Chapter 8

The ARM North Slope of Alaska (NSA) Sites

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1. Introduction

When the ARM Program embarked on its quest to select sites for the proposed ground-based atmospheric observatories, there was a broad consensus that more than one site was needed. One site had to be in the equatorial regions, where a disproportionate share of the solar energy fueling Earth's atmospheric general circulation is received, and the other in a polar location, where radiant energy lost to space greatly exceeds the energy received by the sun. While the latitudinal energy imbalance suggested a polar site, an Arctic location was preferred, because the Arctic plays a stronger role in the general circulation than does the Antarctic (Crowley and North 1991). As far back as 1896, the Swedish scientist Svante Arrhenius suggested that changes in Earth's atmospheric composition would lead to faster changes in the Arctic compared to the rest of the globe (Arrhenius 1896), a process confirmed by general circulation models and now called Arctic amplification [e.g., see summary in Serreze and Barry (2011)]. The high sensitivity of the Arctic to climate change is a result of the susceptibility of the cryosphere (sea ice, land ice, and permafrost) to changes in energy fluxes and influential feedback processes. For example, over the Arctic sea ice, the strong sea ice–albedo feedback amplifies the observed decline in ice extent (e.g., Wendler et al. 2010). Faster changes in the Arctic relative to lower latitudes disturb the latitudinal energy balance and, hence, the general circulation patterns in both the oceans and atmosphere, impacting the entire globe. It may be said that what happens in the Arctic does not stay in the Arctic!

Low temperatures in the Arctic result in low water vapor mixing ratios in the atmosphere, low enough that additional spectral regions, such as the water vapor rotational absorption bands in Earth's emission spectrum, become semitransparent in the cloudless atmosphere, increasing radiative energy losses from the surface (Stamnes et al. 1999). The presence of clouds in the atmosphere alters the atmospheric radiative absorption spectrum and thus has a strong influence on the surface energy budget and radiative losses to space. Most Arctic

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clouds are found in the lower troposphere, where they interact with strong and persistent near-surface temperature inversions, a characteristic of the Arctic environment (Serreze et al. 1992). Most of the uncertainties in the Arctic radiation budget are associated with an incomplete understanding of the process interactions between Earth's surface and the atmosphere through this interfacial layer. Complex interactions involving surface–atmosphere energy and water vapor exchange, multiphase cloud processes, the stratified lower troposphere, and radiative energy profiles combine to make the high latitudes challenging to represent accurately in numerical weather prediction and climate models. These challenges together motivated the ARM Program to establish an Arctic observatory to study the many processes that regulate the flow of radiative energy through the atmospheric system.

2. Site selection

a. The North Slope of Alaska

The initial site scientist for the North Slope of Alaska, Knut Stamnes (University of Alaska, Fairbanks), and Site Manager Bernie Zak (Sandia National Laboratories) were tasked to identify specific candidate ARM site locations within the Arctic region. The early decisions for the Arctic site were driven by analyses that revealed surface warming trends over Arctic land areas (Chapman and Walsh 1993) but no, or perhaps even weak cooling, trends over the central Arctic ice pack (Kahl et al. 1993). The ice pack results conflicted with general circulation model simulations (Walsh 1993), which predicted warming trends in the central Arctic Ocean. These differences between observed and simulated trends suggested that high-latitude ocean–atmosphere–ice interactions were represented poorly in general circulation models (Walsh and Crane 1992) and that processes over both land and sea warranted study. Thus, it became apparent that the single Arctic site had to be in an area that straddles an Arctic coast away from significant topography. Among the areas in the Arctic that meet these criteria, the North Slope of Alaska and the adjacent Arctic Ocean (NSA/AAO) was the area that permitted the most cost-effective scientific operations. As a result, the ARM Arctic facility, consisting of a comprehensive suite of ground-based atmospheric instruments, was established in Barrow, Alaska (71°19′N, 156°37′W).

Barrow is situated well away from the industrial activities associated with the North Slope oil fields around Prudhoe Bay. For three decades (roughly 1950–80), Barrow had been the site of the Naval Arctic Research Laboratory (NARL; Shelesnyak 1948). After the closure of NARL, the National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), and other agencies continued Arctic research in and around Barrow, eventually on and adjacent to 11 square miles of land set aside for that purpose as the Barrow Environmental Observatory (BEO). A site north of the town of Barrow and next to the BEO, located on federal land controlled by the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) and within 100 m of their clean air laboratory, was selected for the ARM facility. This site is a few kilometers from the northernmost point of U.S. territory and close to water (Chukchi Sea and Elson Lagoon) through ~270°, ranging from the southwest to southeast (Fig. 8-1). The winds at the site come predominantly from the ocean (Zak et al. 2002). A supporting office and light laboratory space is located ~2 km west of the primary instrument facility, within the former NARL complex, and leased from the Ukpeagvik Iñupiat Corporation (UIC). UIC is a corporation owned by the native people of Barrow, and scientific facilities located at NARL were administered for UIC by the Barrow Arctic Science Consortium (BASC).

