U.S. DEPARTMENT OF ENERGY | Office of Science

BIOLOGICAL AND ENVIRONMENTAL RESEARCH

Climate and Environmental Sciences Division

NORTH SLOPE OF ALASKA PRIORITIES WORKSHOP
SEPTEMBER 10–12, 2014

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Executive Summary

The U.S. Department of Energy (DOE) Climate and Environmental Sciences Division (CESD) within the Office of Biological and Environmental Research (BER), is hosting a series of workshops to solicit community feedback on how key scientific needs, gaps, and priorities in process model understanding and climate model prediction could be addressed through strategic deployment and operation of instruments and routine high-resolution modeling. In particular, the use of the Atmospheric Radiation Measurement (ARM) Climate Research Facility—a DOE Office of Science user facility— is being reconfigured to better support the integration of observations and high-resolution modeling and to address these types of emerging science questions. As part of ARM's reconfiguration, instruments are being concentrated to produce denser observational capabilities at fewer sites.

In September 2014, the North Slope of Alaska (NSA) Priorities Workshop was held to obtain scientific input on priorities for observational and scientific research activities related to atmospheric processes in the North Slope region and to identify gaps or needs that limit the ability of the research community to address these scientific priorities. Topics of discussion included capabilities at the existing ARM NSA facilities in Barrow and Oliktok Point, additional observations that may supplement and/or link these facilities (e.g., aircraft, unmanned aerial systems, tethered balloons, scanning radar systems, surface stations), and modeling activities.

To begin the discussion, a request for white papers was shared with the broader ARM user community, and in particular with the Atmospheric System Research (ASR) program through which the ARM Facility has a strong collaboration. The white papers sought input on the following three key science questions:

- What are key science questions or objectives relevant to the North Slope region and the DOE CESD that are poorly constrained now, but could be addressed with a more complete observation suite and/or associated modeling activities?
- For the science questions identified, what are the key observable parameters required?
- What modeling strategy would be effective to support these additional measurements toward addressing these science objectives?

The workshop began with an overview of these three science questions and a description of the current and planned facilities on the North Slope. From the white papers, the following four key interrelated themes were drawn and guided the workshop discussion.

- Long-range transport versus local processes
- Aerosols and their impacts
- Cloud processes
- Vertical structure of the atmosphere.

Workshop participants were charged to identify the key science questions within these thematic areas that can be addressed at the ARM NSA facilities and then to identify modeling strategies and observational needs that could be used to address these questions. Workshop participants noted that there are many ongoing and upcoming observational and modeling activities in the Arctic and that increased collaborations with these activities would strengthen the scientific outcomes from ARM and ASR activities on the North Slope.

From the workshop, a set of high-priority actions were identified that could be taken to address the current gaps in observational capabilities needed to address the science questions driving the discussion. Short-term actions included starting tethered balloon and regular unmanned aerial system operations, moving the high spectral resolution lidar from Barrow to Oliktok Point, deploying a baseline suite of atmospheric state, radiation, and cloud instrumentation to Atqasuk, and developing better characterization of bulk precipitation mass for all North Slope sites. Long-term priorities identified included regular, manned aircraft deployments during transition seasons and winter, as well as developing stronger collaborations with interagency activities in the Arctic and with other DOE programs and projects.

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1.0 Introduction

1.1 Background

DOE investments in atmospheric observations and research

The Atmospheric Radiation Measurement (ARM) Climate Research Facility is a U.S. Department of Energy (DOE) Office of Science user facility that is managed by the Climate and Environmental Sciences Division (CESD) of the Office of Biological and Environmental Research (BER). The ARM Climate Research Facility is an observation facility whose mission is to provide 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. The ARM Facility is closely affiliated with the Atmospheric System Research (ASR) program, which uses ARM data, laboratory measurements, and process models to address key atmospheric science issues and improve the parameterization of physical processes in climate models.

The ARM Facility and ASR program are leaders in research on clouds, aerosols, and their influence on radiation and climate. These two DOE programs work cooperatively to connect observations and studies of Earth's atmospheric system with the objective of improving the predictive understanding of Earth's climate system, and informing the development of sustainable solutions to the Nation's energy and environmental challenges. The ARM Facility and ASR have made significant improvements to understanding and representation of aerosol, cloud, and radiation processes in climate models (DOE 2013). In recent years, the ARM and ASR research communities have increased their focus on high-priority science questions that put more emphasis on interactions and coupling between processes, issues of scale and spatial variability, and understanding the full aerosol and cloud life cycles (DOE 2012, DOE 214b).

To better support the integration of observations and high-resolution modeling and to address these types of emerging science questions, the ARM Facility is undergoing a reconfiguration through which instruments will be concentrated to produce denser observational capabilities at fewer sites. Operations at the Tropical Western Pacific (TWP) site have been discontinued while measurement capabilities at the Southern Great Plains (SGP) and North Slope of Alaska (NSA) sites will be augmented. The SGP site has always served as the testbed for ARM development activities as it experiences a wide range of meteorological conditions, while the North Slope represents a region that is undergoing rapid environmental change.

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.

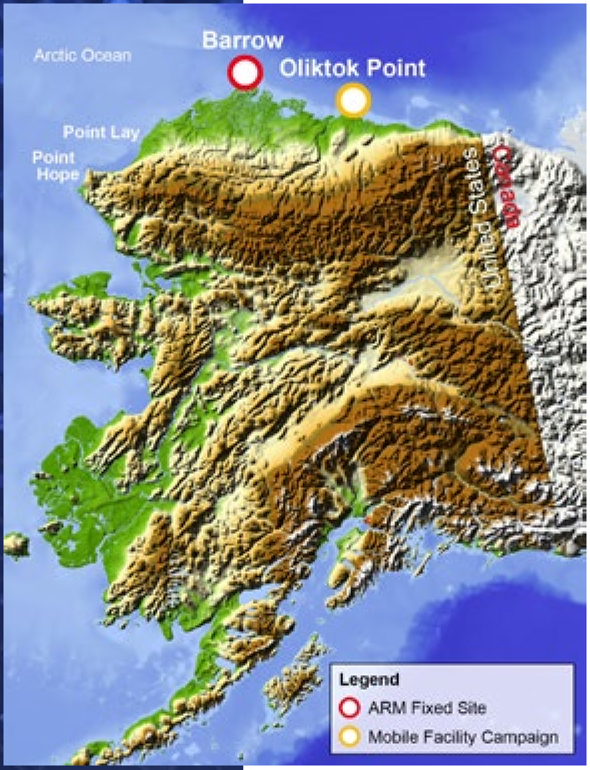
1.2 Workshop Series

The DOE CESD is hosting a series of workshops to solicit community feedback on how key scientific needs, gaps, and priorities in process model understanding and climate model prediction could be addressed through strategic deployment and operation of instruments and routine high-resolution modeling at the SGP and NSA sites. The first workshop was held in May 2014. It focused on high-priority science questions that could be addressed with routine modeling at the SGP site, and observational needs to support these activities. A report for this workshop is available at the following website: **http://science.energy.gov/~/media/ber/pdf/workshop%20reports/doe-sc-0169-high-resolution.pdf.**

A second workshop was held in September 2014 in the Washington DC area. It focused on priorities for observational and scientific research activities related to the North Slope region. This report documents the proceedings from the NSA Priorities Workshop, lists the high-priority scientific questions identified by the workshop attendees, and identifies key measurement capabilities that are needed to address current observational gaps that limit the ability to address these key questions.

A third workshop—planned for May 2015—will focus on needs for aerial measurements to support DOE CESD science questions.

2.0 North Slope of Alaska Priorities Workshop



The arctic environment is changing rapidly and is an important region for scientific investigation. The United States Global Change Research Program (USGCRP) has listed arctic research as one of its interagency priorities for Fiscal Years 2015 and 2016 (USGCRP 2014), and DOE CESD has numerous experimental and modeling investments to address arctic issues.

The NSA Priorities Workshop sought to obtain scientific input on priorities for observational and scientific research activities related to atmospheric processes in the North Slope region and to identify gaps or needs that limit the ability of the research community to address these scientific priorities. Topics of discussion included capabilities at the existing ARM NSA facilities in Barrow and Oliktok Point, additional observations that may supplement and/or link these facilities (e.g., aircraft, unmanned aerial systems, tethered balloons, scanning systems, surface stations), and modeling activities.

Participants at the NSA Priorities Workshop were selected to represent a broad range of interests including observations and modeling, high- and low-resolution modeling, as well as clouds, aerosols, radiation, and land-atmosphere interactions (see full participant list in Appendix A). The workshop invitation letter included the following three key questions:

- What are key science questions or objectives relevant to the North Slope region and the DOE CESD that are poorly constrained now, but could be addressed with a more complete observation suite and/or associated modeling activities?
- For the science questions identified, what are the key observable parameters required?
- What modeling strategy would be effective to support these additional measurements toward addressing these science objectives?

