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Opportunities for Sustained Arctic Observations and Scientific Collaborations at the US Department of Energy Atmospheric Radiation Measurement (ARM) Facilities on the North Slope of Alaska

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Introduction

The U.S. Department of Energy (DOE), Office of Science/Biological and Environmental Research, provides scientific infrastructure and data to the international Arctic research community via atmospheric research facilities located on the North Slope of Alaska (NSA) (www.arm.gov/sites/nsa). An instrumented ARM facility was established on the coast of the Arctic Ocean near Barrow Alaska in 1997. A smaller inland facility was operated in Atqasuk between 1999 and 2010. This facility in Atqasuk included infrastructure that was used on the icebreaker-based Surface Heat Budget of the Arctic (SHEBA) campaign. SHEBA involved the deployment of an instrumented ice camp within the perennial Arctic Ocean ice pack that began in October 1997 and lasted for 12 months. In October of 2013, an ARM Mobile Facility (AMF3) was constructed at Oliktok Point, Alaska. Sandia National Laboratories manages and operates the ARM NSA facilities for DOE. Combined, these sites constitute the ARM NSA Megasite; a network of facilities to provide complementary high-density observations for improved understanding of arctic processes. The locations of Barrow, Oliktok Point and Atqasuk are shown in Figure 1.

Barrow is at the northernmost point in the US, 330 miles north of the Arctic Circle, and contains some of the most robust infrastructure on the North Slope. The Barrow ARM site benefits from this to provide consistent measurements from facilities that include instrumentation, lodging, communications and maintenance support. An extended range AERI (ER-AERI) built specifically for the high latitudes where low water vapor concentrations are common is operating at Barrow, and many instruments have been hardened to withstand temperatures that drop below (-)40 C/^{o}F.

The Oliktok Point site consists mainly of an aircraft hangar, gravel runway, instrumentation vans, and lodging that are located on the grounds of an active US Air Force facility (Oliktok Point Long Range Radar Site, LRRS). Restricted airspace R-2204 encompasses a two mile radius centered on Oliktok Point and can be accessed from a gravel runway and pads at the LRRS. Warning Area W-220 extends approximately 700 nautical miles (nm) into international airspace and is approximately 40 nm wide. The R-2204 and W-220 air spaces are illustrated in Figure 1. Unique among ARM facilities, it is the only ARM site with restricted airspace, providing opportunities for research with tethered balloons, unmanned aircraft systems, and modified manned aircraft, without the need for an FAA waiver. It is also the only ARM site located within the North Slope oilfields, and the only site hosted by the US Air Force. The proximity to the LRRS and to ongoing oil extraction activities provides Oliktok Point with amenities, infrastructure, and logistical services not readily found elsewhere in the Arctic.

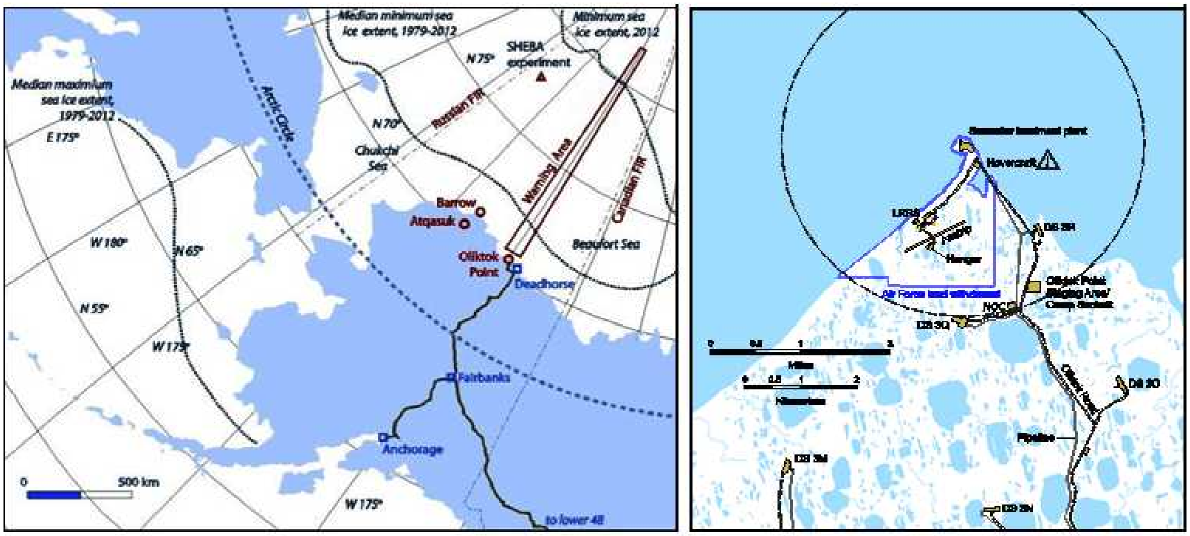

Figure 1: ARM North Slope Facilities and Controlled Air Spaces at Oliktok/AMF3. (**Left**) ARM facility sites (red circles) and W-220 international warning air space; (**Right**) Oliktok R-2204 restricted air space.

