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SOUTHERN GREAT PLAINS

CLOUD AND RADIATION TESTBED SITE

Operated for the U.S. Department of Energy

by Argonne National Laboratory

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A UNIQUE CLIMATE RESEARCH SITE

The Cloud and Radiation Testbed site is a fixed location for climate research, operated by Argonne National Laboratory for the DOE Atmospheric Radiation Measurement (ARM) Program. The site's concentrated collection of instruments is unique. The ARM Program exemplifies teamwork and sharing of expertise and results among investigators from national laboratories, federal agencies, and academic institutions.

Welcome to the Southern Great Plains Cloud and Radiation Testbed (CART),

the U.S. Department of Energy's (DOE's) outdoor laboratory for atmospheric research in Kansas and Oklahoma. DOE established its Atmospheric Radiation Measurement (ARM) Program to answer questions about global climate change. The site you are visiting is the first of three field sites established by the ARM Program to accomplish that mission. This site is managed by Argonne National Laboratory, located near Chicago.

The ARM Program seeks to improve the accuracy of **general circulation models** on which climate forecasts are based. The information generated will provide answers to questions about climate change, thus helping national and international agencies determine better strategies for producing energy and regulating emissions of greenhouse gases. Global change research remains a high priority for the United States. The

National Science and Technology Council's Committee on Environment and Natural Resources Research has established the U.S. Global Change Research Program, of which DOE's ARM Program is a vital part. The ARM Program was designed to address the **interactions of solar radiation and clouds**, the highest-priority research area identified for DOE by the U.S. Global Change Research Program.

To improve general circulation models, the ARM Program is designed to provide data to (1) strengthen the treatment of radiative transfer in general circulation models under clear sky, generally overcast sky, and broken clouds and (2) upgrade the mathematical representation in the models of the properties and formation of clouds. Data from the CART site are allowing researchers, for the first time, to compare climate model calculations with meteorological measurements in near-real time. This capability will accelerate improvements in both observational methods and general circulation models.

Central Facility of the Southern Great Plains Cloud and Radiation Testbed Site

The first instrumentation was deployed at the CART site in May 1992. Additional instruments and data processing capabilities have been added incrementally in succeeding years, making this site the largest and most extensive climate research field site in the world.

The Great Plains of Kansas and Oklahoma were chosen as the location of the CART site for several reasons:

- Relatively homogeneous geography
- Widely variable cloud types and surface flux properties
- Large seasonal variation in temperature and specific humidity
- A large existing network of weather and climate research instrumentation
- The opportunity for mutually beneficial activity with investigators in many other federal and state climate research programs

On the CART site, about three dozen clusters of in-situ and remote sensing instruments are arrayed across approximately 55,000 square miles of north-central Oklahoma and south-central Kansas. The site is similar in size to a grid cell in a general circulation model.

The heart of the **CART** site is the heavily instrumented **central facility**, located on 160 acres of cattle pasture and wheat fields southeast of Lamont, Oklahoma. Here, technicians implement experiments, monitor data from instruments throughout the site, and provide routine maintenance for the instruments.

The instruments automatically collect data on surface and atmospheric properties. The site data system at the central facility routinely communicates with the instruments via fiber-optic lines, both sending instructions and collecting data. The site data system is linked by high-speed communications to the ARM Experiment Center at Pacific Northwest National Laboratory and to the ARM Data Archive at Oak Ridge National Laboratory. Other links are to Argonne National Laboratory and the University of Oklahoma, where instrument performance and data quality are independently monitored. The Experiment Center acquires additional data from other sources, such as National Weather Service satellites and surface stations, and generates both a continuous data stream and tailored data packages for ARM science team members.

The CART site managed by Argonne is the first of the ARM Program's three field laboratories. **Two additional but smaller sites are being established** — one in the tropical western Pacific Ocean (managed by Los Alamos National Laboratory) and one on the North Slope of Alaska (managed by Sandia National Laboratories). Each site is located in an area with unique weather patterns, to facilitate study of the various processes that affect Earth's climate.