In addition to Barrow, an auxiliary North Slope site was established at the inland village of Atqasuk, approximately 100 km south of Barrow. The objective with this site was to study the ocean-to-coast-to-inland transition. This inland site was anticipated to have a more continental character than Barrow, being colder and drier in winter and warmer in summer.

The Barrow site was formally dedicated on 1 July 1997 in a ceremony that included Martha Krebbs, director of the DOE Office of Energy Research; Peter Lunn, DOE ARM program manager; Ben Nageak, mayor of the North Slope Borough; Max Ahgeak, president of UIC; and other luminaries. The dedication ceremony was coordinated with the celebration of the 25th anniversary of the founding of the North Slope Borough. The joint festivities included traditional refreshments, native dances, and dedication speeches. Routine data acquisition began early in 1998 at Barrow and in June 2000 at Atqasuk.

b. The adjacent Arctic Ocean

Getting measurements in the central Arctic requires expensive logistics, because the Arctic sea ice can be unstable during the summer months and impenetrable by ship in the winter months. Long-term measurements using sophisticated instruments, such as those utilized by the ARM Program, place high demands on infrastructure and power resources. The Surface Heat Budget of the Arctic Ocean (SHEBA) project (Moritz et al. 1993), led by the National Science Foundation and the Office of Naval Research, provided an opportunity to take advantage of logistical support funded by other programs. The ARM Program decided to collaborate on this interagency project that was being organized on the same time frame as the new facility

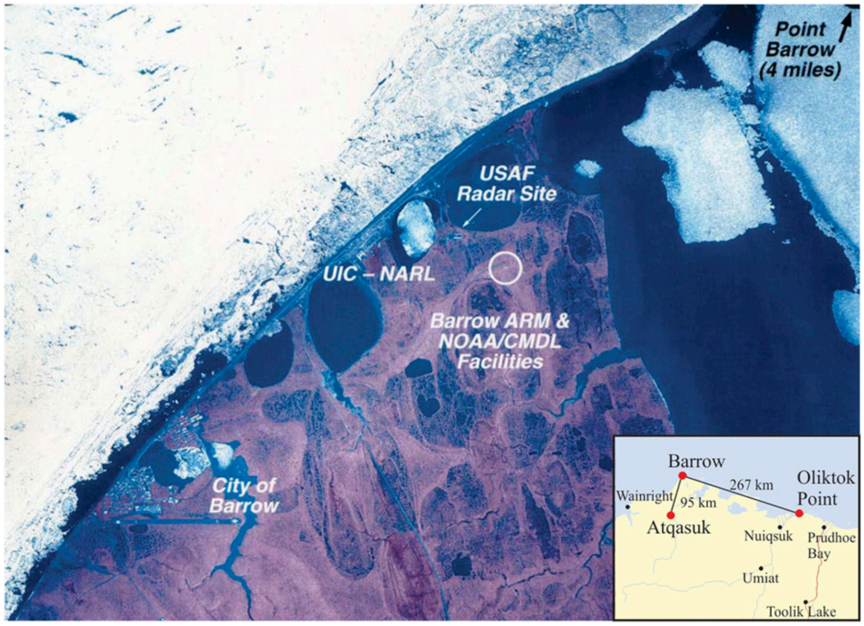

FIG. 8-1. Satellite view of the area around the Barrow NSA facility. The city of Barrow, the location of the old Naval Arctic Research Laboratory (where the ARM duplex is situated), and Point Barrow are indicated. The distance from the facility to the city of Barrow is approximately 6 mi. Elson Lagoon can be seen to the east of the facility. The insert shows the three ARM North Slope of Alaska locations (red dots) along with other population centers.

in Barrow. SHEBA focused on climate-relevant processes in the perennial Arctic ice pack and was centered on the Canadian Coast Guard ice breaker *Des Groseilliers*, which was intentionally frozen into the Arctic ice pack for a full annual cycle starting in fall 1997 (Fig. 8-2). The SHEBA science objectives comprised studying the relationships among radiative fluxes (especially as affected by surface– and cloud–radiative interactions), the mass balance of sea ice, and the storage and release of energy and salt in the ocean mixed layer. These objectives complemented the Arctic-specific ARM research objectives, making ARM participation logical from both scientific and logistical considerations.