Instruments and Scientific Infrastructure at Barrow and Oliktok Point/AMF3

The mission of the ARM North Slope Alaska is to:

- Provide infrastructure support for climate research to the scientific community.
- Provide a broad range of data to help answer questions about Arctic climate change.
- AMF3 is gathering data using instruments that obtain continuous measurements of clouds, aerosols, precipitation, energy, and other meteorological variables.
- Provide climate data that is freely available to the international community through the ARM data archive.

The ARM NSA field campaigns and ongoing baseline measurements are conducted from the Barrow and Oliktok/AMF3 sites. Images of both sites are shown in Figure 2.

Figure 2: ARM North Slope Alaska Facilities. (**Above**) Barrow facilities are fixed, while (**Below**) Oliktok/AMF3 facilities are mobile.

Measurements at the Margins: Trends that point to accelerated warming in the Arctic include the shrinking spread and year-to-year loss of sea-ice and temperatures (rising at twice the rate of the rest of world), and increasing instability in the region's permafrost layer, which stores vast amounts of methane in its frozen grip—for now. Computer models used to test scientific theories have yet to simulate these conditions with a high level of accuracy.   Largely due to the difficulties in obtaining the needed observational data for the models, the ARM NSA facilities collect data to fill those gaps. Instruments that are operated at these sites are listed in Table 1.

Table 1: Atmospheric Observation Instrumentation at ARM NSA Facilities

Barrow Site	Oliktok Point/AMF3
Atmospheric Profiling Instruments	
Automated Balloon-Borne Sounding System (SONDE)	Balloon-Borne Sounding System (SONDE)
Radar Wind Profiler (RWP)	Tether Balloon-Borne Sounding System (SONDE)
	Unmanned Aerial Systems (UAS)
Cloud Instrumentation	
Ceilometer (CEIL)	Vaisala Ceilometer (VCEIL)
Total Sky Imager (TSI)	Total Sky Imager (TSI)
Doppler Lidar (DL)	Doppler Lidar (DL)
Ka-Band Scanning ARM Cloud Radar (KASACR)	Ka-Band Scanning ARM Cloud Radar (KASACR)
Ka-Band ARM Zenith Radar (KAZR)	Ka-Band ARM Zenith Radar (KAZR)
W-Band Scanning ARM Cloud Radar (WSACR)	W-Band Scanning ARM Cloud Radar (WSACR)
Multipulse Lidar (MPL)	Micropulse Lidar (MPL)
Cloud Mask from Multipulse Lidar (MPLCMASK)	Radar Wind Profiler (RWP)
X-Band Scanning ARM Precipitation Radar (XSAPR)	C-Band ARM Precipitation Radar (CSAPR)
	Microwave Radiometer, 3-Channel (MWR3C)
	Raman Lidar (RL)
Radiometers	
Atmospheric Emitted Radiance Interferometer (AERI)	Atmospheric Emitted Radiance Interferometer (AERI)
Infrared Thermometer (IRT)	Infrared Thermometer (IRT)
Cimel Sunphotometer (CSPHOT)	Cimel Sunphotometer (CSPHOT)
Upwelling Radiation (GNDRAD)	Upwelling Radiation (GNDRAD)
G-band (183 GHz) Vapor Radiometer (GVR)	Groupings of broadband instruments such as pyranometers, pyrgeometers, and pyrheliometers.
G-band (183 GHz) Vapor Radiometric Profiler (GVRP)	
High Spectral Resolution Lidar (HSRL)	Multifilter Rotating Shadowband Radiometer (MFRSR)
Downwelling Radiation (SKYRAD)	Multifilter Radiometer (MFR)
Multifilter Radiometer (MFR)	Downwelling Radiation (SKYRAD)
Multifilter Rotating Shadowband Radiometer (MFRSR)	
Microwave Radiometer (MWR)	
Microwave Radiometer – High Frequency (MWRHF)	
Microwave Radiometer Profiler (MWRP)	
Normal Incidence Multifilter Radiometer (NIMFR)	
Surface Meteorology	
Meteorological Instrumentation (MET)	Meteorological Instrumentation (MET)
Facility-specific multi-level Meteorological Instrumentation (TWR)	Eddy Correlation Flux Measurement System (ECOR)
Ameriflux Measurement Component (AMC)	Ameriflux Measurement Component (AMC)
	Multi Angle Snow Camera (MASC)
AMF3 Phase III instruments *(to be added in the near future)*	
Aerosol Observing System (AOS) to include:	
• Ultra-High Sensitivity Aerosol Spectrometer	• Nephelometer, 3-wavelength
• Cloud Condensation Nuclei Counter (CCN)	• Two Condensation Particle Counters (CPC)
• Single Particle Soot Photometer (SP2)	• 7-Wavelength Aethelometer
• Scanning Mobility Particle Sizer (SMPS)	• Hygroscopic Tandem Differential Mobility Analyzer (HTDMA)
• Photo-Acoustic Soot Spectrometer (PASS)	• Particle Soot Absorption Photometer (PSAP)
• Humidigraph	

