamey, Niger, in 2006, gathering an unprecedented data set for studying aerosols and storm clouds in this climatically and meteorologically important region.

Broad international participation in AMMA has led to over 40 papers from U.S. and European scientists using the ARM data on topics ranging from detailed analyses of aerosol properties, the life cycle of monsoon convective cloud systems, and detailed descriptions of the annual cycle. These analyses have global implications because convective systems from West Africa can form hurricanes that reach North America.

Vertical Motion Drives Cloud Lifetimes

Many clouds begin and end with the movement of air as it rises. The ability to measure the motion of air —both inside of clouds and surrounding them—is important for understanding and modeling the life of clouds. Advances in technology and scientific understanding have resulted in the use of new instrumentation that can measure vertical motion under a variety of conditions. Using these measurements, researchers have developed data products and analysis techniques that are critical for evaluating observations and climate model simulations of the cloud life cycle.

For instance, scientists used these new tools to assess model simulations of vertical motion in tropical storms. Compared to observational data, the modeled storm updrafts were far too strong, which could cause erroneous predictions of storm/monsoon length and intensity/severity.

Dissecting Tropical Storm Clouds

Heat and moisture generated by tropical storm clouds are important drivers of Earth's climate system, and directly affect the timing and intensity of regional monsoons. However, these large and complex cloud systems are notoriously difficult for models to simulate. In 2006, the Tropical Warm Pool-International Cloud Experiment augmented measurements from the ARM site in Darwin, Australia, with additional data from a regional radiosonde network and numerous research aircraft. This intensive 3-week observational campaign resulted in the development of a significant "forcing data set" (see inset) for the modeling community.

In one key finding from the many studies that used this forcing data set, researchers discovered that observations of deep convective updrafts appeared significantly weaker than simulated by most models. This suggests that models do not mix enough dry air into the convective updrafts and indicates a path forward for improving model simulations of tropical clouds.

What is model forcing? Atmospheric models that cover only a certain area require information at the boundaries to constrain—or force—the model to run within those boundaries. These "model forcing" data sets include information such as temperature, humidity, wind speed, and wind direction.

Unraveling the Mystery of Complex Arctic Mixed-phase Clouds

Clouds containing both ice and supercooled liquid water are referred to as “mixed-phase” clouds. Because of the year-round prevalence of mixed-phase clouds in the Arctic, even small shifts in their frequency can affect climate parameters such as ice concentration, freshwater runoff, and the productivity and diversity in marine and terrestrial ecosystems. Due in large part to ARM measurements at Barrow, Alaska, combinations of ground-based instruments can now more accurately detect these clouds, while aircraft observations from several ARM field campaigns have provided detailed information about these cloud processes.

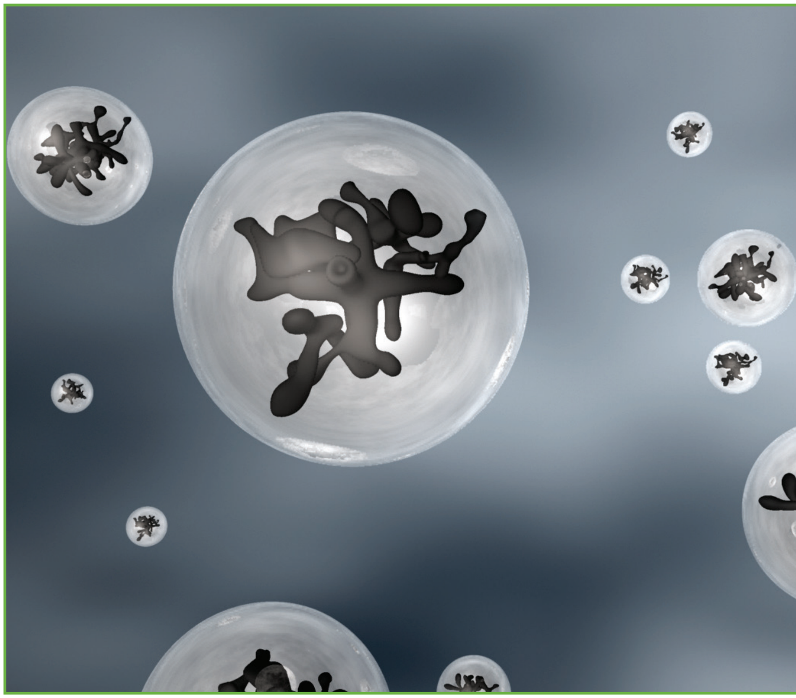
Using these new measurements in conjunction with modeling studies, ASR scientists have identified a complex set of processes that allow mixed-phase clouds to persist in the Arctic long after they would have dissipated in other environments. These processes include the formation and growth of cloud droplets, limited cloud ice formation, radiation moving through the tops of clouds, turbulence, and possible contributions from heat and moisture changes near the ground. This interconnected web of interactions support the resilience of mixed-phase clouds, which play a critical role in modulating Arctic energy flow.