The ARM Program provided a comprehensive set of up- and downwelling radiation measurements to complement and expand the NSF- and ONR-funded instruments.

Specific ARM objectives for participating in SHEBA were to make Barrow atmospheric and radiative data an adequate surrogate for similar data over the Arctic Ocean by doing the following:

- addressing the disparities between model and observational trends along the coast and over the central pack ice;
- investigating if relevant radiative processes and phenomena in the vicinity of Barrow were sufficiently similar to the same processes and phenomena within the central Arctic Ocean (the Arctic ice pack).

Participation in SHEBA also brought with it the benefit of collaboration with the NASA-led First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE) Phase III (Curry et al. 2000), which focused on Arctic clouds using satellite and airborne data.

c. Outreach

The local Iñupiat community in Barrow was familiar with scientific research because virtually every Barrow family had members who had worked for NARL. In addition, the local elders were very interested in climate, having seen their environment change over the decades. As a result, ARM outreach took place in an atmosphere of understanding and could draw on local people and knowledge for help.

A person who was pivotal in this regard was Tom Albert, at the time the chief scientist for the North Slope Borough Department of Wildlife Management. Through a creative, multiyear research effort involving several U.S. universities, Tom was able to show that the bowhead whale population was much more numerous than other researchers had thought. This allowed the International Whaling Commission to regulate, but not

FIG. 8-2. The *Des Groseilliers* and the SHEBA ice camp (photo courtesy of Kevin Widener).

ban, the hunting of bowhead whales. Since subsistence on the bowhead whale was (and remains) a cornerstone of Iñupiat culture on the North Slope, this established Tom as the most trusted scientist by the regional community.

Tom Albert introduced Bernie Zak and Knut Stamnes to the influential organizations in the community, as well as to the local, state, and federal agencies that function on the North Slope, and suggested who they should contact and brief on NSA/AAO plans. A series of public meetings were held in Barrow, Atqasuk, and the other potentially affected North Slope villages in order to ensure that the local people would be aware of what the ARM Program planned to do, why and how, and so that they could influence the plans. With the help of Tom and the Borough, the ARM Program even had Iñupiaq translators participate in the meetings to assure that the older Iñupiat people, some of whom struggled with English, were well informed. Through these efforts, the ARM NSA/AAO became a local North Slope project in which the community was heavily invested, not something simply imposed on the community by outside interests. The ARM Program also developed and funded an interactive educational kiosk featuring interviews by ARM scientists and community elders about climate change, which was placed in the Barrow Iñupiat Heritage Center for many years.

d. Science objectives

The growing understanding that the Arctic region was particularly vulnerable to a changing climate dictated the science objectives for the North Slope site. There was a realization that Arctic system physical processes, in many ways unique compared to other regions around the globe, were not represented well in models used to study climate (Tao et al. 1996). The presence of the ice-covered ocean through most of the year greatly impacts air–sea exchanges and the atmospheric processes in the interfacial layers [see summary in Curry et al. (1996)]. Evaluation of model results showed large differences in surface temperatures, pressures, and atmospheric cloud fractions produced by different models (Tao et al. 1996). Tao et al. (1996) attributed these intermodel differences to different specifications of sea ice, a lack of physically based links between cloudiness and air temperature, differences in model resolution and in formulation of various physical processes, and uncertainties in the observational database. They concluded that the highest priorities for improved simulation of the Arctic environment were the proper treatment of cloud–radiative interactions and local surface–atmosphere interactions. These and other studies (e.g., Curry et al. 1996; Randall et al. 1998) motivated the primary broad objective of the NSA site to collect data on radiation–climate feedbacks, important drivers in Arctic amplification (Stamnes et al. 1999). However, it was also recognized that the unique characteristics of the Arctic environment offered the opportunity to study other fundamental processes important to understanding Earth's climate.

The importance of the snow/ice–albedo feedback in the Arctic had long been recognized (e.g., Budyko 1969). This feedback is envisioned as a warming (cooling) climate leading to increased (decreased) melting of surface snow/ice, reducing (increasing) the surface albedo and leading to increased (decreased) solar radiation absorption by the surface, which in turn leads back to enhanced warming (cooling). However, from the early design of the NSA site, the importance of atmospheric processes on this radiative feedback was understood (e.g., Curry et al. 1996). Stamnes et al. (1999, 54–55) summarized the complexity of the radiation–climate feedbacks as follows:

> A perturbation to the Arctic Ocean radiation balance may arise from increased greenhouse gas concentrations and/or increasing amounts of aerosol. A perturbation in the surface radiation balance of the sea ice results in a change in sea ice characteristics (i.e., ice thickness and areal distribution, surface temperature and surface albedo). These changes in sea ice characteristics, particularly the surface temperature and fraction of open water, will modify fluxes of radiation and surface sensible and latent heat, which will modify the atmospheric temperature, humidity, and dynamics. Modifications to the atmospheric thermodynamic and dynamic structure will modify cloud properties (e.g., cloud fraction, cloud optical depth), which will in turn modify the radiative fluxes.

