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Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAIC) Field Campaign Report

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Executive Summary

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition explored the coupled central arctic climate system from late September 2019 to late September 2020. The project was based on and around the icebreaker *Polarstern*, as it was frozen into, and drifted with, the arctic sea ice from the Siberian sector of the Arctic, past the North Pole, and on towards the Fram Strait. The expedition was designed as a “sea ice Lagrangian” experiment, wherein a specific region of sea ice was passively followed over the course of a year, serving as an integrator of thermodynamic, dynamic, chemical, and biological interactions with the atmosphere and ocean. The overall scientific goal for the mission was to understand the processes driving the ongoing rapid decline of sea ice as well as the implications of those changes on the regional and global climate systems. In particular, the expedition was constructed in a way to observe and understand the physical, chemical, and biological processes that serve to couple and link the arctic atmosphere, sea ice, ocean, and ecosystem. Guiding science questions for the mission include:

1. What are the seasonally varying energy sources, mixing processes, and interfacial fluxes that affect the heat and momentum budgets of the arctic atmosphere, ocean, and sea ice?
2. How does sea ice formation, drift, deformation, and melting couple to atmospheric, oceanic, and ecosystem processes?
3. What processes regulate the formation, properties, precipitation, and life time of arctic clouds and their interactions with aerosols, boundary-layer structure, and atmospheric fluxes?
4. How do interfacial exchange rates of biogeochemical process-related trace gases trigger the arctic climate system?
5. How do sea ice and pelagic ecosystems respond to changes in arctic sea ice?
6. How do ongoing changes in the arctic climate system impact large-scale heat, momentum, and mass fluxes and how do these changes feed back into the arctic climate and ecosystem?

Twenty nations and more than 80 world-leading institutions collaborated to manifest this major, multi-disciplinary effort, led by the Alfred Wegener Institute from Germany. U.S. contributions were made by the Department of Energy, National Science Foundation, National Oceanic and Atmospheric Administration, and National Aeronautics and Space Administration. The Department of Energy Atmospheric Radiation Measurement (ARM) user facility provided the second ARM Mobile Facility (AMF2) as a core element of the MOSAiC atmosphere program. This user facility included approximately 60 instruments designed to measure aerosols and gases, clouds and precipitation, the atmospheric boundary-layer structure, and surface energy fluxes. All of these areas need additional observations and improved understanding in a region that, thus far, has been observed infrequently, particularly in winter. Moreover, all of these measurements contribute towards addressing key scientific questions related to coupling between the atmosphere, sea ice, ocean, and ecosystem.

MOSAiC’s year in the arctic ice was very successful in spite of challenges associated with anomalous atmospheric circulation, rapid ice drift, a very dynamic ice pack, and a global pandemic. In spite of these challenges, the expedition returned home with a wealth of new observations that will serve the research community for decades. This data will serve as a foundation for model evaluation and improvement, supporting improved climate predictions, weather forecasts, and ecosystem assessments.

Acronyms and Abbreviations

AGU	American Geophysical Union
AMF2	second ARM Mobile Facility
AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
ATMOS	MOSAiC atmospheric team
AWI	Alfred Wegener Institute
CIRES	Cooperative Institute for Research in Environmental Sciences
CPC	condensation particle counter
DOE	U.S. Department of Energy
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PI	principal investigator
PWD	present weather detector
SWE	snow water equivalent
TROPOS	Leibniz Institute for Tropospheric Research

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1.0 Background

1.1 The Changing Arctic

The Arctic is rapidly changing, and these changes have substantial societal relevance. First, arctic change is a leading sign of global change, as the warming observed in the Arctic is 2-3 times faster than observed across the rest of the globe (Overland et al. 2019). This so-called arctic amplification is due to numerous feedbacks, including those linked to the declining sea ice. Broad arctic changes are also hypothesized to be related to shifts in large-scale circulation patterns that may have implications for mid-latitude weather (Cohen et al. 2020) and ocean circulation (Sévellec et al. 2017). Arctic change is further affecting the oceans through acidification that threatens food supplies (Qi et al. 2017). Declining sea ice also opens the Arctic for new resource development, shipping routes, tourism, and other commercial activities. Lastly, the changing Arctic is a hotbed for geopolitical challenges as nations vie for influence and control of this resource-rich and newly accessible region. Clearly the Arctic and its changes are playing a huge role in our Earth both from a geophysical and socio-political standpoint.

