U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-17-028

ARM West Antarctic Radiation Experiment (AWARE) Field Campaign Report

D Lubin
AM Vogelmann
LM Russell
DH Bromwich
J Verlinde

September 2017

ARM CLIMATE RESEARCH FACILITY

DISCLAIMER

DOE/SC-ARM-17-028

ARM West Antarctic Radiation Experiment (AWARE) Field Campaign Report

D Lubin, Scripps Institution of Oceanography (SIO)
DH Bromwich, Ohio State University
AM Vogelmann, Brookhaven National Laboratory
J Verlinde, Pennsylvania State University
LM Russell, SIO
Co-Investigators

September 2017

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

AERI	atmospheric emitted radiance interferometer
AGU	American Geophysical Union
AMF	ARM Mobile Facility
AOS	aerosol observing system
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
AWARE	ARM West Antarctic Radiation Experiment
BOM	Australian Bureau of Meteorology
CSPHOT	Cimel Systems sun-tracking photometer
DOE	U.S. Department of Energy
g	gram
GCM	global climate model
GHz	gigahertz
GVRP	G-band vertical radiometer profiling system
HSRL	high-spectral-resolution lidar
HTDMA	humidified tandem diffusion mobility analyzer
KaSACR	Ka-band Scanning ARM Cloud Radar
KaZR	Ka-band zenith radar
km	kilometer
LANL	Los Alamos National Laboratory
LHF	latent heat flux
m	meter
MET	surface meteorology system
MFRSR	multi-frequency rotating shadowband radiometer
MPL	micropulse lidar
MWACR	Marine W-band Scanning ARM Cloud Radar
NSA	North Slope of Alaska
NSF	National Science Foundation
SEBS	surface energy balance system
SHF	sensible heat flux
TCLW	total cloud liquid water
USAP	U.S. Antarctic Program
WAIS	West Antarctic Ice Sheet
XSACR	X-band Scanning ARM Cloud Radar

Contents

Figures

1.0 Summary

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) West Antarctic Radiation Experiment (AWARE) is the most technologically advanced atmospheric and climate science campaign yet fielded in Antarctica. AWARE was motivated be recent concern about the impact of cryospheric mass loss on global sea level rise. Specifically, the West Antarctic Ice Sheet (WAIS) is now the second largest contributor to rising sea level, after the Greenland Ice Sheet. As steadily warming ocean water erodes the grounding lines of WAIS components where they meet the Amundsen and Bellingshausen Seas, the retreating grounding lines moving inland and downslope on the underlying terrain imply mechanical instability of the entire WAIS. There is evidence that this point of instability may have already been reached, perhaps signifying more rapid loss of WAIS ice mass. At the same time, the mechanical support provided by adjacent ice shelves, and also the fundamental stability of exposed ice cliffs at the ice sheet grounding lines, will be adversely impacted by a warming atmosphere that causes more frequent episodes of surface melting. The surface meltwater damages the ice shelves and ice cliffs through hydrofracturing. With the increasing concern regarding these rapid cryospheric changes, AWARE was motivated by the need to (a) diagnose the surface energy balance in West Antarctica as related to both summer season climatology and potential surface melting, and (b) improve global climate model (GCM) performance over Antarctica, such that future cryospheric projections can be more reliable.

Given the numerous engineering and logistical challenges with remote Antarctic fieldwork, AWARE has been remarkably successful. This is due primarily to effective and early collaboration between the DOE Los Alamos National Laboratory (LANL) team managing the second ARM Mobile Facility (AMF2) and the U.S. Antarctic Program (USAP). Even before DOE and the National Science Foundation (NSF) approved funding support, engineering and logistical planning began in early 2014 with twice-monthly teleconferences involving LANL and USAP, followed by a site visit to McMurdo Station in November 2014 by Kim Nitschke and Paul Ortega (LANL) and Prof. Johannes Verlinde (Penn State) to survey potential AMF2 deployment locations. This site visit resulted in the CosRay location being selected for the AMF2. In July 2015 LANL organized a beta test of the AMF2 in its Antarctic configuration at Pagosa Springs, Colorado, hosted by structural contractor Hamelmann Communications. In addition to the LANL and Hammelmann engineers, the AWARE field team included six engineers from the Australian Bureau of Meteorology (BOM) who operated ARM equipment at both field sites. AWARE also owes its success to exceptionally strong support from ARM program management who authorized instrumentation for the WAIS Divide Ice Camp in addition to the full AMF2 deployment at McMurdo Station.