The Unmanned Aerial Systems (UAS) program supports aircraft measurements for priority scientific questions, including in-situ cloud properties, aerosol size, chemical composition, and remote sensing of various atmospheric parameters. Unmanned Aerial Systems (UAS) operations at AMF3/Oliktok include TBS and UAVs. Some images from Oliktok/AMF3 field campaigns involving UASs are shown in Figure 3.
Tethered Balloon (TBS) Operation advantages include:

- Balloons allow for longer flight times.
- Can lift heaver instrumentation packages than typical UAS.
- Slower rate of assent and dissent.
- Lower cost of operation compared to aircraft.
- Small crew required to operate.

Unmanned Aircraft (UAV) Operation advantages include:

- DOE/Sandia operates Restricted Area R-2204 and Warning Area W-220 to protect and control flight operations for testing and data collection.
- Sandia has approval from the USAF for use of selected facilities to conduct scientific experiments for ARM in Restricted Airspace at Oliktok/Long Range Radar Site (LRRS).
- The ability to use UAVs at Oliktok allows measurements of critical Arctic systemsto address gaps in scientific understanding of these processes.
- Ability to control flight allows data over ocean/ice and land/tundra forinformative data sets.
- Small crew able to operate small UAVs.

Figure 3: UAS Operations from Oliktok/AMF3. (Clockwise from upper left): Tethered Helikite launch (Sep. 2014), Helikite with tethered sondes (Sep. 2014), ScanEagle (Arctic Shield, July 2015), DataHawk launch (COALA, Oct. 2014),

DataHawk (ERASMUS, Aug. 2015), Balloon Sonde launch (ERASMUS, Aug 2015), BAT-3 and Aeryon Scout (NMSU UAV Tests, 2012).

Recent Collaborations

During 2014, there were 12 field campaigns based at ARM NSA sites (DOE, 2014). Field campaigns and collaborations that have been conducted at the ARM-NSA sites during 2015 include (DOE, 2015b):

1. Arctic Shield (July 2015) with US Coast Guard, Conoco-Phillips, Insitu/Boeing, NOAA, FAA, NSB and Era Helicopter; using ScanEagle platform.
2. Evaluation of Routine Atmospheric Sounding Measurements using Unmanned Systems (ERASMUS-I, Aug 2015) with CIRES/UC-Boulder; using DataHawk platform.
3. TBS (Tethered Balloon System) (Sep and Oct 2015, Oliktok) with CIRES/UC-Boulder using 35 m^3 helikite and Pilatus platform.
4. ARM Airborne Carbon Measurements on the North Slope of Alaska (ACME V) with Lawrence Berkeley National Lab, NASA, Pacific Northwest National Lab, Brookhaven National Lab, NOOA, Harvard University and University of Colorado; to observe atmospheric trace gases, aerosols, and cloud properties at the NSA.
5. Atqasuk GPS Base Station (ongoing through 2021) with UNAVCO; to provide GPS information to multiple users.
6. ARM Radiosondes for NPOESS/NPP Validation (ongoing) with NASA; for satellite data validation.
7. Support for Next-Generation Ecosystem Experiment (NGEE Arctic) (ongoing); to support data collection of Arctic ecosystem and climate feedback processes.
8. Barrow In-Situ Snow Sampling Study (ongoing through 2016) with Japan Agency for Marine Earth Science Technology (JAMSTEC); to analyze black carbon concentration and size distribution in snow.
9. Arctic Observing eXperiment (AOX, ongoing through 2016) with University of Washington; to provide data in support of modeling and information towards international Arctic/Antarctic programs.
10. EarthScope Seismic Station A21K-6 (ongoing through 2018) with IRIS; to operate a station among an array for seismic observations.
11. Arctic Methane, Carbon Aerosols, and Tracers Study (ongoing through 2016) with Sandia National Labs; to measure methane, black carbon, and source tracers in the atmosphere.
12. Micro-Climate Influences on Bird Arrival Behavior (2015) with Radford University; to study meteorological influences on behaviors of migrating birds.
13. Summertime Aerosol across North Slope of Alaska (ongoing through 2016) with University of Michigan; to study atmospheric chemistry and particulates to model local, regional and long range transport of NSA aerosols in the summer.