This CART site was designed to cover an area roughly 350 kilometers (225 miles) on a side, about the size of a grid cell of a general circulation model. (The grid cell is the

smallest area for which a model makes computations.) Accurate prediction and **modeling of global climate change** are presently impossible, because the complexity and scales of processes affecting climate far exceed the computational abilities of current general circulation models. Too often, the best models disagree not only with each other, but also with actual climate behavior, partly because the data on which they are based are inadequate. The detailed, consistent data generated by the ARM Program will improve the models and allow them to address longer time periods more accurately.

DOE conceived the idea of improving the tools needed to understand global climate change. What makes the idea work in the ARM Program is unprecedented teamwork, sharing of expertise, and research partnerships among the national laboratories and universities, together with the archiving and dissemination of data to the broader scientific community beyond the ARM Program participants.

Participants and collaborators with DOE in the ARM Program include national laboratories, universities, other federal agencies, private concerns, and foreign organizations. Among all these organizations, teamwork of a kind seldom realized is the rule rather than the exception.

DOE Laboratories

- Argonne National Laboratory
- Brookhaven National Laboratory
- Environmental Measurement Laboratory
- Lawrence Berkeley Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratories

Universities

- Colorado State University
- Desert Research Institute, Nevada
- North Carolina State University
- Pennsylvania State University
- Scripps Institute of Oceanography
- State University of New York at Albany
- State University of New York at Stony Brook
- University of Alaska, Fairbanks
- University of California, San Diego
- University of California, Santa Barbara
- University of Colorado
- University of Denver
- University of Maryland
- University of Massachusetts
- University of Oklahoma
- University of Utah
- University of Washington
- University of Wisconsin

Other Government Agencies

- Air Force Philips Laboratory
- NASA Ames Research Center
- NASA Goddard Institute for Space Studies
- NASA Goddard Space Flight Center
- NASA – Jet Propulsion Laboratory
- National Center for Atmospheric Research
- NOAA – Aeronomy Laboratory
- NOAA – Atmospheric Turbulence and Diffusion Laboratory
- NOAA – Climate Monitoring and Diagnostics Laboratory
- NOAA – Forecast Systems Laboratory
- NOAA – Wave Propagation Laboratory
- NOAA – National Environmental Satellite, Data and Information

Foreign Participants

- CSIRO, Division of Atmospheric Research, Victoria, Australia
- European Center for Medium-Range Weather Forecasts, Reading, United Kingdom
- Institute for Atmospheric Optics, Tomsk, Russia
- McGill University, Montreal, Canada

Private Agencies

- Atmospheric and Environmental Research, Inc., Massachusetts
- Mission Research Corp., California
- Science Applications International Corp., California

A NEW SCIENTIFIC OPPORTUNITY

Through the ARM Program, DOE has developed a coherent approach to long-term climate research. Fragmented campaigns generating inconsistent data have been replaced by continuous baseline measurements at a fixed site, supplemented with intensive observation periods. Today, researchers receive data from the CART site's concentrated collection of instruments for climate studies in their own laboratories.

The ARM Program has developed a coherent approach to climate research.

Formerly, measurements were made in field campaigns lasting only a few weeks. Investigators made their own independent observations. Locations and sponsorship varied. The data generated often were fragmented and inconsistent and sometimes were inaccessible. Dissemination of the data to the scientific community often took years. Now, under the ARM Program, a firm foundation of continuous baseline measurements is supplemented with periods of more frequent measurements at the same site, in an area that should provide the widest possible range of meteorological conditions for model testing. A consistent body of data of known quality is processed and disseminated in near-real time.

Specialized instruments are the core of the CART facility. The instruments, which provide a foundation of continuous observations, are deployed across Kansas and Oklahoma at locations selected to provide the spatial and temporal scales required. These instruments measure solar radiation, meteorological conditions, and clouds, allowing interpretation of radiative transfer within and between atmospheric columns every 30 minutes.

