The Atmospheric Radiation Measurement (ARM) Climate Research Facility

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Motivation
Overview of the ARM Climate Research Facility
Facility applications and science highlights
Facility Expansion
Upcoming Activities
BER Climate and Environmental Science Division (CESD) Mission Statement:

To advance a robust predictive understanding of Earth’s climate and environmental systems and to inform the development of sustainable solutions to the Nation’s energy and environmental challenges.*

* From the 2012 BER CESD Strategic Plan
CESD Goals

- **Goal 1**: Synthesize new process knowledge and innovative computational methods advancing next-generation, integrated models of the human-earth system.
- **Goal 2**: Develop, test, and simulate process-level understanding of atmospheric systems and terrestrial ecosystems, extending from bedrock to the top of the vegetative canopy.
- **Goal 3**: Advance fundamental understanding of coupled biogeochemical processes in complex subsurface environments to enable systems-level environmental prediction and decision support.
- **Goal 4**: Enhance the unique capabilities and impacts of the ARM and EMSL scientific user facilities and other BER community resources to advance the frontiers of climate and environmental science.
- **Goal 5**: Identify and address science gaps that limit translation of CESD fundamental science into solutions for DOE’s most pressing energy and environmental challenges.
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Climate Science Issues

- Source and cycling of greenhouse gases
- Source and cycling of aerosols and their radiative and microphysical properties – including biogenic and anthropogenic sources
- Characterization of current cloud properties and radiative feedback due to changes in cloud populations
  - Marine stratus along western continental boundaries
  - Tropical convection systems – e.g. El Nino/La Nina; Madden Julian Oscillation
  - Mixed-phase arctic clouds
  - Southern Ocean storm track systems
- Interactions of clouds and aerosols with the earth surface
The ARM Climate Research Facility

- Research sites – permanent, mobile, and aerial
- Instruments and measurements
- Field campaigns – ground-based, ship-based, airborne
- Data processing, data quality, Data Archive
ARM Mission and Vision Statements

Mission
The ARM Climate Research Facility, a DOE scientific user facility, provides the climate research community with strategically located in situ and remote sensing observatories designed to improve the understanding and representation, in climate and earth system models, of clouds and aerosols as well as their interactions and coupling with the Earth’s surface.

Vision
To provide a detailed and accurate description of the earth atmosphere in diverse climate regimes to resolve the uncertainties in climate and earth system models toward the development of sustainable solutions for the Nation's energy and environmental challenges.

http://www.arm.gov/about/mission
Research Sites

- Southern Great Plains (1993)
- First ARM Mobile Facility (2005); Second ARM Mobile Facility (2010)
- ARM Aerial Facility (2007)
- Eastern North Atlantic and Third ARM Mobile Facility (2013)
Overview: Measurements and Instruments

- Cloud profiles: millimeter radar and lidar
- Temperature/relative humidity/wind profiles: radiosondes
- Column water: microwave radiometer
- Column aerosol: solar spectral radiometer
- In situ aerosol optical and cloud nucleation properties
- Surface radiation budget: solar and terrestrial IR radiometers
- Surface meteorology: T/RH/wind
Most instrument data are processed to a standard NetCDF format before being delivered to the Archive.

When necessary, higher-order Value-Added Products (VAPs) are developed.
Science User Interactions

Individuals become ARM science users through several processes including successful field campaign proposals, successful proposals to use ARM computing facilities, or through peer-reviewed science proposals requiring access to archived ARM data.

Science users interact with the ARM Facility in several ways:

- Data Access
- Field Campaigns and Facility Deployments
- Data Product requests
- Feedback for new capabilities
Tools for Data Discovery and Analysis

Archive Data Discovery

Browser Go to www.arm.gov/data and select “Data Discovery”

Provides faceted data search
Auto-fill quick search
Graphical data quality information

Other recent data advances include:

Digital Object Identifiers
(http://www.arm.gov/data/docs/doi-guidance)
A development area for large data sets
Machine-Readable Data Quality Reports

Archive Statistics

Data flow statistics through the ARM data archive courtesy of Stephanie Shamblin:

- Number of files and volume stored
- Number of files and volume accessed
Number of Files Stored

Files stored per month

- Relatively flat growth over past decade; 2013 average less than 2012.
- 2013 average monthly files stored is only 2x average in 2003.
- ~150,000 new files each month
Data Volume Stored