Tethered Balloon Operations

ARM is developing a tethered balloon system (TBS) capable of routine daily operations at Oliktok/AMF3. Operations will be conducted up to 7,000’ above ground level (AGL) within the R-2204 restricted area (Fig. 1, right), and the balloon will remain aloft for up to 18 hours per day. The TBS will operate within clouds to collect high vertical resolution atmospheric data. Increased vertical resolution of meteorological properties and cloud measurements will improve understanding of arctic cloud processes and complement the data concurrently obtained by existing AMF3 site instrumentation. Currently, the ARM TBS currently includes the following equipment:

- Two 35 m^3 helikites (31 lbs minimum lift @ sea level (MLSL))
- One SkyDoc™ Aerostat (Model #26, 116 lbs minimum lift at MLSL)
- One SkyDoc™ Aerostat Model #28 (121 lbs MLSL)
- Two 10 000 foot (3050 meter) tether capacity winches
- Two 1500 foot (460 meter) tether capacity winches

Current instrumentation used with the ARM TBS include:

- Sixteen tethersondes (measure pressure, relative humidity, temperature, wind speed, wind direction, altitude, latitude, longitude)
- Two upward-facing cameras to monitor the TBS in-flight
- Clinometer used to determine tether angle for redundant calculation of sensor altitude
- Wireless temperature and wetness/icing sensor
- Two supercooled liquid water content (SLWC) sondes

ARM has interest in procuring a distributed temperature sensing (DTS) fiber system. In practice, the DTS fiber would run along the balloon tether and sample temperature every 8 meters at a 30-second sampling rate with an accuracy of 0.06°C.

Science Objectives

The primary purpose of the ARM NSA sites is to provide comprehensive data sets to develop and test Global Climate Model algorithms to describe radiative transfer and cloud processes at high latitudes. Current objectives (DOE, 2015a) are to improve understanding of processes to describe:

- Radiative transfer in both clear and cloudy atmospheres, especially at low temperatures;
- Physical and optical behaviors of surface water (ice) and land, both bare and snow-covered, especially during transitions between winter and summer;
- Physical and optical behavior of ice and mixed phase clouds.

In September 2014, DOE held a workshop focused on scientific priorities for observational activities in the North Slope. Mixed-phase clouds, which contain both liquid droplets and ice particles, are the dominant cloud type over Polar Regions and have a large global coverage. The processes that cause mixed-phase clouds to form, grow, and dissipate are not well understood and are often poorly modeled. Predicting how atmospheric aerosols influence cloud formation and climate is a challenge that limits the accuracy of atmospheric models. This problem is especially true in the Arctic. Results (from the Indirect and Semi-Direct Aerosol Campaign (ISDAC) field study, 2008) also indicate that the number and composition of particles capable of forming clouds over Alaska can be influenced by episodic events such as biomass burning (for example, forest fires) that bring aerosols from the local vicinity and as far away as Siberia (DOE, 2014).

The ARM Science Team provides guidance on the types of measurements that most directly benefit the scientific community, involving four primary research themes: aerosol life cycle, cloud life cycle, cloud-aerosol interactions, and radiative processes. Current NSA objectives revolve around these themes and five broad science subtopics, being:

1. Understanding clear-to-cloudy transitions, with a focus on single-layer low level clouds,
2. Characterization of North Slope aerosol properties and seasonal variability,
3. Understanding high-latitude aerosol-cloud interactions,
4. Characterization of North Slope cloud properties, and
5. Characterization of high-latitude precipitation processes, with emphasis on radar-centric evaluation of precipitation.