Confirming the Impact of Aerosols on Clouds and Precipitation

Aerosols—tiny particles in the air, like dust or soot—typically serve as the nucleus on which water vapor condenses to ultimately grow to a cloud drop. While the amount and type of aerosols present should affect the properties of clouds, conclusive evidence of this connection has remained elusive—until recently. Using an extensive 10-year data set from the ARM Southern Great Plains (SGP) site in Oklahoma, ASR researchers found unprecedented evidence that aerosols can significantly alter the vertical thickness of clouds, as well as the frequency of precipitation.

In general, increases in aerosol or pollution tended to polarize precipitation, making dry places drier and moist regions wetter, thus reducing water usage efficiency—a key factor for life and agriculture. Researchers successfully reproduced the findings using a state-of-the-art cloud-resolving model. These findings, reported by thousands of media around the world in different languages, have implications for sustainable development, especially over regions vulnerable to extreme weather events, like drought or flooding.

Effects of Black Carbon on Heating



Black carbon particles come from the incomplete combustion of fossil fuels, biofuels, and biomass. In the atmosphere, these particles absorb sunlight, resulting in increased temperatures that affect atmospheric circulation and cloud development. In the Arctic, these particles land on snow and ice, darkening the surface and increasing the amount of the sun's energy converted to heat rather than reflected back to space. Through ARM measurements and ASR laboratory studies, researchers now have a better understanding of how black carbon interacts with other aerosol materials, and also how the composition of aerosols affects their ability to absorb light and other properties.

Specifically, one laboratory study verified model predictions that larger grains of snow generate more heat than smaller ones when contaminated by black carbon, thus contributing to ice melting and exacerbating global warming. In a second study, researchers found that many particles actually had a different structure than the commonly used model of a light-absorbing inner core surrounded by a non-absorbing shell, which may affect their ability to absorb sunlight and heat in the atmosphere. Further measurements around urban environments in California showed that the tendency of black carbon to absorb light and generate heat was significantly less pronounced than often simulated in global climate models.

Measuring Trends in Carbon Dioxide Concentrations

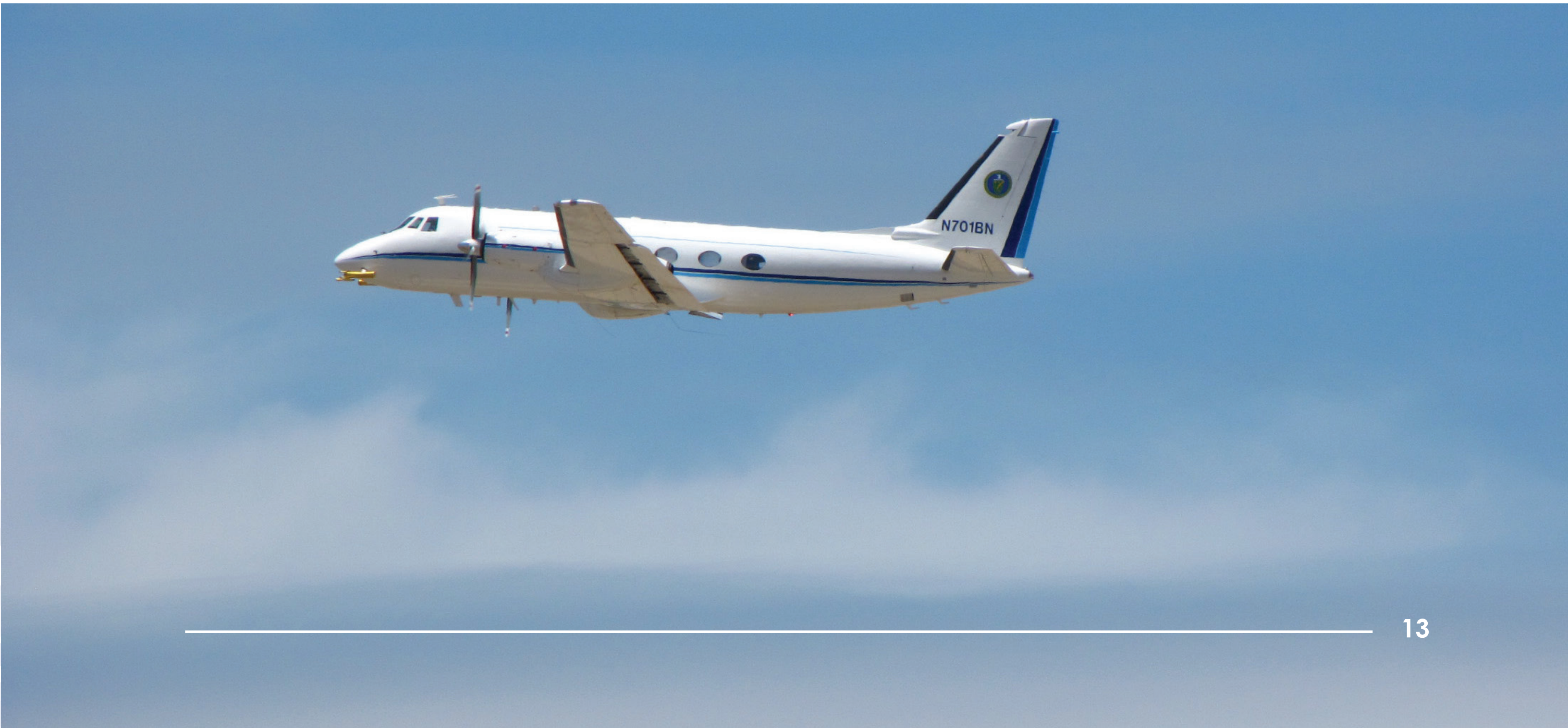
To understand the build-up of carbon dioxide (CO_2) in the atmosphere and forecast how it may change, it is important to understand both the sources of CO_2 and how it is absorbed. Isotopic measurements of CO_2 are valuable for exploring uptake processes because different surface types (e.g., land versus ocean or different land-use types) preferentially take up different ratios of the carbon isotopes. Since 2002, tower-based CO_2 measurements at the ARM SGP site have been one of the few sources of continuous CO_2 isotope observations. Analyses of these data have resulted in significant revisions to uptake rates for crop types prevalent in that region, reducing the uncertainty in CO_2 uptake rates in global models.