More than 7,000 balloons have been launched to date at the CART site. Like those deployed by the National Weather Service, the balloons carry instruments to measure winds, temperature, and relative humidity to heights of 20 kilometers (12.5 miles) above Earth's surface. During routine opera-

tions, balloons are launched five times daily, five days each week; during intensive observation periods, launches occur every three hours around the clock, both at the central facility and at each of four boundary facilities.

Weather balloons have been used in meteorological research for decades. In the ARM Program, the in-situ results generated during balloon flights are still considered important reference measurements for calibration and verification of data from advanced remote sensors.

The continuous observations at the CART site are supplemented by **intensive observation periods**, when the frequency of measurements is increased and special measurements are added to address specific research questions. During such periods, nearly a gigabyte of data (one billion bytes) is generated daily. Both during intensive observation periods and at other times, scientists bring their own specialized instruments to the CART site, typically for several weeks.

The ARM Program uses computers to obtain **calibrated data of known quality** from the field instruments. These data are distributed to scientists quickly enough for use in near-real-time computer simulations. This speed allows researchers to test the predictions of their models while weather patterns are developing, greatly decreasing the time required to refine and validate models.

The CART site has the world's largest collection of remote sensing instruments for climate research. These instruments are all dedicated to addressing the ARM Program's charge to learn more about radiative transfer and clouds. Scientists have speculated that complicated feedback processes between clouds and climate may be a major factor in determining the magnitude of potential warming resulting from increased concentrations of greenhouse gases. The ARM Program is designed to resolve this critical issue.

Clouds may absorb sunlight and convert it to heat, raising temperatures. However, clouds may also reflect and scatter sunlight and infrared radiation, decreasing temperatures. Uncertainty about the relative strengths of these effects contributes greatly to the overall uncertainty that limits the effectiveness of general circulation models. Models need a much more accurate description of **cloud formation and dissipation and the way clouds interact with sunlight and infrared radiation.**

The research community is seeking answers to several specific questions about clouds and climate:

- How is cloudiness distributed?
- What determines the distribution of cloudiness?
- How do clouds directly affect the atmosphere?
- What roles do the effects of clouds play in regulating or maintaining the present climate?
- How do clouds influence climate change?

The ARM Program scientists seek to understand clouds and radiative transfer better so that climate models can be refined to predict trends for longer periods of time. The information generated will help to answer our questions about whether our climate is truly changing and to what extent.

Like clouds, greenhouse gases (water vapor, carbon dioxide, and others) can also absorb radiation and warm the atmosphere. The warming these gases cause can alter their own abundances and distributions. Along with the effects of

clouds, feedback interactions like this contribute to the complexity of modeling weather and climate.

The CART site's climate laboratory gives the scientific community an extraordinary opportunity to study the complex interactions of clouds and radiation. The comprehensive knowledge gained for the single grid cell at the CART site will be applied to other grid cells that cannot be studied in such detail. The result will be a better understanding of climate change.

ADVANCED INSTRUMENTS ACQUIRING CONTINUOUS DATA

The ARM Program deploys specialized remote sensing instruments in a fixed location at the CART site to gather atmospheric data of unprecedented quality, consistency, and completeness. The data are archived for worldwide distribution and can be custom packaged for scientists upon request. The unified data set provided by the ARM Program is being used by individual scientists and by agencies to improve models, test hypotheses, and validate satellite observations.

The ARM Program deploys specialized remote sensing instruments in a fixed location to gather atmospheric data of unprecedented quality, consistency, and completeness. More than 30 *instrument clusters* have been placed around the CART site, at the central facility and at boundary and extended facilities. The locations for the instruments were chosen so that the measurements reflect conditions over the typical distribution of land uses within the site.

The center of operations for this site is the central facility, located between Lamont and Billings, Oklahoma. This 160-acre complex holds the greatest concentration of instruments and the site data system.