To navigate, manage, and respond to the challenges associated with arctic change requires a vastly improved understanding of the coupled arctic system, and the drivers and implications of these changes. It is essential to better understand the physical basis for why the arctic sea ice is declining, the associated feedbacks that work to amplify or modulate this decline, and the myriad ways that the Earth system is responding. As a result of these changes and uncertainties, there are increasing societal needs for improved model predictive skill in the Arctic, to address pressing gaps in global climate prediction, to advance forecast skills for regional and hemispheric weather and sea ice, and to ensure robust ecosystem models that realistically link physical and biological systems. To fulfill these core needs requires new, sophisticated, and cross-cutting observations within the rapidly changing arctic ice pack.

1.2 The MOSAiC Expedition

In response to these needs, an international consortium of world-leading arctic researchers, institutions, and funding agencies developed and implemented the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC), which is the most comprehensive study of the central arctic system to date. The core scientific question guiding MOSAiC is: ***What are the causes and consequences of an evolving and diminished arctic sea ice cover?*** Inherent in this question, it is clear that sea ice is the nexus of interest and that the scientific exploration will examine the processes driving sea-ice change, and the implications of that change on other aspects of the Arctic and global systems. Embedded underneath this leading question is a set of more targeted questions that serve to organize MOSAiC's research and illustrate a multidisciplinary approach towards developing the comprehensive understanding that is needed. These questions include:

1. What seasonally varying energy sources, mixing processes, and interfacial fluxes affect the heat and momentum budgets of the arctic atmosphere, ocean, and sea ice?
2. How does sea ice formation, drift, deformation, and melting couple to atmospheric, oceanic, and ecosystem processes?

3. What processes regulate the formation, properties, precipitation and life time of arctic clouds and their interactions with aerosols, boundary-layer structure, and atmospheric fluxes?
4. How do interfacial exchange rates of biogeochemical process- related trace gases trigger the arctic climate system?
5. How do sea ice and pelagic ecosystems respond to changes in arctic sea ice?
6. How do ongoing changes in the arctic climate system impact large-scale heat, momentum, and mass fluxes and how do these changes feed back into the arctic climate and ecosystem?

All of these questions are motivated by important modeling needs and seek to draw together the observations and analyses that will lead to model advancement. To address these questions, MOSAiC was designed to examine the physical, chemical, and biological processes that serve to couple the arctic atmosphere, sea ice, ocean, and ecosystem.

The multi-scale design of MOSAiC was centered around the research vessel *Polarstern*, a German icebreaker from the Alfred Wegener Institute (AWI), which served as the leading institution for the project. *Polarstern* was embedded within the arctic sea ice to serve as a base of operations for the project and a stable platform for a wide variety of scientific activities, including onboard observing systems, laboratories, and facilities to support the scientific participants (Figure 1). Adjacent to *Polarstern* on the sea ice was an ice camp called the Central Observatory, all within about 2 km of the vessel. Within the Central Observatory was a network of pathways, power lines, and scientific installations, laid out in a manner to minimize the impacts of the vessel on the measurements and to enable direct access to the undisturbed arctic atmosphere, sea ice, ocean, and ecosystem. One of the major on-ice installations was called Met City, containing a wide range of atmospheric and other measurements, and was typically about 400-500 m away from the ship. Collectively the *Polarstern* and Central Observatory were designed to intensively sample and measure the arctic system from the ocean, through the ice, and into the atmosphere, including coupled processes. At this scale, the observations are appropriate for direct comparison and research using high-resolution and single-column models. Extending out to further scales, the Distributed Network comprised numerous semi-autonomous stations and buoys installed at scales of 5-40 km away from *Polarstern* in all directions. Many of these stations included coupled observations of the atmosphere, sea ice, and ocean. Observations made across the Distributed Network were designed to provide important perspectives on spatial gradients and heterogeneity within the system, on scales that are relevant to examine sub-grid variability in large-scale models. These MOSAiC observations were then linked with other observations across the Arctic at land-based stations, from other vessels, from aircraft, and from satellites.



Figure 1. *Polarstern* embedded in sea ice, with key installation locations annotated.

This collection of observational assets was installed into the Siberian sector of the arctic sea ice in October 2019 and left to drift with the ice as it traveled along the Transpolar Drift, heading near the North Pole and then towards Fram Strait (see Figure 2). This design is effectively a “sea-ice Lagrangian” design, tracking a region of ice as it undergoes transitions over the course of a full year through interactions with the atmosphere and ocean. In this case the ice serves as an integrator as it responds to thermodynamic and dynamic forcing from the atmosphere and ocean over the course of the year. During this drifting year, multiple re-supply missions were conducted using partner vessels wherein personnel, fuel, food, and other supplies were transferred. Overall there were five legs of the mission. Due to rapid drift of the observational constellation, related to an anomalous large-scale circulation pattern in early 2020, the *Polarstern* reached the edge of the sea ice at the end of July (Leg 4) and was subsequently repositioned back near the North Pole to complete the full year. The mission finished its scientific observations in late September 2020 before leaving the sea ice.