2.1 Prior Related Reports, Workshops, and Workshop Input

A number of studies and reports have investigated measurement needs and measurement priorities for the ARM NSA facilities. These reports include the following:

- Unmanned Aircraft Systems and Tethered Balloons Workshop held July 2013 (Ivey et al. 2013)
- ARM Decadal Vision (DOE 2014a)
- ARM Priorities List with NSA Unmet Measurement Needs (DOE 2015).

Prior to the NSA Priorities Workshop, white papers were solicited from the participants and the broader scientific community. These white papers focused on the science questions given in at the beginning of this section. The input received from these white papers was broad and thoughtful, and provided much material for synthesis prior to the meeting. The material was organized around four interrelated themes, presented in Section 3, to guide the discussions during the workshop.

2.2 Workshop Agenda

Starting at 1 p.m. on Wednesday, September 10, the NSA Priorities Workshop ran until 5 p.m., which was followed by a full day of discussion on Thursday, September 11. On September 12, a small group that included BER managers, conveners, and rapporteurs met to outline and plan the workshop report. The full workshop agenda is included in Appendix B.

The workshop started with a series of introductory talks followed by breakout sessions. The attendees divided into three groups, with each group discussing the same science question. Four focus areas were discussed in succession. The original plan for the workshop was modified after the Wednesday sessions when it became clear that the progress made towards workshop goals was not sufficient to ensure achievement of the overall workshop goals.

Each breakout produced a list of detailed questions and themes. These were recorded by the breakout facilitators on poster-sized paper temporarily mounted on the meeting room walls. The original workshop plan was to have co-chairs “process and condense” these detailed questions. However, the volume of input from the participants made this plan unpractical given time constraints. The revised workshop plan included using a voting method (i.e., colored "sticky" notes) to distill the list of questions to three top-priority questions for each of the four theme areas, resulting in twelve questions total.

On Thursday afternoon, discussions focused on the observations, measurements, and modeling strategies needed to address these priority questions. These priority questions, three for each area, are presented in Appendix C and in Section 3.2.

3.0 WORKSHOP DISCUSSION

The workshop began with an overview of the previously stated goals and a description of the current and planned facilities on the North Slope. Following these introductory presentations, the workshop organizers presented the themes drawn from the submitted white papers. The four interrelated themes for discussion were:

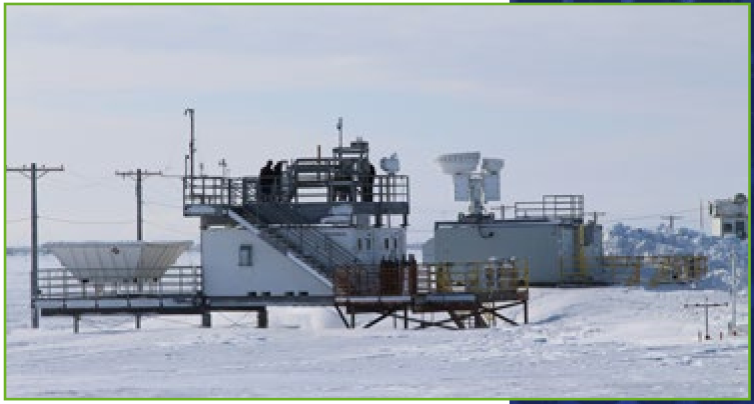
- Long-range transport versus local processes
- Aerosols and their impacts
- Cloud processes
- Vertical structure of the atmosphere.

Workshop participants were charged first to identify the key science questions within these thematic areas that can be addressed at the ARM NSA facilities and then to identify modeling strategies and observational needs that could be used to address these questions. The key science questions determined by the attendees for each theme area are listed at the beginning of each section and provided in Appendix C. For ease of discussion, each question is given an identifier such as V1 for question one under the theme vertical structure of the atmosphere.

3.1 High-level Science Questions

The discussion recognized the unique challenges and opportunities presented by the location of the ARM NSA facilities. Both current ARM facilities on the North Slope are located in the gradient zone along the North Slope coast, where land- and ocean-surface characteristics undergo large spatial and seasonal transitions. The arctic lower troposphere is frequently stably stratified, often with very strong inversions at and above the surface (Vihma et al. 2014). The strength of low-level stability varies as a function of season, surface properties, and the upper atmosphere, and ultimately controls the degree to which the surface interacts with the "free" troposphere (Vihma et al. 2014). Many of the radiatively important cloud processes are influenced by stable layers.

In contrast to the Barrow site, the third ARM Mobile Facility is deployed at Oliktok Point, which is located in the midst of the North Slope oil fields, for an extended deployment to support the NSA strategy. This region is heavily influenced by local gas and aerosol particle emissions that are mixed vertically at rates dependent on the degree of atmospheric stratification. At the same time, the ARM NSA facilities are located along one of three primary regions where meridional advection transports lower latitude air into the Arctic. Any atmospheric process must be understood in the context of these larger-scale advection influences along with the interactions among controlling environmental drivers such as sea-ice, ocean, and land-surface (Morrison et al. 2011). Precipitation and precipitation budgets were highlighted as important topics in the Arctic.



Perhaps one of the greatest difficulties in understanding arctic processes results from the fact that few natural separations in dynamic scales exist among processes that drive the arctic system. Scale-breaks in physical and temporal space allow groups of physical processes to be separated or untangled, simplifying possible modeling and measurement strategies. On the North Slope, even boundary layer processes are not easily separated from the larger scale synoptic and mesoscale air masses in which they are embedded. This is also true in lower latitudes, but much more so in the Arctic. Larger scale flows can drastically alter the local thermal and aerosol properties influencing cloud formation (Stramler et al. 2010, Morrison et al. 2011).

During much of the year, radiative processes alter the vertical and horizontal thermal structure of the atmosphere, influencing not only cloud formation, but also altering the development of synoptic high-pressure systems (Curry 1987). Surface processes feed into these local and larger scale processes; strong thermal and moisture contrasts driven by sea ice and open water over the ocean produce varying conditions influencing cloud and thermal properties over a large scale. Over the arctic landmass, valleys produce steep inversions, and gravity currents can be a primary feature of the lower troposphere during the colder season. Untangling the complex physical features of the arctic atmosphere, where nearly every process has some importance, is a significant challenge. Local processes—which can be measured at the DOE ARM sites—must be interpreted in the context of the larger meso-, synoptic-, and global-scale environments in which the systems of interest are embedded. It is within this context that the domain and scope of each of the high-level science questions were determined.

3.2 Workshop Themes and Science Questions

Theme 1: *Long-range transport versus local processes (S)*

Question S1. What are the most critical feedback mechanisms in the Arctic?

- Longwave radiation (i.e., water vapor, clouds)
- Shortwave radiation (i.e., sea ice, aerosol, clouds)
- Sensible and latent heat fluxes (i.e., sea ice/clouds)
- Net effect of feedbacks to Arctic Amplification.

Question S2. How does variability in long-range versus local sources of heat, water vapor, and aerosols shape the vertical atmospheric structure?

- Transport to vertical structure.

Question S3. What roles do biogeochemical transformations, aerosol aging, dispersion, and atmospheric stratification play in affecting aerosol radiative properties and cloud formation processes?

The Arctic has been warming at a rate faster than the rest of the globe over the last several decades—a phenomenon known as arctic amplification. Arctic amplification is the result of various feedbacks from systematic changes in absorption of radiation in Earth's atmosphere, associated large-scale responses, and adjustments in arctic regional energy budgets. There were considerable differences of opinion among workshop participants as to the relative contributions of the warm season versus cold season ocean/ice feedbacks on the observed warming trends (S1). The warm season feedback involves shortwave radiation and the changing surface reflectivity in contrast to the cold season longwave feedback that involves atmospheric moisture and temperature. Both feedbacks operate on larger (basin) scales and are strongly dependent on cloud fraction, altitude, and phase. In addition to clouds, the longwave feedback is sensitive to water vapor concentration and the shortwave feedback to sea ice and aerosol concentrations.

Shortwave feedbacks in the Arctic are of great interest and have been previously studied extensively. Participants discussed shortwave feedbacks and new modeling work. The role of black carbon aerosol particles on the reduction of surface albedo was discussed, and there was much debate as to whether a significant darkening of the surface from black carbon deposition is substantiated from observations. In the atmosphere, black carbon concentrations increase atmospheric absorption, the warming effects of which may be significant although they have not been quantified. However, these absorbing aerosols reduce the amount of shortwave energy reaching the surface, potentially lessening a darkening effect of black carbon in snow. Because any shortwave radiative effects depend strongly on solar geometry, surface albedo, the vertical structure of absorbing aerosol in the atmosphere, and their relationship to cloud cover, all of these elements must be studied together to determine their true contribution to the changing arctic climate.