The locations of the instrument clusters were selected both to provide the spatial and temporal scales required and to sample conditions over representative land use types. Many of the instruments are the only one of their kind or the first of their kind. This uniqueness sets the CART site apart as a world-class facility.

Central Facility

Measurement Concept

Instruments and Measurements

Solar radiation includes visible, ultraviolet, and near-infrared light. The absorption, transmission, and reflection of these components of solar radiation depend on the wavelength of the light. When scientists can better understand the effects of radiation in Earth's atmosphere, they can make significant progress on the question of whether and to what extent human activity is altering climate. The instruments at the CART site were selected to characterize these effects of radiation. In some cases, new instruments had to be developed.

Radiometric observations include measurements of direct and scattered radiant energy from the sun, as well as the infrared energy emitted from Earth. The ARM Program

uses several types of conventional, broadband solar and infrared radiometers:

- **Pyranometers** measure the total solar radiation coming from the sky or reflected from the surface.
- **Pyrgeometers** measure the total infrared radiation coming from the sky or emitted from the surface.
- **Pyrheliometers** measure the direct-beam solar radiation.
- **Filtered, rotating shadowband radiometers** detect total, direct, and diffused solar radiation in selected wavebands.

The *atmospherically emitted radiance interferometer* is a key instrument for studies of radiative transfer. Used to measure infrared radiances with high accuracy and spectral resolution, this instrument is essential for experiments on the effects of greenhouse gases, clouds, and fine particles

(aerosols) on atmospheric transmission, absorption, and emission of infrared radiation. In addition, specialized radiometers are used to examine the spectral distribution of ultraviolet, visible, and near-infrared radiation.

Cloud observations are desirable, because clouds play an important part in cooling and heating the Earth's atmosphere. Some of the instruments at the site are used to observe clouds for coverage, type, and physical properties (water or ice content, thickness, etc.).

Whole-sky imagers provide a view of the entire sky as seen from the surface. They generate continuous estimates of the fraction of the sky covered by clouds, as well as measurements of the heights of cloud bases and the dimensions of clouds.

Whole-sky imagers are complemented by lidars (devices that operate much like radars but emit pulses of laser light rather than microwaves). These include the **micropulse lidar**, which detects high-level cirrus clouds and maps the distribution of fine particles in the lower troposphere (the lowest, densest part of the atmosphere, in which weather changes occur). Although lidars do not penetrate clouds very deeply, they easily detect thin cirrus clouds that are often missed by conventional radars.

Making measurements within clouds requires the use of radar. **Millimeter-wavelength cloud radar systems** point straight up to map the vertical distribution of clouds.

Aerosol characterization can be accomplished by taking measurements at 10 meters (33 feet) above the ground to document the size, distribution, and concentration of atmospheric particles. Lidar systems provide data on the relative distribution of aerosols in a vertical column of the atmosphere overhead.

Meteorological Observations

Wind, temperature, and humidity greatly influence radiation and cloud processes in the atmosphere as a function of height. Knowledge of the state of the atmosphere is needed to interpret radiometric data and model results.

The **radar wind profilers** use microwave radar to record vertical changes in wind speed and direction. The profilers use high-frequency radar for measurements in the lower atmosphere and low-frequency radar for upper-atmosphere applications. The 915-MHz (megahertz) Doppler radar wind profiler provides information on mean wind speed in the lowest few kilometers of the atmosphere. When the profiler is operated in conjunction with pulsed sounds, the resulting radio acoustic sounding system (RASS) can provide information on temperature as a function of height. Like the wind profilers, the RASS uses two types of radar, one for low-level and one for high-level observations. Depending on atmospheric conditions, the larger 50-MHz radar wind profiler and RASS system can be used for observations to greater heights (up to seven kilometers), but with less vertical resolution.

A **Raman lidar** is used to observe continuous vertical profiles of water vapor content in the lower troposphere (up to seven kilometers).