In addition, since 2007, long-term airborne CO_2 measurements over the SGP site provide trends in CO_2 concentrations and are used to validate measurements of CO_2 from ground- and satellite-based remote sensors. From 2008 to 2010, this CO_2 trend closely matched the trend observed at Mauna Loa in Hawaii, but with higher concentrations based on season and altitude. Researchers have also used the SGP airborne CO_2 measurements in validation experiments to develop a global picture of CO_2 concentrations.

Shedding Light on Organic Aerosols

A large fraction of organic, or carbon-based, aerosols, result from reactions by gas-phase chemicals of both natural (e.g., isoprene from trees) and man-made (e.g., toluene from gasoline) origins. Recent laboratory studies and field work to better understand the nature of these “secondary organic aerosols,” or SOA, have resulted in the development of new instruments capable of probing the detailed structure of aerosol particles and measuring gas-phase aerosol precursors. The ASR laboratory work revealed that, contrary to assumptions—the viscosity of SOA particles was upwards of a million times greater than expected; similar to that of tar!

Using data from ARM surface and airborne observations near Sacramento, California—an area influenced both by natural emissions from forests and urban man-made emissions—researchers found that SOA is far more likely to form when a mixture of both natural and man-made sources are present, rather than just one type. This result is being used for calculating SOA concentrations in climate models.



Getting on the Scale to Reduce Variability and Uncertainty

The interaction between aerosols and clouds remain the largest source of uncertainty in simulations of warming and cooling effects—or energy feedbacks—in climate models. This is because of the wide variability in measurements of their dynamic parameters, such as aerosol concentration. A key recent advance in this area revealed the importance of "scale-dependence" in measuring these effects.

In analyzing a combination of ARM data, satellite observations, and high-resolution model simulations, ASR researchers found that as measurements of aerosol and cloud properties were made at larger and larger scales, the variability of those parameters was greatly reduced. This was also true for the underlying relationships among the measured parameters, leading to erroneous conclusions about these relationships in previous studies. Using a combination of observations and model simulations to develop relationships among parameters at fine scales, then aggregating those relationships to coarser scales, researchers developed calculations of aerosol-cloud interactions that are more appropriate for evaluating global models. This scaling technique represents a very promising method for reducing a large source of uncertainty in climate models.

Joining Forces to Address Global Climate Issues: Science with the European Union

The ARM mobile facilities represent a unique capability for studying climate issues anywhere in the world. Based on their success, several countries are emulating the ARM model. In 2012, scientists supported by DOE and the European Union met to explore avenues for closer cooperation and accelerate progress related to understanding climate issues. The meeting resulted in a commitment to collaborate in select areas of opportunity, including cloud property measurements, cloud radar calibration, and data sharing.

Looking Ahead

Increasingly, research using ARM data, both within ASR and the broader scientific community, is focused on understanding the life cycles of clouds and aerosols, as well as their interactions. Studying these processes requires greater attention to the spatial characteristics of cloud and aerosol fields, as well as the integration of many measurements. With these needs in mind, and through funding provided by the American Recovery and Reinvestment Act of 2009, ARM's recently expanded and diversified measurement capabilities include instruments such as scanning cloud and precipitation radars and advanced aerosol probes. ARM also integrates data from multiple instruments into special data products for addressing critical scientific questions.

In the coming years, ASR will apply these new measurements to resolve these challenging life cycle related science issues. These measurements, in concert with high resolution process modeling, will provide the needed information to develop improved representations of aerosol and cloud life cycles in regional and global climate models that will enhance their predictive capabilities.

For more information

ARM website: ***http://www.arm.gov***

ASR website: ***http://asr.science.energy.gov***

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