GB stored per month

- 2013 average monthly storage volume is more than 20x average in 2003.
- Much larger range in terms of volume: 5 TB – 30 TB per month in 2013.
- Quickly approaching rate of 1 TB per day.
Number of Files Requested

Files requested per month

- Average number of files requested per month in 2013 is around 6x average in 2003.
- Up 40% over 2012.
Data Volume Requested
GB requested per month

- Increasing at an increasing rate
- Average 9 TB of routine data distributed each month so far in 2013 – ~40% higher than 2012.
Annual Field Campaign Call (>300K)

- ARM Facility Announcement- Call for Preproposals: January for FY(n+2)
  - ARM-all, BAMS, EOS, and ARM Website
- Preproposals Call Closed: February 1
- Notifications sent for Full Proposal: Mid-February
- Full Proposals Due: May 15
- Infrastructure Costs and Logistics Analysis: June 15
- Field Campaign Proposals + Costs to Science Board: June 15
- Reviews by Science Board due 2 weeks before Science Board meeting
- Science Board Review: Mid-August
- Award for ARM Fixed Sites, AMF, and AAF Campaigns: End-September
- Science Plan developed and Field Campaign is executed
- Experiment results and all collaborative data submitted to ARM Archive within 6 months after end of field campaign
AMF1 Transportable and Land-Based Deployments

Facility Manager: Kim Nitschke
Los Alamos National Laboratory

North America (California): 2005
Africa (Niger): 2006
Europe (Germany): 2007
Asia (China): 2008
Europe (Azores): 2009-2010
Asia (India): 2011-2012
North America (Cape Cod): 2012-2013
South America (Brazil): 2014
AMF2: Modular for Ship and Complex Terrain Deployments

Facility Manager: Nicki Hickmon
Argonne National Laboratory

North America (Colorado): 2011
Asia (Maldives): 2012
Eastern Pacific (Ship-based): 2012-13
Europe (Finland): 2013-14
The ARM Aerial Facility (AAF)

Virtual Hangar
- ISDAC, Alaska: 4/2008
- RACORO, Oklahoma: 1–6/2009
- SPARTICUS, Oklahoma: 1–6/2010
- So far worked with 13 aircraft: ER-2, Lear 25, P-3 (2), B-200, CV-580, J-31, G-1, Twin Otters (3), C206, Bell 206

+ Instrumentation
- Legacy (AVP, ASP)
- Recovery Act
- PIs
- Maturation Program

+ G-1
- PNNL since 1989
- ARM since 2010
- CARES, Sacramento: 6/2010
- TCAP, Cape Cod: 7/2012, 2/2013
- BBOP, Washington, Tennessee
Value-Added Products (VAPs)

- VAPs are algorithms that translate measurements of geophysical parameters into data products that enable scientific analysis.
  - Merging data from multiple instruments
  - Providing derived parameters
  - Adding QC/QA information
- Production of a VAP consists of 4 stages:
  - Initiation – idea to implementation plan
  - Development – programming, review and beta testing
  - Evaluation – user testing and feedback
  - Release – quality control and documentation
- Use feedback from the ASR Science and Infrastructure Steering Committee (SISC), ASR working groups, and the wider user community to assess priorities
Model Best Estimate/Evaluation Data Sets

- ARM Best Estimate Products (formerly CMBE): Parameters on 1-hour Grid; specifically intended for model evaluation
- Variational analysis based model forcing datasets
- Radiatively Important Parameters Best Estimate: Set of inputs for a Radiative transfer model on 1-min and 30-min grid

Availability of ARM Cloud Retrieval Ensemble Dataset. Courtesy: Shaocheng Xie

Information on these and other Value Added data products including vertical velocities, aerosol properties, and thermodynamic profiles is available at: [http://www.arm.gov/data/vaps/](http://www.arm.gov/data/vaps/)
User Feedback

- ASR science team and working group meetings
- ASR Science and Infrastructure Steering Committee meetings and interactions
- User workshops
  - Archive User Meeting, 2007
  - ARM Climate Research Facility Expansion workshop, 2007
  - ARM Climate Research Facility workshop, 2008
  - AAF Airborne Instrumentation workshop, 2009
- User surveys, 2009, 2011
- General science meetings (e.g. AGU, AMS, EGU)
Broadband radiation measurement techniques, e.g., development of a diffuse shortwave standard: Michalsky et al., 2007, JGR.