Proponents for the longwave feedback argued that the short period of higher solar zenith angles suggests that another mechanism must be operating, and presented arguments that downwelling longwave radiation from atmospheric water vapor must be the dominant contributor. This longwave radiative feedback was hypothesized to include a dynamic component. The atmospheric flow responds to a warming arctic basin that in turn results from increasing sensible and latent heat fluxes with decreasing ice thicknesses. The downwelling longwave radiation is strongly influenced by clouds; however, very little is known about cold season clouds (and the atmospheric state). This clear gap in knowledge is the result of the difficulty in taking measurements during the polar winter, and the fact that local cloud processes are difficult to separate from the larger environment that, in part, produces the stable cloudy environment.

Assessments of both feedbacks require a strong understanding of the local and large-scale controls on the composition and vertical structure of the atmosphere (S2). As long as the lower atmosphere is composed of statically stable layers, local (i.e., surface) sources of water vapor, sensible heat, and aerosol particles will impact only the lowest layers in the troposphere, with little influence on the free troposphere aloft. Free troposphere water vapor and aerosol often originates from lower latitudes. The layers between the surface and lower-latitude source dominated layers exhibit strong vertical gradients in moisture and aerosol properties, the nature of which is determined by both local processes and long-range transport. Radiative processes are important in this context because they influence the thermal structure of the atmosphere over a broad scale, yet respond to local moisture, aerosol, and cloud particle distributions. Radiation, in effect, can link local processes to the development of larger-scale synoptic systems through alterations in the vertical cloud mass and thermal structure of the atmosphere.

Radiative processes are the primary drivers of thermal stratification for a quiescent arctic atmosphere; however, the atmospheric structure is modified by large synoptic systems that modify the stable lower tropospheric layers and associated cloud and precipitation processes. Moreover, strong surface thermal contrasts can greatly disrupt the overlying atmosphere leading to large vertical and horizontal gradients in atmospheric properties. For instance, leads, polynyas and open water produce large surface-based horizontal gradients in moisture, thermal energy, and possibly aerosol. Large surface sensible heat fluxes drive buoyant convection over polynyas, thus producing internal boundary layers in the downwind region beyond the polynas. These sources of moisture and energy modify the local environment, but also influence atmospheric properties far downstream depending on the synoptic conditions. It is clear that the ARM NSA sites need to be considered in the context of both flows from lower latitudes and local influences that become important over the coastline as well as over the ocean.

Given that radiative processes are local, but strongly dependent on both local and long-range processes that determine the atmospheric profile, two additional questions were framed (S2) and (S3). The NSA domain is located in one of the three major storm tracks through which lower-latitude air characteristically enters the Arctic, thus transporting energy, aerosols and clouds. Historical ARM measurements at Barrow provide a good record of the vertical atmospheric profile, but cannot easily be used to assess the processes responsible for those profiles. The composition of the atmospheric profile depends strongly on the source of the region of the air, the aerosols in particular, and the meteorology.

Workshop participants suggested that answering these questions requires that detailed information on mid-latitude dynamics and aerosol source regions becomes a component of arctic scientific research. More specifically, Northern Hemisphere aerosol sources that impact the NSA domain, including aerosol source location and type, amounts, frequency, transport pathways, and seasonality of source impacts over the NSA domain are important issues to consider. Factors that affect aerosol radiative properties were discussed. These factors include biogeochemical transformations, aerosol aging, and others.

Theme 2: *Aerosols and their impacts (A)*

2

Question A1. What is the black carbon deposition to the surface, how does it impact the surface energy budget, and how does this feedback to atmospheric processes?

Question A2. What are the characteristics, sources, activity, and spatiotemporal distribution of ice and liquid nucleating aerosol in the arctic column?

Question A3. How do aerosol emissions, transport, processing, and removal effect the spatiotemporal distribution and radiative impacts of arctic aerosol? How do absorbing aerosol affect the stability of the atmosphere and cloud development?

It has long been recognized that anthropogenic aerosol from lower latitudes penetrates the Arctic, causing the seasonal phenomenon of arctic haze. Long-term measurements of aerosol at a few sites have been used to characterize the chemical, optical, and microphysical properties of this broad seasonal variability over high northern latitude landmasses. While much has been learned, there are major gaps in the understanding of aerosol impacts in the Arctic that stem from a lack of observations. Most notably, there are very few observations of aerosol over the Arctic Ocean and detailed information of the vertical structure is sparse, limited to infrequent airborne field campaigns that have only occurred in summertime. Even so, these data show that climate models are unable to predict these seasonal cycles or vertical distributions of aerosol well.

The vertical distribution is a prominent characteristic of aerosol in the Arctic due to the strong stratification in the region. The local vertical distribution becomes a function of upwind point and area sources, combined with spatially variable transport pathways and air mass transformation. Aerosol from urban/industrial and forest fire emissions remains stratified over long distances as it is transported over the region, and tends to remain in elevated, sometimes tenuous layers. Local emissions are generally confined to the strong surface inversion layer and are likely dominated by marine biogenic and sea salt emissions. These sources themselves are seasonal, with higher concentrations in the warmer months under conditions of less sea ice cover, so the near surface vertical structure may follow a different annual pattern than elevated layers. In addition, increasing anthropogenic activity in the Arctic, such as oil extraction and shipping, may serve as a significant local source in some areas.

Improving the representation of arctic aerosol in climate models requires an integrated understanding of local and hemispheric, natural and anthropogenic emission sources, meteorology, and aerosol processing and radiative effects. Some of the most critical issues that arose in the workshop discussion were:

- What are the mechanisms for aerosol transport into the Arctic?
- What are the fluxes of aerosol out of open water areas including leads and polynyas?
- What are the local aerosol production sources and how are they apportioned between natural and anthropogenic emissions?

Source attribution of black carbon in the Arctic was also called out as important in determining the pathways of black carbon to surface deposition, which may impact snow albedo.

As mentioned previously, deposition of black carbon aerosol to the surface in the Arctic may have a significant impact on shortwave radiative forcing in this region, but many questions remain that preclude a rigorous evaluation of the climate impact. Direct measurements of black carbon deposition rates to the surface are exceedingly rare and are needed in coordination with atmospheric concentrations. Wet versus dry deposition rates are not well simulated by models, but there is little information to guide further model development.

Black carbon is only one constituent of aerosol in the Arctic, and existing observations reveal a diverse population whose different composition and size from different sources lead to varying cloud nucleating and optical properties. Aging processes that occur during long transport times to the Arctic can have a profound impact on the optical properties of aerosol, often reducing the efficiency with which they absorb solar radiation. Better characterization of the spatiotemporal distribution of aerosol physical, chemical, and optical properties is needed, in accord with better knowledge of transport pathways, to improve skill at representing aerosol processing that occurs along those pathways. Likewise, knowledge of locally emitted aerosol, their physico-chemical properties, and evolution as they become horizontally and vertically distributed is needed.

Because of the strong stratification and transport mechanisms, characterizing the discontinuity of aerosol properties above and below the top of the boundary layer is critical for better understanding of direct and indirect forcing. Quantifying the aerosol discontinuity would provide the basis for an assessment of how representative surface in situ measurements are of the total aerosol population that perturbs the atmospheric system. One of the most important sources of aerosol to the cloud is just above the boundary layer, so it is also critical in understanding the potential for and extent to which aerosol interacts with cloud. Cloud condensation nuclei and/or ice nuclei measured at the surface may be representative of aerosol entering the cloud from below, but if the above cloud aerosol is derived from a completely distinct source with different physic-chemical properties, the efficiency of this aerosol to activate cloud droplets or ice particles may be very different.

Finally, knowledge of aerosol optical and cloud nucleating properties alone is not sufficient in determining their radiative impacts. As was discussed with regard to black carbon, the direct radiative forcing of aerosol is a function of solar zenith angle and surface albedo. These two ancillary properties vary significantly throughout the annual cycle in the Arctic and their relationship to each other can change the forcing of the same aerosol from positive to negative. In addition, these considerations must be convolved with cloud cover at particular solar and surface conditions to determine the total radiative impact. Feedbacks must also be considered where differential heating and cooling, which drive atmospheric circulations and cloud development, and the extent to which this further modifies cloud microphysical properties and the cloud life cycle.