The presence/absence of clouds and aerosol particles in the atmosphere constitutes the greatest source of variability in the radiative energy flow through the atmosphere. Widespread and persistent low-level clouds impart a net warming effect on the Arctic surface energy budget throughout most of the year (e.g., Curry and Ebert 1992). This warming effect derives from downwelling longwave radiation by these clouds and plays a critical role in modulating the snow/ice–albedo feedback by impacting the timing and rate of surface albedo changes induced by melting snow. During sunlit months, the clouds also serve to shade the surface from solar radiation. The seasonal interplay of the warming and cooling effects is related to the sun angle, surface albedo, cloud properties, and temperature (e.g., Shupe and Intrieri 2004). These considerations highlight the need for a proper understanding of the processes that determine cloud, atmosphere, and surface characteristics, their interactions, and seasonal evolution.

Cloud processes have a big impact on general circulation model simulations because of the significant role clouds play in regulating the radiative energy fluxes through the atmosphere. Yet much uncertainty existed in our understanding of the processes responsible for the formation, evolution, and dissipation of clouds in the stable Arctic lower troposphere. The net effect of changes in cloudiness (warming or cooling) on climate depends on cloud microphysical properties, such as water phase partitioning, hydrometeor size and shape, and macrophysical properties, such as cloud morphology, altitude, thickness, and spatial inhomogeneity (Stamnes et al. 1999). All these cloud properties are strong functions of atmospheric aerosol particles, the numbers and composition of which undergo large seasonal changes. Curry et al. (1996) concluded that the general lack of understanding of fundamental cloud processes precluded a determination of the role of cloud feedbacks on modulating Arctic amplification.

Cloud–radiation feedback processes are coupled closely to atmospheric temperature and water vapor feedbacks. Changes in the ocean–atmosphere mean temperature and water vapor fluxes resulting from changes in the surface state (liquid/solid) imply large changes in the absolute water vapor content of the atmosphere. Such changes alter the radiative fluxes through the atmosphere, with a warmer atmosphere with more water vapor leading to enhanced warming at the surface, which is a positive feedback. Curry et al. (1995, 1996) argued that the complicated structure of the cold lower troposphere may lead to an enhanced water vapor feedback. They suggested that this enhanced feedback is the result of reduced vertical mixing through the stable lower troposphere and the role of cold-cloud precipitation processes in keeping the relative humidity close to ice saturation. Curry et al. (1996) also suggested that the magnitude of this important feedback is uncertain, because it depends on accurate modeling of the role of low-level clouds on the vertical temperature and humidity profiles.

Because the snow/ice–albedo is inextricably linked to atmospheric feedback processes, studying one in isolation from the others may be quite misleading. Stamnes et al. (1999) argued that it is essential to improve our physical understanding of the component processes of the radiation–climate feedback in order to characterize the interdependence among these feedback processes to reduce the uncertainty in their combined effects. This understanding motivated the primary scientific objectives (Stamnes et al. 1999) for the ARM NSA site to focus on improving:

- the treatment of radiative transfer in the coupled atmosphere–snow–ice–surface system;
- the treatment of radiative effects of mixed-phase and ice-phase clouds, aerosols, and cloud–aerosol mixtures;
- the description of basic cloud microphysical properties and how these are influenced by atmospheric and aerosol characteristics;
- a better understanding of the relative importance of surface and advective fluxes of moisture for the formation of clouds;
- a better understanding of the interactions among turbulence, radiation, and cloud microphysical processes in the evolution of the cloudy atmosphere.

In addition to these Arctic-centric objectives, it was also realized that environmental conditions at Barrow presented the opportunity for easier access to address several climate-important phenomena. Clouds forming in the cold and stable Arctic environment tend to be predominantly stratiform mixed phase (liquid water and ice in the same general volume) or fully glaciated. These frequently occurring low-altitude clouds were viewed as an opportunity to study marine stratus, in general, and cold cloud microphysics processes with application well beyond just Arctic clouds. Arctic summer marine stratus processes may be taken as a surrogate for eastern ocean margin marine stratus. Similarly, the glaciated wintertime cloud processes may provide insight into ice clouds that are present around the globe at much higher altitudes that are less accessible to researchers. The low water vapor amounts in the winter Arctic atmosphere also offered the opportunity to study processes contributing to global longwave radiative losses through the cold and dry upper troposphere.