In the context of an ARM User Facility, AWARE can be conceived as deploying a “Central Facility” to McMurdo Station on Ross Island (77º51’S, 166º40’E) and an “Extended Facility” to the WAIS Divide Ice Camp (79º28’S, 112º5’W). McMurdo Station is the only USAP station that can realistically accommodate the instrument siting, construction, and power requirements of the full AMF2. WAIS Divide is a summer-only field camp that establishes an ice runway and maintains sufficient cargo handling and power generation capability for a subset of core ARM Facility measurements. The distance between the two sites is approximately 1600 km.

The full AMF2 plus an additional complement of ARM instruments for WAIS Divide were successfully transported to McMurdo Station in October and early November 2015. A field party of 12 led by Kim Nitschke and Heath Powers (LANL) deployed to McMurdo in early November 2015 and spent two weeks setting up the AMF2 in its customized Antarctic configuration at CosRay. CosRay is an unused laboratory building where ionosphere and space physics experiments were once housed, approximately 1 km from McMurdo Station along the main road between McMurdo and New Zealand's Scott Base. This site has locally flat terrain and relatively less obstruction by adjacent hills than most other locations near McMurdo. CosRay offered the ARM cloud radars a good scanning field of view to the south and east, the prevailing directions for most of Ross Island's weather. By late November 2015 several AMF2 instruments were operational, and the official campaign start with all instruments was 1 December. The AMF2 collected data for AWARE through 1 January 2017.

AMF2 instrument performance at CosRay was remarkably successful given the harsh polar environment. All of the basic radiometric and meteorological instruments operated continuously with minimal interruption. The atmospheric emitted radiance interferometer (AERI), high-spectral-resolution lidar (HSRL), and micropulse lidar (MPL) all operated continuously with minimal interruption. AWARE acquired research radar data comparable to most other AMF campaigns. All four radars operated between December 2015 and February 2016. In March 2016 the Marine W-band ARM Cloud Radar (MWACR) was taken offline because of a failed power supply that could not be replaced in time for the rest of the campaign. The Ka-band Scanning ARM Cloud Radar (KaSACR) operated throughout the Antarctic winter until September 2016. The Ka-band zenith radar (KaZR) and X-band Scanning ARM Cloud Radar (XSACR) operated throughout the entire campaign. Thus there is zenith and volumetric scanning radar data throughout the campaign. The Aerosol Observing System (AOS) operated successfully throughout the campaign, collecting a unique seasonal cycle in Antarctic aerosol measurements. The two major AOS issues were significant down time with the Humidified Tandem Diffusion Mobility Analyzer (HDTMA), and contamination of the sampling by local vehicle exhaust along the adjacent main road. This contamination affects approximately 30% of the total AOS data set, but the remaining data in all months contain unique information about subtle polar marine aerosol microphysics. Rawinsonde launches supporting AWARE were made twice daily by USAP. Figure 1 shows the AMF2 installation at CosRay.

USAP logistical constraints restricted the AWARE Extended Facility deployment at WAIS Divide to a single U.S. Air National Guard LC-130 flight. All equipment and personnel, including helium for sondes, had to fit on a single transport aircraft from McMurdo Station. The original AMF2 campaign proposal called for this AWARE support flight to go to WAIS Divide immediately after the first several flights took USAP personnel to the site to set up the summer ice camp. Early summer 2015 was a strong El Niño year, and a series of storms throughout November delayed both the transport flights and the actual station setup at WAIS Divide. The AWARE transport LC-130 mission did not occur until 2 December, 2015. The field party of four led by Heath Powers (LANL) worked efficiently and got ARM instruments operating between 4-7 December. The first system on line was the rawinsonde system, and on 4 December ARM made the first sonde launches from West Antarctica since 1967. The WAIS Divide campaign continued until 18 January, 2016, when all equipment had to be dismantled for station takedown. Thus we collected 42-45 days of data depending on instrument. At first this was a disappointment compared with the 75 days originally called for in the original AMF2 proposal. However, the same El Niño conditions that delayed the AWARE transport mission throughout November also brought a strong surface melt event in January 2016 that AWARE was able to sample with exactly the right suite of instruments. This made the AWARE campaign an unqualified success.