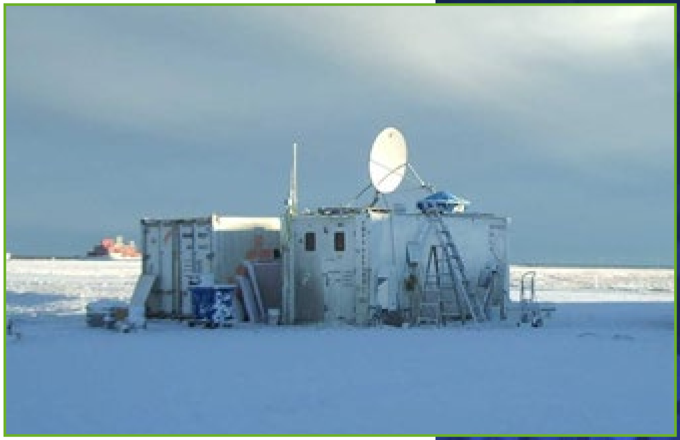
Theme 3: *Cloud processes (C)*

Question C1. What processes control the life cycle of mixed-phase single- and multi-layer cloud systems?

Question C2. How do clouds interact with and respond to varying and heterogeneous terrestrial/ocean/sea-ice surface conditions?

Question C3. What processes control the seasonal cycle of the vertical distribution of radiative fluxes in the Arctic?

Arctic clouds have long been recognized as unique and perplexing. It has been well known since at least the late 1960s that supercooled liquid clouds can occur down to temperatures as low as –40° Celcius, and that clouds and aerosol often occur in stratified layers. Supercooling to low temperatures requires a very “clean” environment with low aerosol concentrations. Indeed, the Arctic is often a relatively pristine environment with low concentrations of both cloud condensation nuclei and ice nuclei. There are seasonal cycles in aerosol concentrations due to long range transport from Asia that can strongly perturb local aerosol properties. These cycles lead to differences in cloud microphysical processes between the autumn, studied during the Mixed-Phase Arctic Cloud Experiment (MPACE, Verlinde et al. 2007) and spring, studied during the Indirect and Semi-direct Aerosol Campaign (ISDAC, McFarquhar et al. 2011) transition seasons. For instance, under very low aerosol conditions liquid and snow precipitation efficiencies may remain low leading to longer-lived cloud layers and, hence, a stronger cloud impact on the surface radiative budget.



Cloud responses to aerosol depend on the local processes that dynamically drive the cloud layer along with the larger synoptic and mesoscale environment that can set the stage for a given aerosol response. Past research has focused primarily on single-layer stratiform arctic cloud layers, both liquid and mixed phase, with a view to understanding their microphysical and dynamic drivers. These clouds can often be reasonably studied with modeling systems that isolate the cloud layer from the larger environment, although larger-scale fluxes are often included in a simplified form. These studies have attempted to understand the controls on cloud liquid water longevity in the presence of ice processes that can quickly glaciate and dissipate the cloud layer.

Numerous hypotheses have been put forward to describe and explain mixed-phase cloud longevity that is associated with clean environments (e.g., low ice nuclei concentrations), self-inhibiting nucleating feedbacks, larger-scale vapor sources and humidity inversions, ice nuclei concentration inversions, the production of isometric instead of extreme particle habits, cloud-scale dynamic, thermal and radiative processes that drive liquid water formation, and/or the general lack of dissipative processes. The consensus among participants was that it is still unclear how microphysical, dynamic, aerosol, and radiative processes combine to produce long-lived single-layer clouds (C1). Some keys to untangling this complex system include identifying the primary ice nucleation mechanisms, characterizing the roles of radiation and turbulence in microphysical processes, and understanding how atmospheric stratification influences the vertical mixing of heat, moisture, and aerosols.

While single-layered cloud systems occur frequently as a quasi-background state, multi-layered cloud systems with more intense precipitation are common on weekly time scales. These systems are driven by some combination of frontal forcing, weak meso- and synoptic-scale motions, latent heat release, and strong infrared cooling. Very complex, mixed-phase, multi-layered precipitating systems can occur year round. Cloud systems forming in such conditions, and their internal dynamic, aerosol, and microphysical responses are probably constrained by the larger-scale thermal conditions. Therefore, weak larger scale motions and moisture sources may dominate the cloud microphysical and aerosol processes more so than local, cloud-scale dynamics. Though little work has been done on these cloud systems, it is likely that understanding the links among radiation and mesoscale dynamics will be critical to isolating multiple-layered cloud system processes (C1). A major challenge will be properly understanding and modeling cloud interactions in weakly to moderately stably stratified layers. This poses a significant challenge as strong internal gravity waves along with strong speed and directional wind shear likely impact cloud processes.

The varying arctic surface is another unique feature of the polar environment, influencing the thermal and moisture budget of the lower atmosphere, and partially determining cloud processes. During winter, leads and polynyas are a significant source of water vapor and thermal energy for the arctic atmosphere. Clouds emanating from leads have properties strikingly similar to low-level mixed-phase stratus and can extend to cover large spatial areas. Air flowing off the polar ice over open water can produce relatively deep mixing and persistent roll clouds with substantial snow precipitation. Open water might also be a source of aerosol, some of which may act as ice nuclei.

During winter, the frozen and snow covered arctic terrestrial surface is a weak source of vapor and thermal energy with most cloud processes being associated with larger-scale systems advecting moisture into the region from lower latitudes. During the transition into summer, as surface snow cover melts and rivers break-up, the exposed land surface and nearly continuous solar radiation drives enhanced atmospheric mixing and increased energy fluxes into terrestrial surfaces. Local sources of aerosol are also exposed with the melting snow. How clouds interact with—and respond to—the changes in surface types are not well understood at present (C2).

The radiative impacts of clouds on the surface energy budget and the thermal stratification of the atmosphere depend on the microphysical properties of clouds, in particular liquid/ice partitioning and the size distributions of all cloud particles. Microphysical processes play out in local feedbacks acting in meso- and large-scale dynamical settings to process available water vapor and aerosol particles. Extensive cloud and water vapor layers can alter the thermal budget of the atmosphere enough to change the synoptic conditions over a broader scale, as hypothesized in the longwave radiative feedback. Our current understanding of the processes determining the vertical distribution of radiative fluxes is built on a relatively small number of golden day case studies in the transition seasons. Very little is known about the role of meso- and synoptic-scale influences on the cloud processes as these determine the radiative fluxes. One question (C3) focused on controlling processes of the seasonal variation of the vertical distribution of radiative fluxes, with a strong emphasis on the transition seasons and polar night.

Theme 4: *Vertical structure of the atmosphere (V)*

Question V1. How are the components of the vertical distribution coupled with the surface energy budget and interfacial fluxes over heterogeneous and evolving surfaces (e.g., land/ocean/sea ice)?

Question V2. What controls the development of the vertical thermal, vapor, aerosol and cloud microphysical structure of the atmosphere, its seasonal dependence and influence at local and large-scale processes?

Question V3. What is the vertical distribution of aerosol and cloud particles and how does it impact the radiative flux divergence in the arctic atmosphere?

Strong vertical thermal and composition stratification is a defining characteristic of the arctic lower atmosphere for most of the year. Low-level stable layers serve as an interface between the surface and free troposphere. Much of the workshop discussion focused on the processes that develop, maintain, and destabilize this stable layer. Radiative fluxes are the primary drivers of lower atmospheric thermal stratification. Atmospheric absorbing and scattering layers, and hence composition, determine the radiative flux profile, and can drive turbulent fluxes that counteract stratification. Surface and free-troposphere moisture, thermal, and precipitation particle fluxes complete the factors that play a role in determining the lower atmosphere vertical structure.

In the quiescent atmosphere away from air mass boundaries, surface fluxes play a large role in determining the atmospheric constituent composition. Because large local spatial and temporal heterogeneity in the surface state is common through most of year, having two ARM sites on the North Slope, is advantageous. This heterogeneity in the surface state translates into highly variable fluxes, which introduce large variability in the structure of the lower atmosphere. Understanding the thermodynamic and kinematic coupling between surface fluxes and the vertical distributions of different atmospheric components (i.e., vapor content, thermal stratification, and cloud/aerosol layers and their characteristics) are required for model parameterization development and testing (V1). Participants argued that observations of these profiles should be obtained for model sub-grid scales ranging from 1-100 kilometers for application in different models.