Improvements in water vapor measurements using radiosondes and microwave radiometers: e.g., Turner et al., 2003, JAOT (RS-80); Cady-Pereira et al., 2008, JAOT (RS-80/RS-90).
Measurement Techniques: Cloud Properties

Derivation of cloud macrophysical and microphysical properties using millimeter radar and lidar, e.g., climatology of cloud properties at SGP (Mace, 2008; below) or an analysis of ice nucleation in the arctic (de Boer et al., 2011; right).
Characterization of the Sahel

- Research highlights include analyses of:
  - The column radiation budget
  - Relationships among thermodynamic and radiative parameters
  - Cloud microphysics properties
  - Aerosol properties
  - Convective anvil properties

Diurnal cycle of cloud occurrence (precipitating, shaded contours; non-precipitating, solid lines) from the cloud radar retrievals from Bouniol, 2012 (J. Appl. Met.)
Measurement Techniques: Aerosols

There has been an emphasis on measurements of aerosol optical properties, e.g., the sensitivity of radiative forcing to aerosol optical properties (McComiskey et al., 2008; right) and the effects of scale (McComiskey and Feingold, 2012) and the representativeness of aerosol radiative forcing derived from surface measurements vs. airborne measurements (Andrews et al., 2004; below).
The 2010 Carbonaceous Aerosols and Radiative Effects Study (CARES) included measurements of aerosol composition and structure (mixing state) from the ground and the G1 aircraft downwind of Sacramento, CA. Analysis of these data show:

- A high fraction (88%) of particles measured contained internal mixtures of multiple chemical species with key aerosol components including soot, organic carbon, sulfate, and nitrate.
- The aerosol composition varied significantly with location as well as time.

Quantifying the effect of aerosols on climate requires predicting the evolution of aerosol properties. This study describes the properties of aerosols in a region affected by pollutants and biogenic sources and emphasizes the need to carefully account for regional aerosol sources. Cahil et al., 2012 (ACP)
Observational data provides a grounding for physical understanding that leads to improvement of GCM processes. Diagram source: Pier Siebesma
Merged data products such as the Climate Modeling Best Estimate (CMBE) facilitate complex analyses involving multiple parameters or both observations and model data.

Zhang and Klein (2010; JAS) used CMBE and other data sets to explore the factors associated with the transition from shallow to deep convection over the SGP.
Arctic Mixed-Phase Clouds

Significant advances in ability to measure mixed-phase cloud properties using airborne measurements from two campaigns and combinations of ground-based sensors (Shupe et al., 2008 (BAMS; right); de Boer, 2011 (GRL)).

Modeling studies have advanced understanding of mixed clouds (e.g. Morrison et al. 2009) and have improved their representation in GCMs (Liu et al. 2009; left).
The 2006 Tropical Warm Pool International Cloud Experiment has led to over 50 publications ranging from analyses of cloud observations to model studies. Key studies to date include:

- Ice cloud properties from ground-based remote sensors and aircraft
- Vertical structure of heating in deep convection
- Sensitivity of convection in GCMs to mid-troposphere humidity
- Sensitivity of convection in GCMs to model resolution
- Observations of vertical motion in convective cores

Collis, 2013

Wu, 2009
Cloud/Radiation Interactions in Global Models

Use of the RRTMG radiation code plus the Monte Carlo Independent Column Approximation (MCICA) scheme for radiation/cloud interaction in the ECMWF model led to improvements relative to the ERA40 reanalysis (Morcrette et al. and Barker et al. 2008)

[Image: Graphs showing differences in pressure and temperature between Zonal Mean Average T (n=3) in Climate Forecast (esd8) and ERA40 over 3 Dates: 20000801, ..., Averaging Period Start: 200009, Length: 12 Months]
Contributions to the Community Atmosphere Model (CAM) Version 5

- CAM5 has been modified substantially with a range of enhancements and improvement in the representation of physical processes since version 4 (CAM4).

- DOE/ARM contributions to the model include:
  - Rapid Radiative Transfer Method for GCMs (RRTMG)
  - Three-mode modal aerosol scheme
  - Two-mode cloud microphysics scheme
  - Planetary Boundary Layer/Shallow convection scheme

- The ARMBE data product also serves as part of the suite of standard CAM validation data products
User Feedback: 2007/2008 Workshops

- 2007: Provided feedback regarding siting priorities, data infrastructure needs, aircraft measurement needs, and design priorities for a second mobile facility.
  - The 2007 workshop led to design requirements for the second mobile facility and provided important insights into data infrastructure needs.