3. Establishment of the sites

The NSA facilities implementation took place in several phases to take maximum advantage of lessons learned from the Southern Great Plains and Tropical Western Pacific sites and the opportunity offered by the interagency SHEBA project. The first phase (1997–98) sought to acquire experimental data to study radiative transfer processes through the atmosphere (in which both radiative energy flows and the surface and atmospheric characteristics that influence them are measured). These data were to be collected in the coastal environment of Barrow and simultaneously within the perennial Arctic ice pack as part of the SHEBA project to study radiative transfer. In the second phase (1999), the ARM instruments that were part of SHEBA were moved to Atqasuk to complete the ocean–coastal transition–inland transect of radiometric and atmospheric/surface experimental data. An anticipated third phase of multiple distributed sites to broaden the focus on cloud formation/dissipation studies was never implemented because of fiscal constraints. However, the science objectives envisioned for phase three were pursued by a series of short-term intensive observing periods.

In addition to more traditional instruments (e.g., radiosondes, surface meteorology, and surface broadband radiometers; see Stamnes et al. 1999 for a full list), the ARM Program deployed some very unique remote sensors to the NSA site. These instruments, many of which were developed as part of the ARM's Instrument Development Program (Stokes 2016, chapter 2), include the extended-range atmospheric emitted radiance interferometer (Tobin et al. 1999) to explore the strong water vapor absorption and emission lines in the 16–25-μm (400–600 cm^{-1}) portion of the spectrum and a polarization-sensitive micropulse lidar (Flynn et al. 2007) for phase discrimination in optically thin clouds.

Operating a suite of advanced instruments in the Arctic presented a series of challenges. While the SHEBA instruments were deployed for a limited period on the flight deck of the ice breaker *Des Groseilliers*, which provided a stable platform and where technical support personnel was readily available, the two North Slope facilities presented greater challenges. These facilities had to be located close to, but with limited impact from, two local communities. The North Slope land areas consist mostly of tundra, the top of the Arctic permafrost. In the short summer months, the top layer of the permafrost melts, leaving the ground soggy and wet. Any structure must be erected on pilings driven into the permafrost layer or on a gravel pad, which prevents the underlying tundra from melting. The Barrow facility rests on several piling platforms, whereas the Atqasuk facility was built on a gravel pad next to the road between the village and the local airport (virtually every village in rural Alaska has an airport). Originally, most of the inside equipment in Barrow resided in the ''Great White'' shelter (Fig. 8-3), while at Atqasuk, equipment was sheltered in the ''Pumpkin'' (Fig. 8-4), both named for the primary colors of the shelters. The Barrow facility had two additional instrument platforms added after the initial deployment. In the early 2000s, the need for additional space to host guest instruments and the facility data system led to the construction of a two-room additional shelter at Barrow, which was completed in 2005. The final expansion at Barrow came through the American Recovery and Reinvestment Act funding in 2010, when two additional shelters were required to host the new scanning cloud radar and lidar systems. Additional laboratory space and the new 3-cm precipitation radar were located in the Barrow Arctic Research Center (BARC), which is 2.2 km west from the Great White (see Fig. 8-1). The NSA site administrative office is located in a duplex in the old NARL complex, close to the BARC, rented from UIC to serve the dual purpose of office space and housing for visiting scientists. The availability of six bedrooms to accommodate visitors proved to be highly advantageous in the late 2000s with the increasing pressure on housing in Barrow coming from an expanding oil industry presence.

The second major challenge faced during the implementation was maintaining and servicing the cutting-edge technology instrumentation throughout the year. The need was met with the appointment of Walter Brower at Barrow as facility manager and initially Jimmy Ivanov and later Doug Whiteman as site operators at Atqasuk. Being native to the North Slope, these

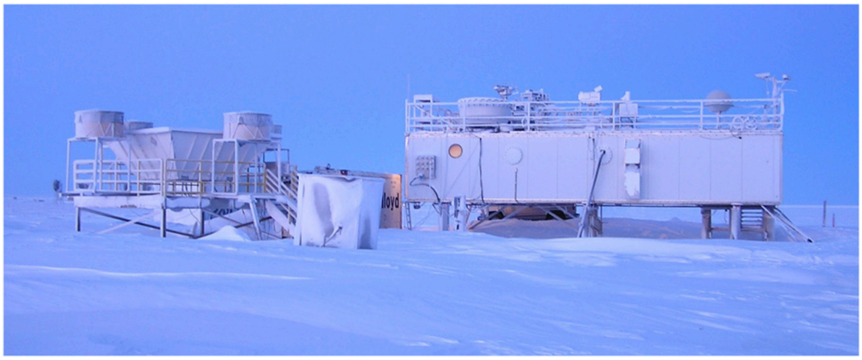

FIG. 8-3. The Great White in Barrow in the early 2000s. The large container housed most of the instruments and all computers (photo courtesy of Mark Ivey).

men brought a wealth of practical experience to the program along with a natural ability to find a solution to almost any problem. Hence, they quickly accomplished several tasks that otherwise would have required an instrument engineer to travel to Barrow. At the same time, they provided a source of local information to visitors unfamiliar with the dangers inherent to life in the Arctic.