During the warm season and fall transition, surface fluxes are frequently strong enough to produce well-mixed boundary layers over the North Slope region depending on the synoptic-scale flow patterns. While some of these processes have been the focus of recent studies, detailed understanding of the relationships between the underlying surface, the long-range transport, vertical mixing processes, and the vertical structure of the atmosphere is largely lacking (V2). Because of the large seasonal changes and the general lack of dark season observations, participants stressed the importance of studying the full seasonality of these relationships and not only limited case studies. Such a study will require combined multiscale modeling and simulation using as initial and boundary conditions the routine observations of the surface state and atmosphere structure at and around the ARM NSA sites throughout the year.

Radiative processes respond to the local moisture, aerosol, and cloud particle distributions. Our current understanding of cloud and aerosol particle composition in the vertical profile in the Arctic is derived from a limited number of aircraft campaigns in the summer and transition seasons. Even then, analyses focused mostly on the simplest profile structures such as low-level, single-layer clouds, with relatively little attention paid to deeper precipitating systems, which frequently consist of multiple liquid-cloud layers embedded in ice precipitation. The phase partitioning of water in clouds has a significant impact on the radiative flux divergence, and depends on cloud dynamics, moisture availability, and aerosols. In these deeper precipitating systems atmospheric layers interact through radiative driven turbulent mixing and precipitation.

The nature of the coupling between the atmospheric flow patterns giving rise to the complex layered structure, the aerosol particle compositions in each layer, the cloud particle vertical distribution, and the radiatively driven mixing processes remains largely unexplored. Participants argued that simultaneous measurements of aerosol particle composition, cloud particle characteristics, and radiative flux divergence profiles are needed to study vertical mixing processes and to assess the impact of these deeper systems on the surface energy budget (V3).

3.3 Modeling Tools and Strategies

Though modeling was not a separate agenda item, modeling naturally arose in the discussions since it is both a predictive and interpretive tool that is critical for understanding the Arctic. It was recognized that the Arctic's environment is not easily amenable to a single modeling strategy given its complexity; the vertical structure is frequently composed of many vertically stratified thermal layers, strong wind shear, layered mixed- and ice-phase clouds along with intermittent turbulence and frequent gravity-wave activity. These processes are linked with horizontally diverse, shallow synoptic, and mesoscale systems along with a slowly evolving lower surface of ocean, sea ice, and snow-covered land leading to variable surface fluxes. Both the Barrow and Oliktok Point observing sites are coastal locations, making local spatial heterogeneity a key consideration.

A question was raised regarding the technical maturity of the programs with respect to readiness for routine modeling. Input on this question included the opinion that future work will be needed to outline specific modeling activities that will be most appropriate and impactful. To get to a suitably mature state, ARM and ASR will need to 1) Learn from forthcoming routine modeling activities at SGP; 2) further augment observing capabilities, especially over spatial scales, as outlined here; and 3) gain a better understanding of the spatial considerations for model forcing in the region.

Given these challenges, the workshop participants generally recognized that a combination of small-scale modeling, e.g., large eddy simulation (LES), LES nested within mesoscale models, and mesoscale/regional modeling was the best overall approach for representing and studying the arctic system. The LES models with bin or bulk microphysics were thought to be best suited for addressing process problems that occur on local (i.e., cloud) scales. However, it was also recognized that even LES models are limited because physical processes like heterogeneous ice nucleation remain uncertain and unconstrained.

The utility of LES for stably stratified atmospheres was also questioned for several reasons. First, while some subgrid closure models exist for stably stratified turbulence, these are often designed for weak stratification. It is not clear how turbulence is modeled under strong, stable stratification with gravity-wave activity, as ultimately is required in arctic applications. Second, cloud and aerosol systems evolving among vertically-stratified layers may be driven by larger-scale flows for which LES is less appropriate. As a consequence, some workshop participants suggested using nested approaches, whereby high-resolution LES nests are run within mesoscale model domains.

This is an attractive approach because larger-scale mesoscale models appear to capture the larger-scale thermal and dynamic flow fields, but have difficulty resolving cloud and other smaller-scale atmospheric features. Nested models were also considered to be attractive as a modeling strategy because they allow for heterogeneous surfaces, and can contain models of sea-ice thermodynamics and dynamics. The relative priority of mesoscale-LES modeling at the NSA sites needs to be discussed further with the research community.

The link between modeling and the network of available arctic data was also discussed. Though the Barrow and Oliktok facilities provide a wealth of data, methods to link those data to processes over a larger horizontal domain were discussed. It was pointed out that the North Slope domain is situated in one of the major storm track paths through which lower-troposphere energy and moisture is advected into the Arctic, and that characterizing the lateral boundary conditions will be important. Participants discussed using the capabilities of the scanning radars to effectively extend the horizontal range of the data. In addition, some participants noted the potential benefit of inland observations for constraining model boundary conditions. Lastly, some felt that data assimilation is a viable approach to provide forcing for smaller-scale models and to provide surrogate data over a larger domain.

Several participants pointed to the modeling collaboration opportunities offered by the upcoming World Meteorological Organization (WMO) World Weather Research Programme (WWRP) Polar Prediction Project's (PPP) Year of Polar Prediction (YOPP), currently scheduled for mid-2017 through mid-2019. A key element of this international program is to do coordinated, intensive observational and modeling activities to improve polar prediction capabilities over a wide-range of time scales. The location of the ARM NSA sites—in one of the important storm tracks—suggests that participation by the ARM Facility and ASR program will be mutually beneficial, with the ARM Facility providing detailed local observational data sets and PPP providing detailed boundary conditions.

Modeling tools and strategies (M)

M1. Multiscale modeling should be a high-priority focus for future arctic cloud modeling research. The mesoscale-to-LES nested approach is particularly appropriate for the Arctic where fine-scale processes must be considered (e.g., shallow clouds, highly stratified environment, mixing, spatial variability in phase partitioning, etc.) especially within the context of mesoscale meteorology (e.g., large-scale water vapor advection, air mass transformation, and modification, etc.). The nested approach can be used to target specific processes at the Barrow and Oliktok Point sites and can encompass the domain over the Arctic Ocean where future unmanned aerial system missions will be conducted. This approach also provides the means to up-scale the detailed observational and LES modeling results that have been developed within the DOE program to the larger-scales appropriate for climate models.

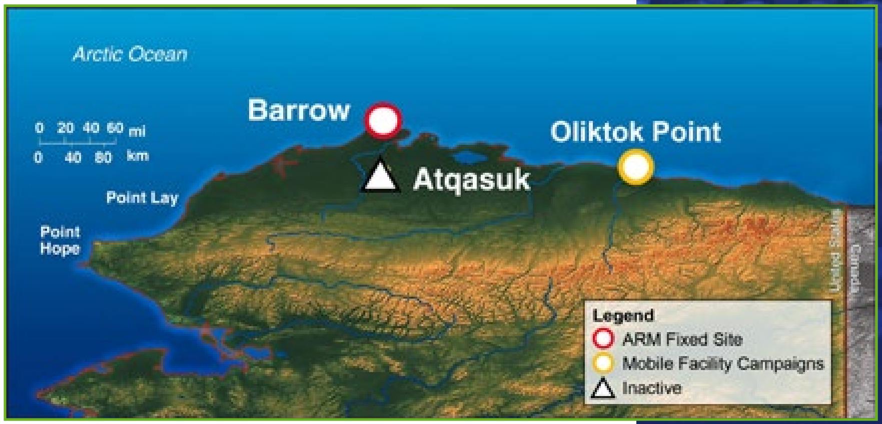
M2. The community should consider linking with other DOE modeling programs. DOE-funded work is currently being done on the Regional Arctic System Model (RASM), which is a pan-Arctic coupled system model. Answering big arctic climate questions related to transitions in the cryosphere and land surface will require links with larger-scale, coupled system models. Connections with the modeling work that is being done by the DOE Next-Generation Ecosystem Experiments Arctic (NGEE Arctic) project should also be considered as an action item. Atmosphere-surface-sub-surface interactions are clearly important for the NGEE Arctic project, and this is a growing interest area in ARM-measurement design and ASR research.

M3. YOPP will be an important international activity in the near future, and the ASR program should be involved. The Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC) field campaign should be underway by that time, thus bringing more ARM resources to the arctic regional modeling and observational problem. DOE researchers and programs should take advantage of the large array of other international observing and modeling activities going on around YOPP. Workshop participants advocated that positioning ARM activities to feed the YOPP process with observations and targeted-modeling activities would enhance the value of its observations for regional model activities.

3.4 Measurement Needs

Background

The observational challenges presented by the arctic environment are substantial. Locations for surface sites are limited and generally cost-prohibitive, and frequent mixed-phase clouds present significant icing hazards for any airborne platform. The safest option is spatial remote sensing. Remote sensing has the weakness that it is not a direct measurement of the atmospheric state, but instead relies on uncertain assumptions and inferences. In the last few years, the ARM Facility has made progress in expanding from the soda-straw profile of measurements over Barrow to include some spatial sampling with the precipitation radar at Barrow. The science community is beginning to develop expertise in interpreting these measurements. The early experience with these scanning systems in the harsh arctic environment indicates that routine, high-quality spatial measurements will continue to be a challenge.