The WAIS Divide Extended Facility was designed to fit within a small container ("skip container") housing the data system, with radiometers on the roof and several larger instruments deployed nearby out on the snow surface (Figure 2). Instruments included the broadband SKYRAD and GNDRAD radiometer systems, surface energy balance system (SEBS), multi-frequency rotating shadowband radiometer (MFRSR), Cimel Systems sun-tracking photometer (CSPHOT), and surface meteorology (MET). We were also allocated a second MPL and ceilometer system. The ARM Facility was particularly generous to AWARE in taking the G-band vertical radiometer profiling system (GVRP) from the North Slope of Alaska (NSA) site and allocating it to AWARE for WAIS Divide. GVRP data would prove to be crucial in providing high-time-resolution vertical profiles of lower tropospheric temperature and moisture to help diagnose the surface melt conditions that occurred in January 2016.

Figure 1. The AMF2 deployment at the CosRay site 1 km from McMurdo Station on Ross Island.

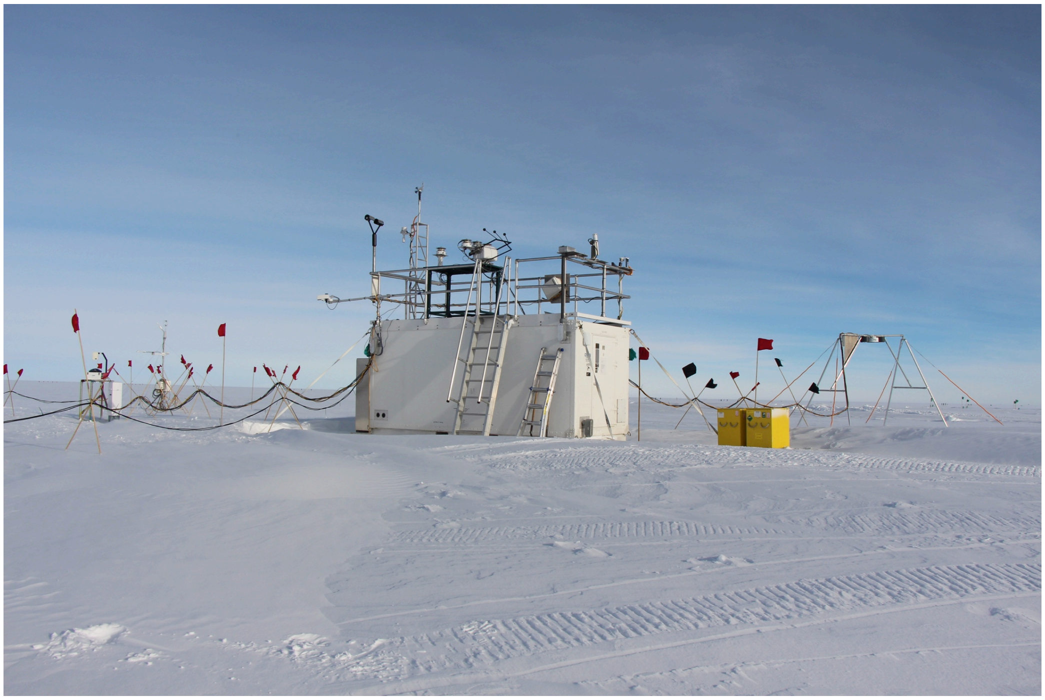

Figure 2. The "skip container" housing the AWARE Extended Facility instruments at the WAIS Divide Ice Camp.

2.0 Results

The first month of data from WAIS Divide comprised typical climatological scenarios for summer in West Antarctica. As these had never before been sampled with advanced atmospheric instrumentation, this data set was already valuable. On 10 January, 2016 the prevailing El Niño conditions set up a strong "blocking high" over the Amundsen Sea that channeled warm and moist air (enhanced by a sea surface temperature anomaly) over the Ross Ice Shelf and onto the WAIS. This caused one of the three largest West Antarctic surface melt events on record, and the AWARE Extended Facility at WAIS Divide was on hand to sample this event. The Polar Meteorology Group at Byrd Polar and Climate Research Center, led by AWARE Science Team member Professor David Bromwich, made a detailed study of this melt event that was published in *Nature Communications* (Nicolas et al. 2017).