- 2008: Provided feedback regarding instrument/measurement needs. Needs identified included improved remote sensing to better retrieve cloud properties, scanning capability, improved boundary layer fluxes, and improved aerosol measurements.
  - The 2008 workshop recommendations were the primary source of input for the Recovery Act instrument plan.
Recovery Act

In 2009, ARM received $60M from the DOE Office of Science for investments in instrumentation and research infrastructure to support the instrumentation and the associated increase in data volume and complexity.

http://www.arm.gov/about/recovery-act
Measurements and Instruments

Baseline Capabilities
- Cloud profiles: millimeter radar and lidar
- T/RH/Wind profiles: radiosondes
- Column water: microwave radiometer
- Column aerosol: solar spectral radiometer
- In situ aerosol optical and cloud nucleation properties
- Surface radiation budget
- Surface meteorology

New Measurements as of 2011
- 3-dimensional measurements of cloud properties
- Enhanced measurements atmospheric aerosol absorption, scattering, composition and chemistry
- Improved measurements of humidity and vertical motion
- Expanded capabilities for airborne measurements
Aerosol Observing System: Provides measurements of optical properties (scattering and absorption) and CCN concentration: Southern Great Plains, Barrow (with NOAA), **Darwin**, AMF1, AMF2

Mobile Aerosol Observing System: Provides measurements particle size distributions and composition. Instruments include:
- Single Particle Soot Photometer (SP2)
- Photon Transfer Reaction Mass Spectrometer (PTRMS)
- Particle-into-Liquid Sampler (PILS)
- Aerosol Chemistry Speciation Monitor (ACSM)
- Ultra-High Sensitivity Aerosol Spectrometer (UHSAS)

Initial deployment at Brookhaven National Laboratory – summer, 2011
Mobile Aerosol Observing System (MAOS)

MAOS provides a suite of instruments to address science questions posed by aerosol and aerosol-cloud interaction field campaigns

- Carbonaceous aerosols and secondary organic aerosol formation
- Optical properties – absorption and scattering
- Size distribution from 10 to 3000 nm
- Relationships between trace gases and aerosols
- Cloud condensation nuclei

Carbonaceous aerosol observations from the Single Particle Soot Photometer (SP2); Sedlacek et al., 2012
HSRL, Raman, and Doppler Lidars

- HSRL located at Barrow and 2nd mobile facility
- HSRL provides aerosol extinction and liquid/ice discrimination in thin clouds

- Doppler/Raman at Darwin and SGP
- Provides means to study details of convection, water vapor profiles and fluxes
- Raman also provides improved sensitivity (over MPL) to optically thin tropical cirrus

Aerosol backscatter from Barrow, AK, March 2013

PDF of vertical velocities from the Darwin Doppler Lidar from Feb 2011.

Water vapor mixing ratio from Darwin ARM site from Dec. 2010 (Plot courtesy Dave Turner).
Cloud-Detecting mm-wavelength radars include:
- Zenith-pointing Ka (35 GHz) and W (94 GHz)
- Scanning Ka/W or Ka/X (10 GHz)

Scan geometries sample cloud properties and 3-D structures with modes including:
- Zenith-pointing
- PPI (conical scan)
- Horizon to horizon scans
- Volume sector scans

cm-wavelength radars focused on precipitation and storm dynamics are deployed at Oklahoma (X and C-band), Barrow (X-band), and Manus (C-band).

The combination of radars at multiple wavelengths with lidars gives profiles of particles from aerosols to clouds to precipitaiton.
Radar Science and Operations Group

**Operations Team**

Manages day-to-day operations, technical advances, procurements

- Engineering/lead radar points of contact
- Site operations
- Data Quality Office
- Product development

**Science Team**

Liaison to science community, provides recommendations for science needs/priorities, assists with quality assessment

- Steering committee
- Product liaisons/"translators"

Ensure dialog between operations and science through:

- Clear structure/roles
- Monthly meetings/reports
- Annual workshop
- Clear goals/expectations

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Radar Calibration

- The Sun can be used to calibrate the absolute position of the pedestal
- The location of the sun is well known for a given geo-location
- The Sun is also a noise source which can be observed with the radar

Corner reflector with good Signal to Clutter Ratio (SCR)

Observation of sun for maintaining pointing accuracy. The observation is with Ka-SACR.