The final challenge faced in establishing the sites was related to operating instruments not specifically designed for the harsh Arctic environment. Prior to SHEBA, the NSA/AAO site scientist team (Knut Stamnes working with Rune Storvold) deployed selected ARM instruments at Fairbanks to observe problems and develop solutions, after which the ARM/SHEBA hardware was deployed for a cold test at Barrow during February–April 1997. The effects of low temperatures and the formation of hoarfrost on optical instrumentation were recognized early. To minimize measurement errors, instruments were sheltered to protect them from the cold, while ventilation and modest heating were added to several instruments to prevent frost accumulation. The site scientist team developed routines for near-real-time data quality inspection of all the data by dedicated personnel: first, by graduate students within the field during SHEBA and, later, in Fairbanks, until the ARM Data Quality Office was established.

4. Scientific contributions

The SHEBA project provided an early focus for much of the scientific effort. The SHEBA suite of instruments (Uttal et al. 2002) included cloud radar and lidar, a microwave radiometer, a spectral infrared radiometer, radiosonde soundings, and longwave and shortwave broadband radiometers. These instruments complemented similarly sophisticated measurements in the sea ice and ocean. While there have been shorter-term experiments operating similar suites of atmospheric instruments within the sea ice since that time (i.e., Tjernström et al. 2014), SHEBA is the only example to date of year-round, comprehensive cloud–atmosphere measurements in the central Arctic. As a result, many groundbreaking findings from SHEBA provided a first look into cloud and atmospheric processes over the central Arctic sea ice and thus account for a major component of the community knowledge in that area.

For the first time, the annual cycle of cloud occurrence fraction and type was derived from objective, comprehensive ground-based instruments (e.g., Intrieri et al. 2002b; Shupe et al. 2005). Mixed-phase clouds were characterized in detail and found to be particularly frequent and persistent (Turner 2005; Shupe et al. 2006), with these liquid-containing clouds playing a previously unknown dominant role in the surface radiation budget over the sea ice (Shupe and Intrieri 2004). A variety of remote sensor techniques was used to develop the first characterization of Arctic cloud microphysical properties over an annual cycle (Westwater et al. 2001; Lin et al. 2003; Turner 2005; Shupe et al. 2001, 2005, 2006), which could be linked to the annual evolution of surface cloud radiative forcing (Intrieri et al. 2002a) and net surface energy budget (Persson et al. 2002). With such unique, first and one-of-a-kind findings, SHEBA has been the basis for many Arctic regional model parameterization evaluation and development activities (Khvorostyanov et al. 2001; Zhang and Lohmann 2003; Morrison et al. 2003, 2005; Fu and Hollars 2004; Wyser and Jones 2005; Rinke et al. 2006; Tjernström et al. 2008; Wyser et al. 2008; Du et al. 2011; de Boer et al. 2012; Fridlind et al. 2012).

The extreme environmental conditions at the North Slope provided an early focus for scientific activities at Barrow. Early investigations into the performance of instruments to accurately measure downwelling atmospheric radiative fluxes continued with the International

FIG. 8-4. The Pumpkin at Atqasuk with the local mode of transportation (photo courtesy of Will Shaw and Jim Barnard).

Pyrgeometer and Absolute Sky-Scanning Radiometer Comparison (IPASRC II) in 2001, which focused on both measurement and modeling of downward longwave irradiance (Marty et al. 2003). The next challenge was accurate characterization of the typically low precipitable water vapor and integrated cloud liquid.

The Millimeter-Wave Radiometric Arctic Winter Measurements Experiment Intensive Observing Period in 2004 (Racette et al. 2005) led to the addition of a high-frequency radiometer (183 GHz) to the NSA complement of instruments in 2005 (Cadeddu et al. 2007). The addition of this new instrument improved the accuracy of retrieved precipitable water and liquid water path in winter, when these quantities can drop to very low values.

The Radiative Heating in Underexplored Bands Campaign (RHUBC) in 2007 at Barrow took advantage of the low wintertime water vapor contents as a proxy to explore radiative cooling and heating in the mid-to-upper troposphere globally (Turner and Mlawer 2010) while also offering another opportunity to confirm the precision of the precipitable water retrievals (Cimini et al. 2009).