AWARE surface energy balance (SEB) measurements were able to capture the impulse that led to the surface showing melt onset. Figure 3 shows these SEB components. Total cloud liquid water content (TCLW) observed from the GVRP was frequently within 10–40 g m^{-2}, i.e., the range where the cloud radiative enhancement effect previously observed over Greenland occurs. In this range, the clouds are thick enough to enhance the downwelling longwave radiation (Figure 3a) but thin enough to also allow shortwave radiation to reach the surface (Figure 3b). TCLW was within this range 30–40% of the time during 10–13 January, suggesting that this enhancement mechanism contributed to the melt event. This is further supported by the frequent and widespread occurrence of clouds with TCLW within 10–40 g m^{-2} simulated by ERA-Interim reanalysis during the same period. However, we also notice a significant frequency of TCLW > 40 g m^{-2}, under which shortwave flux will be attenuated and longwave flux will be similar to blackbody radiation at the cloud effective temperature. These optically thicker clouds represent a contrast to the Greenland cloud radiative enhancement effect in that they signify a more prominent role of thermal blanketing as a consequence of the warm air advection. The total surface energy budget (Figure 3e) shows a marked increase in the net energy input into the snowpack (up to 40 Wm^{-2}), mainly attributable to enhanced downwelling longwave radiation (Figure 3a,c). This effect of this additional energy input is apparent in the satellite passive microwave-measured brightness temperatures (Figure 3e). This melt event data, combined with the prior month of data in the normal climatological range, will provide a useful benchmark for climate models in simulating changing SEB conditions over West Antarctica in a steadily warming atmosphere.

AWARE data from the full AMF2 at CosRay are also providing unique scenarios for testing cloud microphysical and climate model simulations. Figure 4 shows an example of zenith radar data exhibiting much larger vertical velocities than found in the Arctic. In contrast to the high Arctic, the rugged Antarctic terrain induces significant orographic forcing of transiting air masses, and the McMurdo Station region provides examples on various spatial scales depending on the prevailing wind direction. Some cloud formation is influenced by local terrain forcing, while other cloud systems sampled by AWARE show influence of terrain forcing by the Transantarctic Mountains. A third type of cloud system sampled by AWARE involves moisture transported directly from the Ross Sea, which yields marine stratocumulus more typical of the high Arctic with limited terrain forcing. AWARE Science Team member Professor Johannes Verlinde is leading the effort to diagnose these scenarios from the AMF2 radar data, to describe a set of case studies for climate modelers that provide a strong contrast from the Arctic.

Research papers are emerging within the first year following AWARE (Nicolas et al. 2017, Scott et al. 2017, Wilson et al. 2017). In December 2015 an AWARE press release at the American Geophysical Union (AGU) Fall Meeting was covered by *Nature* (Witze 2016). AWARE has also been covered in several invited talks at major geophysical conferences. By the end of 2018 we anticipate that each AWARE Science Team research group will have produced publications deriving fundamental atmospheric science results directly from the data, which will help the larger climate science and climate modeling community better understand and make projections for the Antarctic. As of this report, we know of one additional research effort supported by the NSF Division of Polar Programs and one to be supported by the DOE Atmospheric System Research (ASR) Program that will specifically work with AWARE data. These efforts do not include the original AWARE Science Team, and hence the success of the AWARE campaign is already influencing the larger atmospheric and climate science communities.