- A corner reflector mounted on a tower is used to calibrate scanning radars
- Raster scans also provide detailed information about the antenna pattern
- Operation of a scanning radar next to a zenith-pointing instrument provides a transfer standard

Source: Nitin Bharadwaj.
Upcoming Activities

- Maturation of applications for new instruments
- Focus groups
  - Vertical Velocities
  - Quantification of Uncertainties In Cloud Retrievals
- Upcoming AMF Deployments
- Collaborative activities with the European Union
- New Sites
Cloud (mm-wavelength) Radars
- Cloud mask for upgraded zenith-view cloud radar
- 3-D cloud mask for scanning cloud radars
- Corrections for attenuation and velocity folding
- Optimization of radar scanning modes

Precipitation (cm-wavelength) radars
- Gridded precipitation from X and C-band radars
- Multi-Doppler storm dynamics

Corrected Moments in Antenna Coordinates (CMAC)
- Correct for velocity aliasing
- Correct polarimetric parameters
- Correct for liquid path attenuation
- Estimate rainfall rates using the specific attenuation.

(Scott Collis) 47
Vertical Velocity

Vertical motion is central to many atmospheric science issues and particularly the cloud life cycle. New measurement capabilities puts in reach the ability to characterize vertical motion like never before:

- Radars scanning broad range of frequency make it possible to study precipitating and non-precipitating clouds
- Doppler lidars probe clear air below cloud base
- Array of data products coming on-line to capitalize on these measurements
- Special session at this year’s AGU will explore measurement techniques and applications of these measurements.
We are working to better document and communicate measurement uncertainties. Recent activities include:

- Collection of instrument level uncertainties from all instrument mentors. Documentation of this process is on-going.
- Applications of machine-readable Data Quality Reports (DQRs) and associated web services.
- Joint ARM/ASR focus group for the Quantification of Uncertainties in Cloud Retrievals (QUICR).
GOAmazon – Collaborative Research in a Tropical Rainforest

The Next deployment of the first AMF will be to Manaus, Brazil in the heart of the Amazon to study anthropogenic and biogenic aerosols and their effect on tropical convection. GOAmazon begins in January 2014 and will run for two years. Both GOAmazon and TCAP include the following observation systems:

- AMF1
- AAF G1 Aircraft
- Mobile Aerosol Observing System

Additional partnerships with CESD modeling and Terrestrial Ecosystems, EMSL, partners in Brazil, as well as other agencies and nationalities
Second ARM Mobile Facility: Biogenic Aerosols

The next AMF2 campaign will be to study Biogenic Aerosols – effects on clouds and climate at the Hyytiala field station north of Helsinki.

Hyytiala has a long history as a terrestrial ecosystem research facility. Recent study (Nature Geo., 2013) suggests negative climate feedbacks from biological processes. ARM data will help to test this.

The site is also part of Pan-Eurasia Experiment (PEEX), an iLEAPS coordinating regional climate research.

http://www.atm.helsinki.fi/peex/
In November 2012 the US Department of Energy hosted a workshop with colleagues from the European Union. The purpose of the workshop was to identify strategies for advancing the application of ground-based remote sensing measurements to key atmospheric science research problems.

Key outcomes from the meeting included plans for joint efforts related to:

- Cloud retrievals
- Radar calibrations
- Microwave radiometry
- Model forcing data sets
- A common data portal
- LES model simulations
- Field campaigns


On-line Meta-data Editor (OME)
Two New ARM Sites in 2013

Led by Kim Nitschke at Los Alamos National Laboratory

Led by Mark Ivey at Sandia National Laboratory

- Sites scheduled to come on line by September 2013
- The facility at Oliktok Point is a mobile facility deployed for an extended term
- Instruments at these sites match those found at other sites including many of the enhancements added through the Recovery Act and plans to add Unmanned Aerial component at Oliktok – workshop planned for July

Azores

The Azores are an island group in the Eastern North Atlantic (ENA) ocean in a region characterized by marine stratocumulus. Marine stratocumulus have a strong influence on climate yet are poorly represented in global climate models.

Oliktok Point

The Oliktok Point site is located approximately 300 km Southeast of the existing ARM site in Barrow and provides an opportunity to link coastal conditions from the standard ARM measurement suite with near-coast conditions using an Unmanned Aerial System (UAS).
For More Information on ARM

- Description of sites, instruments, data
- Upcoming campaigns
- Science highlights
- ARM News (subscribe to RSS feed); proposal and job opportunities
- Social Media: Facebook, YouTube, Flickr, Twitter
- Contacts

Visit the ARM website:  [http://www.arm.gov](http://www.arm.gov)