The **60-meter (197-foot) tower** and the surface flux station are used to collect information on wind speed and direction, temperature, humidity, and solar and infrared radiation in the lowest part of the atmosphere. The surface flux station is also used to record the movement of heat and moisture between the ground and the atmosphere.

The balloon-borne sounding system uses helium balloons to carry lightweight instrument packages to altitudes of about 20 kilometers (12.5 miles). These 285-gram (10-ounce) packages (including battery) radio information on temperature, humidity, and wind direction and speed to computers at the central facility. Technicians release **radiosondes** on balloons as frequently as eight times per day. Typically, the balloons travel horizontally about 130 kilometers (80 miles) before they burst and parachute safely back to Earth.

Water vapor in the atmosphere gives off very small but detectable amounts of microwave energy. **Microwave radio-meters** that point vertically help infer the amounts of water vapor and liquid integrated in a column of atmosphere. They are used to observe sky radiance at 23.8 GHz (gigahertz) and 31.4 GHz, the unique absorption bands of water vapor in Earth's atmosphere.

Energy balance Bowen ratio or eddy correlation stations are used to measure the rates of heat and moisture exchange between the surface of the Earth and the atmosphere at selected locations. Conventional meteorological stations measure temperature, humidity, wind speed and direction, precipitation rate, snow depth, and atmospheric pressure at the surface.

Computing Facilities

Data from the CART site's instruments are handled and displayed graphically by computer workstations in the control trailer at the central facility, with monitoring by the site operators. The site's computers communicate with hundreds of individual instruments clustered across the CART site (55,000 square miles). The network of workstations is designed to handle **a gigabyte of data each day**.

Calibrated data of known quality are sent (1) to the ARM Experiment Center at Pacific Northwest National Laboratory, and then on to ARM science team members, and (2) to the ARM Data Archive at Oak Ridge National Laboratory, where the information becomes available to the general scientific community. Data are transmitted electronically via high-speed communications linkages, including the Internet.

The data streams also go to the University of Oklahoma and to Argonne, where data quality and the performance of instruments are independently monitored. Argonne scientists have designed systems and software to acquire readings from the various instruments, to perform automated quality control checks on the data streams, and to provide CART site operators with graphic representations of the results.

Data from the CART site are used worldwide by researchers in their individual studies and by scientists working for other agencies. Customized packages can be sent to researchers upon request. The results from studies based on CART site data are presented annually at a scientific conference sponsored by the ARM Program.

Scientific Milestones

In return for its investment of nearly \$40 million annually for 10 years in the ARM Program, DOE is realizing handsome benefits in the form of significant scientific milestones. The unique facilities at the CART site are attracting scientific participants from many other agencies, who come to use the site for research that cannot be performed elsewhere. More than a hundred major experiments were conducted in the site's first three years of operation. The following significant technical milestones have been met:

- The ARM Program is generating a long-term set of spectral radiation and meteorological data of unprecedented accuracy for use in testing climate-related hypotheses.
- Measurements from the CART site are being used by many different agencies (the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the Department of Defense, and others) to validate models and satellite data.
- Algorithms developed from ARM data are being used to improve general circulation models by agencies including the Goddard Fluid Dynamics Laboratory, the Goddard Space Flight Center, the British Meteorological Office, and the European Centre for Medium-Range Weather Forecasts.
- Use of data from the atmospherically emitted radiance interferometer has reduced the uncertainty in estimates of incoming longwave radiation fluxes by 75%.
- Support from the ARM Program has led to the development of a rapid radiative transfer module for use in climate models that has significantly improved agreement with results from line-by-line radiative transfer models.

FROM CLIMATE TO WEATHER

Operations at the CART site are scheduled to continue through 2002. Argonne is developing a complementary user facility within the CART site boundaries to focus on smaller-scale studies of the atmospheric phenomena related to weather. Argonne plans to continue operations for an additional 15 years, benefiting from DOE's investment in the ARM Program and also generating a return on that investment by gathering data of interest to DOE. Argonne's facility will advance atmospheric research for the farmer, the aviator, the weather forecaster, and the nation.