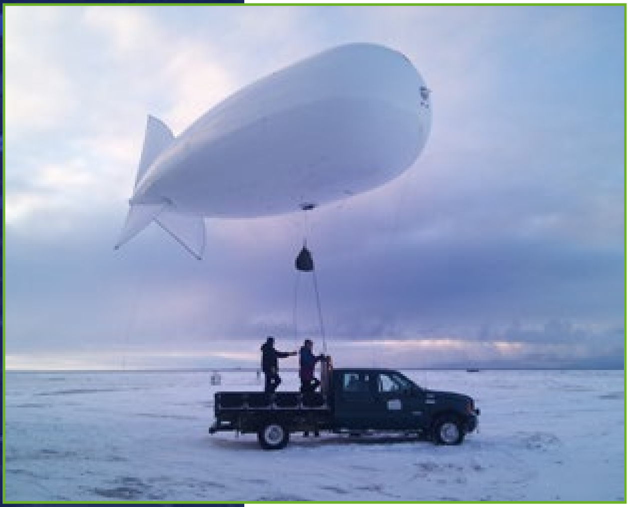
The addition of the Oliktok Point site expanded the ARM measurements, but when the Atqasuk facility was closed, the ARM Facility lost valuable inland observations. Workshop participants strongly advocated a return to the original concept of the ARM NSA site as the North Slope and *Adjacent Ocean site*. Measurements should extend from the two coastal sites across the North Slope interior and out over the adjacent oceans. Therefore, a high priority is for the ARM Facility to return to observations at the Atqasuk facility with at least basic atmospheric state, radiation, and cloud instrumentation.

Recent legislative changes have relaxed regulations for operating an Unmanned Aerial System (UAS), creating an opportunity for the NSA site. The ARM Facility is well advanced in securing Federal Aviation Administration approval to conduct regular flights over the Arctic Ocean. However, workshop participants agreed that no single observing system can provide all the observations needed to address the broader science questions, but that combinations of remote-sensing instruments, manned and unmanned aircraft systems would be required.

The needs for spatially extended measurements (A2, A3, C1, C2, V1, V2) include regular, all season (including the polar night), atmospheric state profiles, and surface characterization. There was a realization among workshop participants that one cannot require too much from these spatially distributed measurements because of the lack of potential fixed surface sites. The zeroth-order measurement need is for atmospheric thermodynamic profiles spatially distributed to represent the variety of surfaces that are within and/or influencing the NSA domain. These must include profiles away from the coast over the North Slope and over the ocean. While UAS platforms present a viable option under clear-sky conditions, UAS are not yet proven under cloudy-sky conditions when icing presents a clear danger to the aircraft.

Surface energy budget

The need for surface flux/energy budget measurements would strongly benefit from a more comprehensive network of surface sites although UAS platforms offer some possibilities for sampling spatial variability. Possible locations for such sites are limited on the North Slope, but workshop participants argued that the three sites currently available to ARM (Barrow, Atqasuk, and Oliktok Point) should all be equipped with identical energy budget measurements. These measurements include radiative (i.e., full radiometer suites), sensible and latent heat, carbon dioxide, methane (e.g., Eddy Correlation Flux Measurement Systems) and precipitation flux measurements. Facilities at Barrow and Oliktok Point already have most of the required measurements, but Atqasuk would have to be revived as an operational site.



To represent the different surface conditions present at each location, there is a need to install multiple surface flux suites at each of the above sites. This could be accomplished using autonomous mobile facilities—such as National Center for Atmospheric Research Portable Automated Mesonet stations—that could be deployed at other locations for shorter durations during the transition seasons as an alternative to routine, manned aircraft operations. Smaller UAS platforms offer yet another possibility for measuring fluxes close to the surface, but are as yet not tested for this application. The ARM Facility will conduct initial testing of UAS abilities to measure low-level fluxes at Oliktok Point during the

Evaluation of Routine Atmospheric Scientific Measurements using Unmanned Systems (ERASMUS) campaign.

Associated with the surface radiation balance is a need to characterize the surface albedo and the factors that affect the albedo. In order to resolve the debate about the role of black and brown carbon on the surface albedo, routine snow samples—at different heights within the snow pack—could be analyzed using a Single Particle Soot Photometer. It was also noted that information about ice crystal size distributions in the snow pack would be useful, as would measurements of spectral albedo and fractional snow cover. Fractional snow cover measurements would only be important during transition seasons because it would be either completely snow covered or snow free for most of the year. Spatial distributions of surface spectral albedo and fractional snow cover could be made using UAS, tethered balloon, and/or tower-mounted equipment.

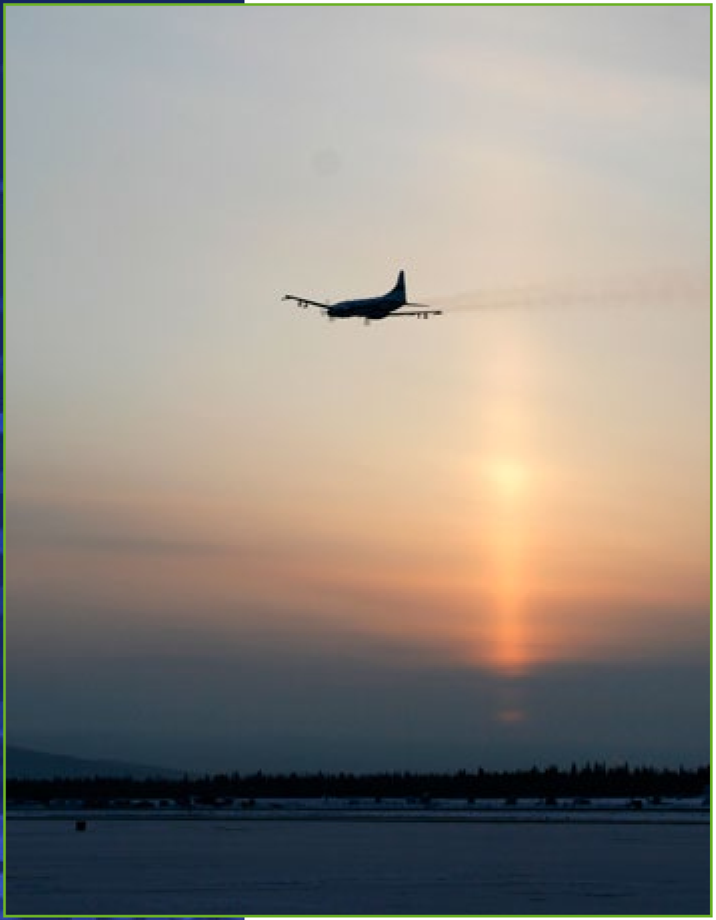
Measuring the precipitation flux and its contribution to the surface moisture and energy budgets remains a problem in the Arctic, but is a critical measurement. The presence of Ka-band zenith radars and scanning polarimetric radars at Barrow and Oliktok Point represent an opportunity to get spatial precipitation measurements when combined with Doppler lidar at Barrow and Oliktok and precipitation particle images from the multi-angle snow camera at Oliktok Point. There are no high-confidence measurements of precipitation flux at any of the NSA sites; precipitation flux measurements remain a research problem that must be addressed. To address these gaps, a multi-angle snow camera could be added to the Barrow instrument suite, and options should be explored to add single-particle mass measurements of the sampled ice crystals. In addition, improved measurements of bulk precipitation mass at the surface are needed.

Fixed surface sites cannot address the need for surface energy and precipitation fluxes over the ocean/sea ice, nor will such sites capture the ice transition line movement with its associated heterogeneity in surface conditions during the transition season. These spatial measurements are also needed to evaluate effects of black carbon on surface albedo in larger-scale models where the grid surface albedo scales with heterogeneity.

To provide the link between the ARM-detailed atmospheric observations and the surface active layer, each site's measurements should also include soil temperature and moisture profiles through multiple local soil type regimes. The DOE NGEE Arctic project currently collects these measurements at the Barrow Environmental Observatory adjacent to the ARM Barrow site. Improved coordination and collaboration between ARM, ASR, and NGEE Arctic would be useful to address science questions associated with the coupling between the active layer and the atmosphere.