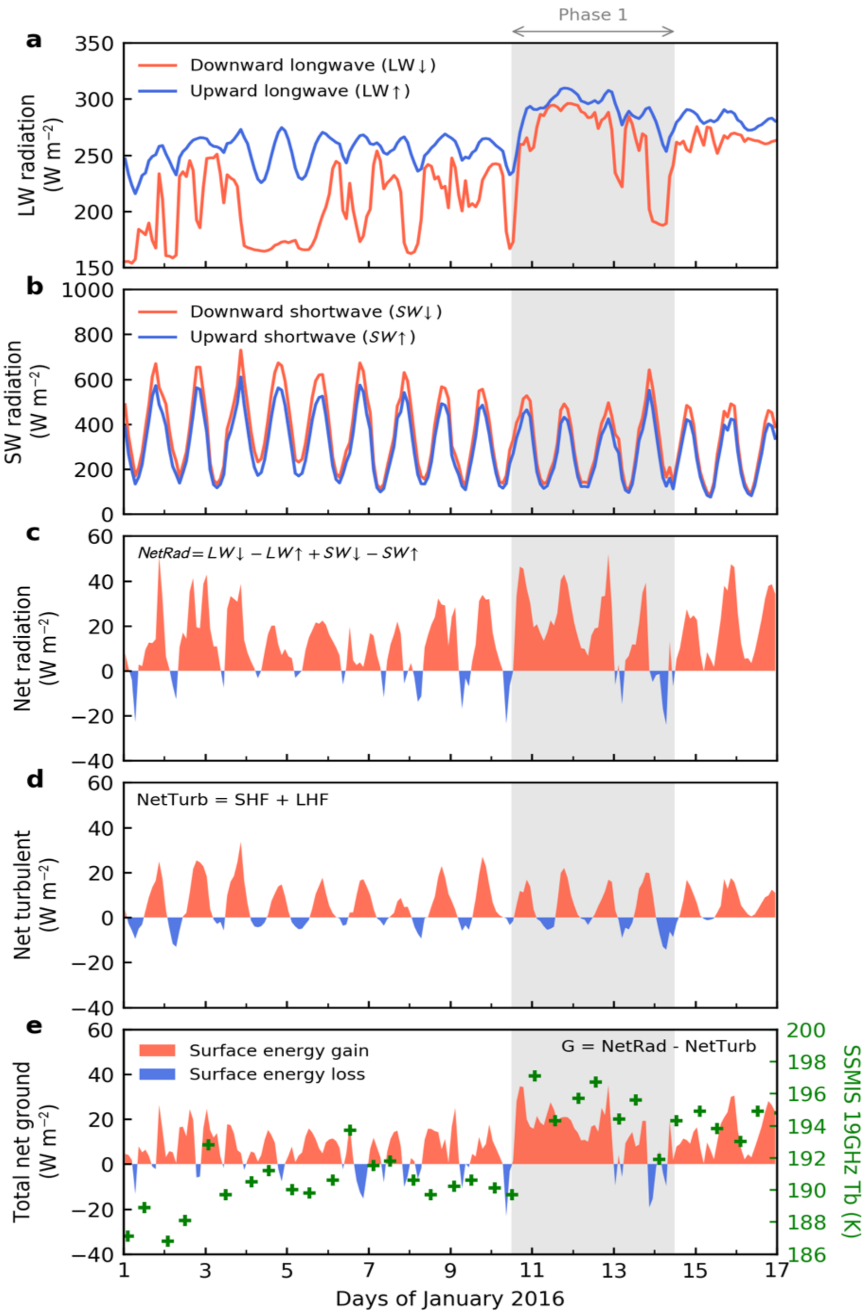

Figure 3. Surface energy budget at WAIS Divide in January 2016. a, Downward and upward longwave radiation fluxes. b, Downward and upward shortwave radiation fluxes. c, Net radiation flux. d, Net turbulent flux, calculated as the sum of sensible (SHF) and latent (LHF) fluxes, where positive is energy transfer away from the surface to the atmosphere. e, Total net energy flux into the ground (snowpack) calculated as net radiation minus net turbulent fluxes. The green crosses represent the satellite passive microwave 19 GHz horizontally polarized brightness temperatures measured from space at the location of WAIS Divide. From Nicolas et al. (2017).