The transition of the NSA site scientist responsibilities from Knut Stamnes to Hans Verlinde in 2002 resulted in a greater focus on cloud processes. The Mixed-Phase Arctic Cloud Experiment (M-PACE) in fall of 2004 (Verlinde et al. 2007) sought to characterize mixed-phase cloud properties and processes. The design of the experiment built on the original NSA third-phase plans by establishing an extensive observing facility at Oliktok Point on the coast to the east of Barrow and a radiosonde site at Toolik Field Station just north of the Brooks Range along the haul road between Fairbanks and Prudhoe Bay. This experiment was the first extensive ARM aircraft campaign on the North Slope and brought the University of North Dakota Citation and the ARM-UAV *Proteus* aircraft. In situ observations from this campaign (McFarquhar et al. 2007) served as the basis for new surface remote sensing methods (i.e., Shupe et al. 2008a,b; Luke et al. 2010; de Boer et al. 2011; Rambukkange et al. 2011) and many cloud modeling studies (i.e., Fridlind et al. 2007; Solomon et al. 2009; Fan et al. 2009) of these fall transition season mixed-phase clouds. These combined efforts from many research groups resulted in a better description of the eddy structure and microphysical processes associated with single-layer mixed-phase clouds, as summarized in Morrison et al. (2012), and rejuvenated an interest in ice nucleation and ice growth processes in these clouds.

The detailed and distributed M-PACE measurements were used for evaluation of cloud process parameterizations. Xie et al. (2006) evaluated the European Centre for Medium-Range Weather Forecasts (ECMWF) model for the M-PACE period and found that, while it successfully represented the large-scale dynamic and thermodynamic structure and near-surface conditions, the model underpredicted liquid water path and thus downwelling longwave radiation. A two-part series of papers (Klein et al. 2009; Morrison et al. 2009) evaluated microphysical parameterizations of varying complexity in single- and multilayer mixed-phase clouds and found that more detailed parameterizations produced better comparisons with observations but that agreement depended on the type (single-/multilayer) of cloud modeled. Xie et al. (2008) evaluated a community climate model and found that improving the microphysical parameterizations produced better agreement with observed cloud properties and longwave radiative fluxes.

The impacts of aerosol particles on mixed-phase clouds were explored in another aircraft campaign: the Indirect and Semi-Direct Aerosol Campaign (ISDAC) conducted around Barrow in the spring transition season in 2008 (McFarquhar et al. 2011). The spring transition period, with sea ice covering the ocean adjacent to Barrow, stands in contrast to the fall, open ocean conditions observed during M-PACE, in addition to higher aerosol concentrations in the spring versus the fall. The extensive suite of aerosol and cloud instruments on the aircraft for ISDAC allowed in-depth studies of the aerosol particle characteristics over Barrow (e.g., Shantz et al. 2014), their relationship to cloud microphysical properties (e.g., Jackson et al. 2012; Ervens et al. 2011), and impact on cloud evolution (e.g., Avramov et al. 2011; Solomon et al. 2011). The combined SHEBA, M-PACE, and ISDAC datasets are still being explored to gain a better understanding of the fundamental processes that determine cloud formation, evolution, and dissipation.

Not many studies have addressed the coast-to-inland transition captured in the Barrow and Atqasuk data. Summertime clouds over Atqasuk exhibited generally larger liquid water paths (Doran et al. 2002), greater optical depths, and smaller ratios of measured to clear-sky irradiances (Doran et al. 2006) than clouds over Barrow. These differences were attributed to greater upward heat and water vapor fluxes over the wet tundra and lakes.

Although much was gained from the shorter-duration campaigns at the North Slope, the ongoing, long-term measurements are also of great value. Dong and Mace (2003) analyzed stratus cloud properties in liquid (or liquid-dominated) clouds observed in a five-month study from May through September 2000 to show a transition in microphysical characteristics from early May going into the summer season as the lower troposphere destabilizes and more effective precipitation processes reduce the aerosol concentrations. This analysis was followed by a 10-yr study providing a climatology of the cloud radiative forcing and cloud fraction (Dong et al. 2010). That study found that Barrow cloud occurrence fractions are comparable to those derived from ground-based radar–lidar observations during SHEBA and from satellite observations over the western Arctic regions. Furthermore, they found that, as a result of differences in latitude and surface conditions, clouds have a more pronounced and extended period of net surface radiative cooling at Barrow relative to SHEBA, demonstrating one strength of having observations in both regions. Shupe et al. (2011) and Shupe (2011) compiled data on cloud occurrence fraction, persistence, phase, and phase–temperature dependence at Barrow and Atqasuk and compared them with similar measurements at other Arctic observing sites. All sites exhibited a clear annual cycle of cloud occurrence with clouds least frequent in winter and most frequent in the late-summer-to-fall transition season at most sites. By comparing observations from Barrow with similar ones from Eureka, Canada, Cox et al. (2012) showed the influence of larger-scale climatological flow patterns on the radiative fluxes. Advection from Greenland and the central Arctic causes a drier and colder atmosphere at Eureka in the Canadian Archipelago compared to Barrow, where advection is predominantly from warmer locations leading to increased longwave radiative fluxes.