Aerosol and cloud properties

The aerosol- and cloud-related science questions each require profile measurements and would benefit from a combination of in situ and remote sensing observations. Many aerosol questions associated with the cloud-free environment may be addressed using a



combination of in situ measurements from small-payload platforms with lidar measurements. Currently, aerosol chemistry studies require extensive payloads on larger manned aircraft and/or can be made over longer periods only at the surface, but some limited chemical composition can be measured from even small UAS. Cloud-related science questions require extensive and comprehensive sets of measurements, dictating larger aircraft platforms deployed for shorter focused campaigns, such as those that ARM has conducted in the past near the NSA (e.g., MPACE and ISDAC).

The current state of knowledge for arctic aerosol distributions derives almost exclusively from surface measurements that, because of the stratification of the lower troposphere, may be decoupled from aerosol properties aloft. Aerosol scientists commented that any routine in situ profile measurements would be a significant contribution. Lack of information about the vertical distribution of aerosol—even if only particle concentration with some limited composition information—is a real limiting factor to progress. The current state of knowledge of the aerosol vertical profile is derived primarily from lidar remote sensing and a few detailed aircraft campaigns, such as ISDAC. Existing lidar measurements at the sites are limited to identifying aerosol layers and total extinction, but cannot be used to determine the critical vertical profiles of radiative fluxes associated with these because the lidar does not distinguish between absorption and scattering. However, new techniques for extracting this partitioning of the extinction are in development for multi-wavelength lidar systems discussed below. Moreover, lidar measurements become fully attenuated in many cloud layers, inhibiting the derivation of aerosol information in these environments.

Oliktok Point is a priority site for aerosol profiling because the restricted air space over the site will allow for regular tethered balloon and/or UAS in situ sampling to supplement the planned aerosol observing system surface measurements. If possible, aerosol profiling both above and below low-level clouds will provide critical information on the source of aerosol for cloud processes. The aerosol sampling capabilities could be further enhanced by deploying aerosol typing instruments, such as the National Aeronautics and Space Administration (NASA) high spectral resolution lidar that uses 3-wavelengths for backscatter and 2-wavelengths for extinction. Temporarily moving the high spectral resolution lidar currently deployed at Barrow to be co-located with the third ARM Mobile Facility's Raman lidar system at Oliktok Point would meet this need in the short-term. More limited UAS aerosol profiles should augment these focused Oliktok Point profiles to provide spatial context from a variety of surface and atmospheric states. The UAS aerosol package should include a micro aethalometer to address the gap in black carbon measurements.

Although the greatest needs for aerosol measurements are to sample vertical profiles, there is also a need for building longer-term statistics from measurements that probably can only be made from the surface at Oliktok Point. These statistics included inorganic composition (especially sea salt) from an aerosol composition speciation monitor and ice nuclei concentrations and properties. Ice nuclei measurements would also be of great interest in the vertical column; however, in the near term, this may only be possible using filter-based measurements flown from tethered balloon or manned aircraft campaigns.

The cloud-related science questions require more comprehensive in situ measurements, and require platforms that can operate in icing conditions. Only two platform types are available for these types of measurements: a tethered balloon system or piloted aircraft. UAS platforms with icing detection and avoidance ability can be used to sample aerosol particles in close proximity to, but not in, clouds. Such measurements would be useful for low-level stratiform clouds where a cloud-driven mixed layer extends below the cloud base, but may have aerosol properties that are representative of those influencing the cloud formation. A tethered balloon system can sample the lower troposphere (< 2 kilometers) regularly and is the only platform that can profile long-duration measurements at the cloud-layer interfaces, and more importantly, in and above the cloud-top region.

Although payload capacity is limited on any given flight, payloads may easily be exchanged by bringing the tethered balloon back to the surface. A suitable instrument package for cloud-aerosol interaction studies has been developed under the DOE Small Business Innovation Research funding. This package includes:

- Aerosol – size distribution or chemical composition sampler, a cloud condensation nucleus counter, and an ice nucleus filter system
- Cloud microphysics – a combination optical particle probe to measure particle size distributions from cloud drops to precipitation sizes and an in situ cloud Lidar to measure liquid water content, effective drop radius and total extinction
- Shortwave and longwave radiation – “4-pi” radiometer
- Basic meteorological measurement system – temperature, humidity, and winds.

The addition of a turbulence probe to this package will allow investigation of the processes responsible for vertical mixing in the lower troposphere. Strong arguments were presented for the need to continue all profile measurements throughout the polar night due to seasonal differences in atmospheric stability, aerosol properties, and cloud phase. It is understood that these measurements represent significant logistical challenges, but the current lack of knowledge on the arctic winter inhibits important studies of key processes, such as longwave radiative feedbacks.

While the tethered balloon system can provide regular profiles of some cloud and aerosol particle characteristics, existing balloon payloads are currently too small to get the simultaneous and comprehensive cloud microphysics, dynamics- and aerosol-related measurements needed to adequately address the detailed cloud process questions raised by the workshop participants. Further development is needed in this area. There continues to be a need for occasional, but detailed particle-size distribution measurements, from cloud drops to large hydrometeors, speciation and composition of cloud condensation and ice nuclei, and detailed aerosol-size distribution, and composition measurements. To close the current gap from the microphysics to the radiative characteristics of the clouds in order to derive the profile of radiative fluxes these measurements should be augmented by an open path extinction measurement and up/downwelling long/shortwave fluxes.

Measurements of radiative fluxes are needed over and away from the fixed sites over the North Slope interior and over the Beaufort Sea, off the coast at Oliktok Point. These measurements could involve both manned and unmanned aircraft. These measurements and related issues will be discussed during the third DOE CESD workshop to be held in May 2015 for aerial measurement needs.

Observing the mesoscale and large-scale environments

Scanning radars are the primary, and on the North Slope the only viable, instrument currently available to document the mesoscale environment. Because the separation between Barrow and Oliktok Point is such that there is no overlap between the two radars, there is a need for an X-band or C-band scanning precipitation radar deployed at Atqasuk to provide greater detail on the mesoscale environment over the North Slope using conventional dual-Doppler analyses, if distances between sites permit. Keeping these radars operational should be a high priority, and tools must be developed to process measurements. Data assimilation was discussed as an option to provide good mesoscale environmental context for LES and/or context for analyses of in situ profile measurements. In order to complete the mesoscale structure measurements, the instrument complement at Atqasuk needs to be supplemented with a ceilometer, an atmospheric emitted radiance interferometer, a microwave radiometer, and surface precipitation measurements. These are needed to provide information on the thermodynamic profile, cloud presence, height, liquid-water path, and precipitation.

The North Slope is also significantly influenced by long-range transport. There was interest expressed in carrying out field campaigns involving vertical profiles of thermodynamic and aerosol properties along a transect connecting the Barrow or Oliktok sites. Such a campaign would require careful planning to select an appropriate transect and some flexibility to adjust the transect according to changing conditions.

4.0 External Collaborations

Workshop participants noted that there are many ongoing and upcoming observational and modeling activities in the Arctic and that increased collaborations with these activities would strengthen the scientific outcomes from ARM and ASR activities on the North Slope. The following list of agencies, programs, and collaborations involving work in the Arctic were identified as important opportunities for ARM and ASR:

- The WMO has a decadal program to develop a Global Integrated Polar Prediction System (GIPPS). As part of this effort, there are twin activities happening; 1) WWRP Polar Prediction Project (PPP, **www.polarprediction.net**), which is targeting predictability on hours to seasons, and 2) World Climate Research Programme (WCRP) Polar Climate Predictability Initiative (PCPI), which is targeting predictability on scales of seasons and longer. The WMO acknowledges that the success of GIPPS will require research along many lines that can be facilitated by ARM measurements, including improved process understanding, improvement of assimilation systems, and development of model components.
- The WWRP PPP is organizing an extended period of enhanced observational and modeling efforts to improve polar predictive capabilities called YOPP, which is occurring mid-2017 to mid-2019. Enhanced observational activities will occur across the Arctic during this timeframe, including activities that are appropriate for ARM participation. These include increase radiosonde frequency, unmanned aircraft activities, and participation in MOSAIC.
- In Japan, the Japan Agency for Marine-Earth Science and Technology/National Institute of Polar Research (JAMSTEC/NIPR) has been undertaking enhanced arctic observing activities in recent years. These activities include ship-based observations in the Beaufort and Chukchi Seas, and specifically, enhanced radiosonde activities for evaluating model data assimilation systems. Additional radiosoundings at Barrow and/or Oliktok Point would be one way to coordinate activities.
- A working group of the Arctic Council, the Arctic Monitoring and Assessment Program (AMAP) has established a UAS expert group to help promote the use of UAS for arctic research and to address barriers to such activities. This expert group can be a key resource for developing UAS campaigns at Oliktok Point.
- The U.S. Navy's Office of Naval Research has undertaken a number of recent Directed Research Initiatives, targeting arctic system processes and forecasting arctic sea ice. These include the Marginal Ice Zone project in the Beaufort Sea in 2014 and the Sea State project in 2015. Future arctic missions are likely.
- The National Science Foundation Arctic Observing Network supports a wide variety of observations across the Arctic, with enhanced activities in northern Alaska supporting research on sea ice, ocean, atmosphere, and terrestrial themes.
- NASA has various activities in the Arctic that hold potential for DOE coordination. These include routine ice flights as part of the IceBridge mission and periodic flight campaigns targeting atmospheric clouds, aerosols, and radiation, such as the 2008

Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) and 2014 Arctic Radiation - IceBridge Sea & Ice Experiment (ARISE) projects near Barrow. The NASA ABOVE program—targeting land surface and permafrost change—is another research area for potential coordination that could also include the DOE NGEE Arctic project.