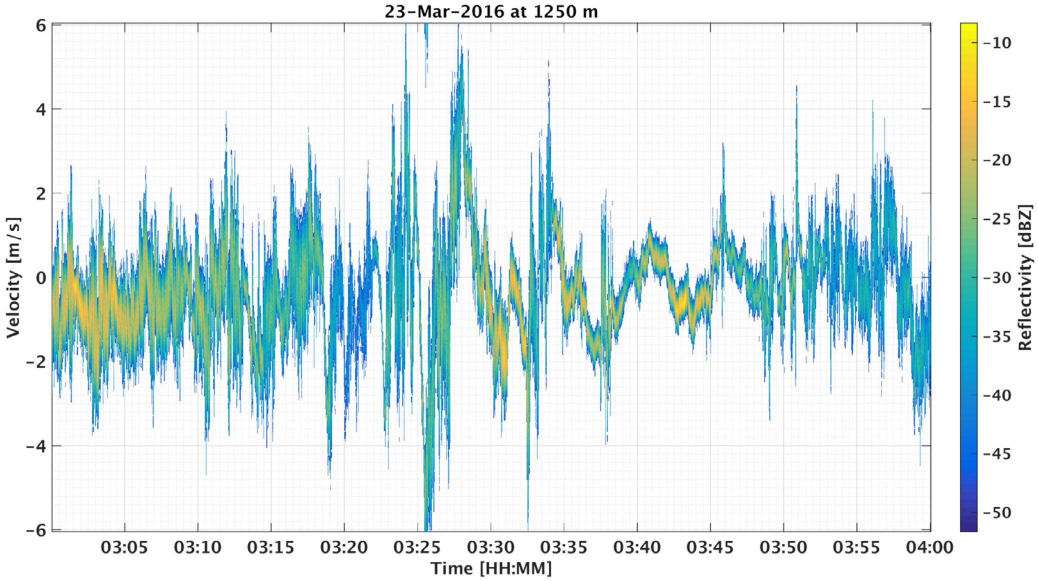

Figure 4. Example of vertical velocity in cloud sampled by the KaZR at CosRay. These velocities are up to a factor of 10 larger than typically found in the high Arctic. Figure courtesy of J. Verlinde and I. Silber, Pennsylvania State University.

3.0 Publications and References

Nicolas, JP, AM Vogelmann, RC Scott, AB Wilson, MP Cadeddu, DH Bromwich, J Verlinde, D Lubin, LM Russell, C Jenkinson, HH Powers, M Ryczek, G Stone, and JD Wille. 2017. "January 2016 extensive summer melt in West Antarctica favored by strong El Niño." *Nature Communications* 8: 15799, doi:10.1038/ncomms15799.

Scott, RC, D Lubin, AM Vogelmann, and S Kato. 2017. "West Antarctic Ice Sheet clouds and radiation budget from NASA A-Train satellites." *Journal of Climate* 30: 6151-6170, doi:10.1175/JCLI-D-16-0644.1.

Wilson, A, RC Scott, M Cadeddu, and D Lubin. 2017. "Cloud optical properties over West Antarctica from the ARM West Antarctic Radiation Measurement Experiment (AWARE)." *Journal of Geophysical Research*, in review.

Witze, A, 2016. "Antarctic cloud study takes off: Scientists probe atmosphere above ice sheet for the first time since the 1960s." *Nature* 529: 12.

Invited Presentations on AWARE

Lubin, D, DH Bromwich, A Vogelmann, J Verlinde, and LM Russell. 2016. ARM West Antarctic Radiation Experiment: A Joint NSF-DOE ARM Mobile Facility Campaign. Presented at US CLIVAR Process Study – Model Improvement Panel (PSMIP) webinar, 2 March 2016.

Lubin, D, DH Bromwich, A Vogelmann, J Verlinde, and LM Russell. 2016. ARM West Antarctic Radiation Experiment: A Joint NSF-DOE ARM Mobile Facility Campaign. Presented at European Geophysical Union Annual Meeting, Vienna, Austria, 19 April 2016.

Lubin, D, DH Bromwich, A Vogelmann, J Verlinde, and LM Russell. 2017. The ARM West Antarctic Radiation Experiment (AWARE). Presented at American Meteorological Society Annual Meeting, Seattle, Washington, 24 January 2017.

Lubin, D, DH Bromwich, A Vogelmann, J Verlinde, LM Russell, and RC Scott. 2017. The ARM West Antarctic Radiation Experiment (AWARE). Presented at 2017 ARM/ASR Joint User Facility PI Meeting, Tysons, Virginia, 16 March 2017.

Lubin, D, DH Bromwich, A Vogelmann, J Verlinde, LM Russell, and RC Scott. 2017. The ARM West Antarctic Radiation Experiment (AWARE). Presented at 2017 DOE Biological and Environmental Research and Advisory Committee (BERAC) Meeting, Gaithersburg, Maryland, 20 April 2017.

ARM

CLIMATE RESEARCH FACILITY

www.arm.gov

U.S. DEPARTMENT OF ENERGY

Office of Science