The longer-term measurements also proved useful to study details of Arctic aerosol–cloud interactions and their net effect on the surface radiative properties of low clouds. Using coordinated long-term ARM-funded aerosol measurements at the NOAA facility directly adjacent to the Barrow NSA site, Garrett et al. (2004) found that the microphysical properties of low clouds at Barrow were strongly sensitive to the long-range transport of pollution. The effect of these aerosols can impact the cloud emissivity and can lead to changes in downwelling longwave radiation of 3–5 $\mathrm{W\,m^{-2}}$ (Lubin and Vogelmann 2006; Garrett and Zhao 2006). When combined with aerosol indirect shortwave effects (Lubin and Vogelmann 2007), the total indirect effect of aerosols at Barrow was shown to vary annually from a maximum warming of $+3\,\mathrm{W\,m^{-2}}$ in March to a cooling of $-11\,\mathrm{W\,m^{-2}}$ in May (Lubin and Vogelmann 2010).

Comparisons of numerical weather prediction and climate model cloud and radiation simulations against Barrow observations have revealed deficiencies in model parameterizations. Zhao and Wang (2010), using nine years of Barrow observations for the period 1999–2007, found that although the ECMWF model captured the general seasonal variation of surface fluxes and low-level cloud fraction, it experienced difficulty representing the boundary layer temperature inversion height and strength, overestimated the cloud fraction by 20% or more, and underestimated the liquid water path by over 50% in the cold season. In similar studies, but looking at different models, de Boer et al. (2012) found similar problems with the critical lower-troposphere processes and phenomena in the Community Climate System Model, version 4, and Walsh et al. (2009) found biases in radiative fluxes and cloud radiative forcing in reanalyses products.

5. Summary

The decision to place the ARM polar observing site in the Arctic proved to have been timely, in light of recent dramatic regional changes since its establishment. The rate of summer Arctic sea ice decline has exceeded that predicted by most of the models that contributed to the Intergovernmental Panel on Climate Change (IPCC) process (Stroeve et al. 2007), reaching new sea ice extent minima in 2007 and 2012. At the same time, ice volume declines even more precipitously (Kwok et al. 2009) with the loss of perennial ice (Maslanik et al. 2011). The urgency for understanding the physical causes of these larger-than-predicted ice losses is great (Stroeve et al. 2012). There is a growing community-wide understanding of the important role of lower-tropospheric cloud processes (Francis and Hunter 2006; Kay et al. 2008; Stroeve et al. 2012). This realization motivated the recent decision to deploy an ARM Mobile Facility at Oliktok Point starting in 2013, effectively completing the original phase-three plans. Taking advantage of a restricted air zone established for M-PACE, Oliktok Point will be a base for tethered balloon and unmanned aerial system operations exploring the lower-troposphere structure across the land-to-Arctic Ocean transition.

The recent addition of scanning polarimetric precipitation and dual-frequency cloud radars will expose new avenues for cloud process research to new dimensions. Not only will researchers be able to have a first look at the three-dimensional mesoscale structure of cloud and precipitating systems, but exploitation of the three frequency and polarimetric measurements will allow for detailed characterization of cloud and hydrometeor properties in the context of those structures. Such studies will help to develop the physical understanding needed to adapt the lower-troposphere parameterizations currently employed in large-scale models, mostly developed from lower- and midlatitude observations, to represent better processes in the stable polar air. The recent establishment of the Department of Energy Next-Generation Ecosystem Experiments (NGEE) site at Barrow will also provide a comprehensive set of measurements to study terrestrial–lower atmosphere interactions in even greater detail.

If imitation is the highest form of flattery, the establishment of several additional circum-Arctic sites is a testimony to the farsightedness of the original DOE-ARM planning. Since the establishment of the NSA site, the Canadians established Eureka on Ellesmere Island in Nunavut, the northernmost of Canada's three territories; the National Science Foundation is supporting similar measurements at Summit Station on the Greenland ice sheet; and at the Tiksi Hydrometeorological Observatory located in the Russian Far East, a partnership of U.S./Russian/Finnish agencies supports a subset of the typical DOE-ARM suite.

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