- Within DOE there are also important opportunities for coordination. The NGEE Arctic project seeks to understand and model the coupled-system processes that influence the terrestrial carbon cycle and permafrost degradation in the Arctic. Their enhanced observational activities near Barrow and potentially elsewhere in the Arctic provide a unique opportunity to couple intensive atmospheric measurements made by the ARM Facility with the surface and sub-surface measurements made by NGEE Arctic.
- Also, the DOE Regional and Global Climate Modeling (RGCM) program has prioritized arctic processes as a priority modeling theme. Among other activities, the RGCM program is supporting the development of a coupled-system regional model that seeks to represent process interactions among the atmosphere-ice-ocean-land system. These model development activities are in need of detailed observations, specifically those that help to characterize temporal and spatial variability of parameters and processes.

5.0 Conclusions and Next Steps

Discussions at the NSA Priorities Workshop resulted in the identification of a number of high-priority actions that could be taken to address the current gaps in observational capabilities needed to address the science questions discussed above. These high-priority actions included both actions that could be taken in the short term and actions with longer-term timeframes.

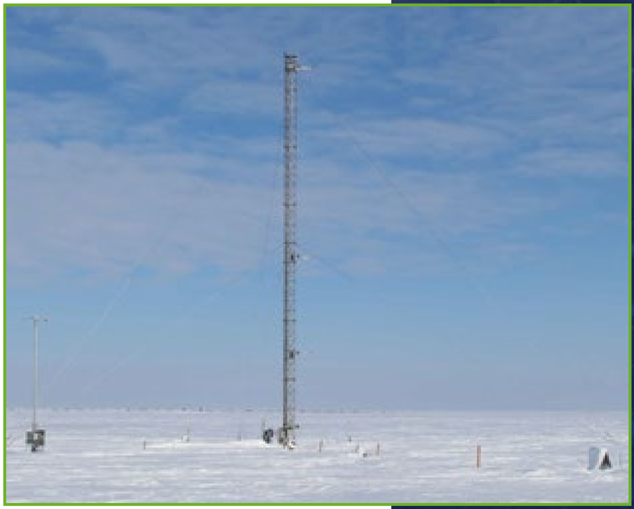
Short-term, high-priority actions:

- Commence regular tethered balloon operations, up to 1+ kilometers, with aerosol/microphysics packages and turbulence measurements.
- Commence regular UAS operations with instrumentation for surface characterization, fluxes, aerosol properties (e.g., particle counter, micro aethalometer for black carbon).
- Move the high spectral resolution lidar from Barrow to Oliktok Point to address aerosol profiling needs.
- Measure soil properties, including temperature profiles, moisture, and heat fluxes, in a representative sample of surface types at each site.
- Deploy surface fluxes/energy budget, ceilometer, atmospheric emitted radiance interferometer, and microwave radiometer instruments to Atqasuk.
- Add a multi-angle snow camera at Barrow to develop individual particle mass measurement ability.
- Develop better characterization of bulk precipitation mass for all sites.

- Inventory North Slope emission sources and model the meridional transport of aerosol to receptor points on the North Slope.

Longer-term, high-priority actions:

- Consider placement of an ARM scanning precipitation radar at Atqasuk.
- Conduct regular, manned aircraft deployments during transition seasons and winter (e.g., from 7 kilometers to 200-300 kilometers inland and over the Arctic Ocean).
- Develop stronger collaborations with interagency activities in the Arctic, as well as with other DOE programs and projects.



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Appendix A – Participants

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Rick Petty	Atmospheric Radiation Measurement Climate Research Facility
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Appendix B – Agenda and Workshop Format

DOE Workshop for North Slope of Alaska Priorities
September 10–12, 2014

Wednesday, September 10

1:00 p.m.	BER Managers: **Introductions and "Charge"**
1:30 p.m.	Mark Ivey: **Review of North Slope ARM Facilities**
2:00 p.m.	Hans Verlinde: **Overview of Science Topics Extracted from White Papers**
2:30 p.m.	Bob Ellingson: **Directions for Breakout Sessions, Rapporteurs, Breakout Rooms**
2:40 p.m.	10-minute Break
2:50 p.m.	Breakout 1. **Long-range Transport versus Local Processes**
4:00 p.m.	10-minute Break (shuffle groups)
4:10 p.m.	Breakout 2. **Cloud Processes**
5:20 p.m.	Adjourn

Thursday, September 11

8:00 a.m.	Breakout 3. **Aerosols and their Impacts**
9:10 a.m.	10-minute Break (shuffle groups)
9:20 a.m.	Breakout 4. **Vertical Structure of the Atmosphere**
10:30 a.m.	30-minute Break (then reconvene as one group)
11:00 a.m.	**Science Questions** Reconvene full group to present prioritized science questions under each topic. *Can questions under same and/or different topics be combined?*
12:00 p.m.	Lunch (provided) Flip charts with combined list of science questions provided. Each workshop participant will be provided five numbered stickers, which they are to distribute over all the questions as they return from lunch.

Thursday, September 11

1:00 p.m.	**Two Breakout Groups** Groups discuss science questions in terms of ranked priorities. *What are key observables, measurement strategies, and modeling strategies?*
2:30 p.m.	15-minute Break
2:45 p.m.	**Two Breakout Groups** Groups discuss science questions in terms of ranked priorities. *What are key observables, measurement strategies, and modeling strategies?*
4:20 p.m.	10-minute Break
4:30 p.m.	**Summary Discussion** Later breakouts may benefit from discussions of earlier breakout
5:30 p.m.	Adjourn

Friday, September 12

8:30 a.m. to Noon	Conveners and rapporteurs meet to review notes and discuss workshop report.

Appendix C – Themes and Questions

Theme 1: Long-range transport versus local processes (S)

Question S1. What are the most critical feedback mechanisms in the Arctic?

- Longwave radiation (i.e., water vapor, clouds)
- Shortwave radiation (i.e., sea ice, aerosol, clouds)
- Sensible and latent heat fluxes (i.e., sea ice/clouds)
- Net effect of feedbacks to Arctic Amplification.

Question S2. How does variability in long-range versus local sources of heat, water vapor, and aerosols shape the vertical atmospheric structure?

- Transport to vertical structure.

Question S3. What roles do biogeochemical transformations, aerosol aging, dispersion, and atmospheric stratification play in affecting aerosol radiative properties and cloud formation processes?

Theme 2: Aerosols and their impacts (A)

Question A1. What is the black carbon deposition to the surface, how does it impact the surface energy budget, and how does this feedback to atmospheric processes?

Question A2. What are the characteristics, sources, activity, and spatiotemporal distribution of ice and liquid nucleating aerosol in the arctic column?

Question A3. How do aerosol emissions, transport, processing, and removal effect the spatiotemporal distribution and radiative impacts of arctic aerosol? How do absorbing aerosol affect the stability of the atmosphere and cloud development?

Theme 3: Cloud processes (C)

Question C1. What processes control the life cycle of mixed-phase single- and multi-layer cloud systems?

Question C2. How do clouds interact with and respond to varying and heterogeneous terrestrial/ocean/sea-ice surface conditions?

Question C3. What processes control the seasonal cycle of the vertical distribution of radiative fluxes in the Arctic?

Theme 4: Vertical structure of the atmosphere (V)

Question V1. How are the components of the vertical distribution coupled with the surface energy budget and interfacial fluxes over heterogeneous and evolving surfaces (e.g., land/ocean/sea ice)?

Question V2. What controls the development of the vertical thermal, vapor, aerosol and cloud microphysical structure of the atmosphere, its seasonal dependence and influence at local and large-scale processes?

Question V3. What is the vertical distribution of aerosol and cloud particles and how does it impact the radiative flux divergence in the arctic atmosphere?

For More Information

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