Understanding clear-to-cloudy transitions, with a focus on single-layer low level clouds: To understand the evolution of the lower troposphere during transitions from clear to cloudy conditions, frequent profiling of aerosol and thermodynamic properties of the lower atmosphere during the time period prior to stratiform cloud formation is a critical piece of information. There is also interest in measurement of the cloud-top region to assess properties relative to cloud lifetime. Another potentially important component to evaluate cloud lifecycle and lifetime is detailed measurement of the surface energy budget, with emphasis on turbulent surface fluxes, as well as onshore and offshore radiative and aerosol fluxes. Due to the coastal nature of the Oliktok and Barrow sites, having information on surface fluxes from the ocean/ice surface is important, particularly given the potential for the land surface to impact land-based measurements.

Characterization of North Slope aerosol properties and seasonal variability: Once the Deployment of the Aerosol Observing System (AOS) in 2016 will enable data of seasonal variability in aerosol properties. However, because the Arctic atmosphere can be very stratified, translating surface aerosol properties to understand aerosol-cloud interactions and aerosol radiative impacts is unclear. Capabilities for routine profiling of aerosol properties would be beneficial, particularly during the late-winter and early spring Arctic Haze period, with an intent to obtain representative sampling of all seasons and atmospheric conditions. Profiles should provide information on particle size distribution, absorption and scattering, and offer an opportunity to collect filter samples for evaluation of chemical composition and cloud nucleation properties. Information on cloud nucleation (cloud condensation nucleation (CCN) and ice nucleation (IN)) activity is a critical component of aerosol-cloud interaction studies.

Understanding high-latitude aerosol-cloud interactions: A major hurdle to improving our understanding of aerosol-cloud interactions is limited information on aerosol profiles. While surface-based measurements are available, frequent stratification of the Arctic atmosphere introduces uncertainty in use of this data. Therefore, profiles of basic information on aerosols (e.g. number, size) can shed substantial light on this issue. It is important to get information on cloud microphysical properties, with a focus on liquid water droplet properties. Measurements of droplet size distribution would provide key insight into how the cloud microphysics responds to changes in aerosol properties. Frequent sampling is required to build sufficient statistics; observing similar cases under both clean and polluted conditions. It is critically important to have frequent profiling of aerosol properties when single-layer liquid-containing stratiform clouds are present.

Characterization of North Slope cloud properties: This subject area can generally be handled using continuously operational remote (land-based) sensors. UASs could provide in-situ measurements of cloud microphysical properties (liquid and ice particle size distributions, liquid and ice water path, ice crystal habit, etc.).

Characterization of high-latitude precipitation processes, with emphasis on radar-centric evaluation of precipitation: Efforts in this area are generally focused on development and evaluation of radar-centric precipitation rate and water content information, along with ice hydrometeor habit parameter development. Information to help tune and evaluate relevant radar retrievals will be of greatest help. This includes measurements of cloud microphysics, with a focus on ice habit and ice crystal size distributions; ideally measured in the cloud close to that sampled by the radar systems. Turbulence measurements throughout the cloud depth will improve turbulent mixing process assumptions.

In general, there are major obstacles in using new sensors and platforms, such as those introduced for UASs. Characterization of sensor performance, error analysis, and evaluation of sensor operation under UAS deployment is critical to ensure that measurements are usable.

Future Prospects

The continued development of the Megasite concept for ARM NSA facilities provides opportunities for continued operations and research in Barrow, Oliktok and Atqasuk. Collaborations across ARM and with North Slope partners is expanding and bringing new skills and tools to support varied interests. With the extended deployment of AMF3, the establishment of controlled air spaces R-2204 and W-220, and having the northernmost surface road connection to the lower 48 States, Oliktok is well situated to serve expanded UAS and field operations. Promising discussions are in place to establish a long-term Science Camp at Oliktok in order to provide a stronger infrastructure, continue research and build on the observations from AMF3. With Federal Aviation Administration (FAA) approvals, UAVs can also operate out of Barrow or Atqasuk to provide coordinated operations along the North Slope. Testing of new sensors and approaches for data collection (e.g. drop sondes/gliders from tethered balloons) are but one area of interest for novel observations in the Arctic. The ARM NSA facilities provide a baseline of instruments and user facilities to support many users for research, search and rescue operations, wildlife management, earth studies and others. Ongoing and future field campaigns and collaborations are expected to provide important information to support the core mission of the DOE ARM NSA program, as well as partner programs.

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