The ARM Program is devoted to a single problem — improving the accuracy of the numerical models used to predict climate change.

Addressing other important atmospheric problems with an approach like that used by the ARM Program would also have great benefits. For example, improving the accuracy of short-term and medium-term weather forecasts — for periods of hours to months — could save billions of dollars and hundreds of lives annually. Improved forecasts would help us prepare for weather-related disasters like tornadoes, blizzards, floods, and droughts and would make air travel safer by helping aviators avoid icing conditions, air turbulence, and wind shear.

Operations at the CART site in Kansas and Oklahoma began in 1992 and will continue for a decade. In addition to its management and scientific activities for the ARM Program, Argonne is developing a parallel user facility within the CART site to focus on smaller-scale studies of the atmospheric phenomena related to weather. These studies are also of interest to the ARM Program; they represent additional benefit from DOE's investment in the CART site. Argonne plans to operate its facility for 15 years.

Improving weather forecasts depends on obtaining a much better understanding of extremely complex atmospheric

phenomena on much smaller scales. New technologies in remote sensing, instrumentation, computation, and data handling give atmospheric scientists an unprecedented opportunity to make significant advances quickly, if the technologies are integrated effectively at relevant spatial scales. Accomplishing this challenging task in a way that provides open access for the broad scientific community can best be accomplished by a national laboratory.

Argonne is building on its existing capabilities in atmospheric science, remote sensing, advanced computation, information processing, and facility management to develop **a new national observatory for long-term atmospheric research.** Argonne is initially developing a complementary user facility focused on understanding the dynamics of the planetary boundary layer (the lowest three kilometers of the atmosphere). Argonne's 50-kilometer-square facility will be established within the CART site domain, both to provide its complementary data to ARM Program scientists and to benefit from the CART data streams that are relevant to shorter-term phenomena.

The new facility, the **Argonne Planetary Boundary Layer Facility**, will combine state-of-the-art atmospheric instrumentation with the latest technologies in modeling, data delivery, and data visualization. The research will involve national laboratory scientists and a broad,

multidisciplinary user community. Data streams will be available to all qualified users, and the infrastructure will be designed to accommodate visiting instruments, experiments, and campaigns.

Conceptual planning for Argonne's Planetary Boundary Layer Facility was completed in 1995, and the initial scientific approaches were defined. The facility is expected to be operational by 1997. Surface-based observations of the profiles of temperature, humidity, and wind and of the air-surface exchange rates of heat, moisture, and momentum will be

made by a dense array of instruments distributed over an area approximately 50 kilometers square within the CART site in Kansas and Oklahoma. The candidate site selected is the **Walnut River Watershed** in southern Kansas.

Argonne's Planetary Boundary Layer Facility is expected to provide the broad scientific community with the following:

1. A stable set of instruments, methods, and data streams ideal for comparisons and evaluations of new techniques under a wide variety of conditions, including large-scale integration of new technologies in remote sensing, instrumentation, computation, and data handling.
2. Improved statistical sampling of planetary boundary layer processes (over many frontal passages at the same locations in all seasons), including continuous, long-term observations over large spatial scales.
3. Opportunities to couple meteorological observations with hydrologic and ecologic studies in the region, thereby providing links between these disciplines.

Minisodar for Argonne Planetary Boundary Layer Facility

The initiative to establish the Argonne Planetary Boundary Layer Facility will build on both DOE's capital investment in the CART site and the recognized strength of the DOE national laboratories in establishing and overseeing the operation of large-scale, complex scientific facilities.

The atmospheric research to be conducted at this facility will **benefit the nation** by:

- Promoting the effective and environmentally protective production and use of energy and
- Contributing in the areas of
 - Mitigation and public safety relating to natural disasters,
 - Agriculture,
 - Safe and efficient aviation and other transportation,
 - Water resources management, and
 - Defense.