Scientific participation in MOSAiC came from 20 different nations and more than 80 world-leading institutions. The United States had major contributions from the U.S. Department of Energy (DOE), the National Science Foundation, the National Oceanic and Atmospheric Administration, and the National Aeronautics and Space Administration. Of particular interest for this report is the DOE Atmospheric Radiation Measurement (ARM) user facility’s contribution, which was the single largest scientific project and a major foundation for the MOSAiC atmospheric (ATMOS) team. For MOSAiC, ARM contributed the second ARM Mobile Facility (AMF2), which included an extensive suite of instruments to measure the atmospheric state, clouds, precipitation, aerosols, radiation, and more, including two guest aerosol measurement systems. In addition to the ARM contribution, the DOE Atmospheric System Research (ASR) program is supporting a collection of scientific research projects designed to capitalize on these unique measurements towards advancing our knowledge.

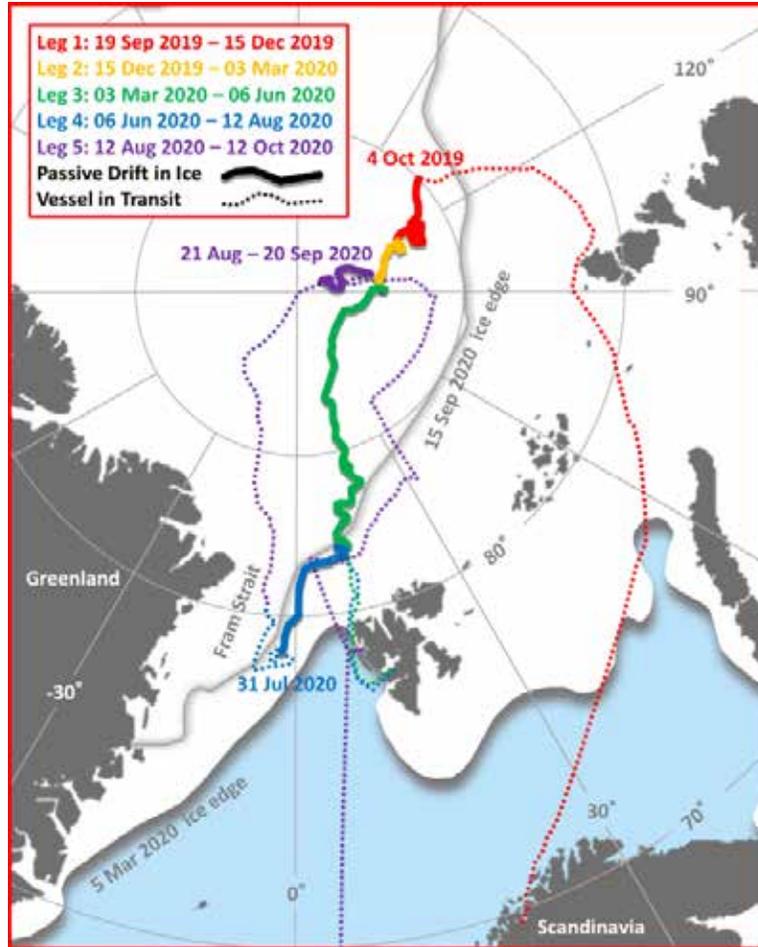


Figure 2. The MOSAic Expedition route, including the passive drift of the MOSAic ice floe (solid) with dates of drift annotated, and the transit movements of *Polarstern* (dashed) delineated by legs (colors).

1.3 ARM's Role in MOSAic

The involvement of ARM in MOSAic was guided by a collection of scientific foci that comprise an important contribution to the overall MOSAic Science Plan by specifically examining essential atmospheric processes. As context, it is informative to consider the fluxes of energy through the arctic system that impact the changing sea ice. Figure 3 provides observational estimates of regional energy fluxes for an ice-covered Arctic Ocean system, the relative importance of the different processes, and the intricate coupling among the processes. It is notable that the atmospheric terms are large and dominated by radiative fluxes. For context on this system it is important to consider that an estimated excess of $\sim 1 \text{ W/m}^2$ in the net annual surface energy flux over the past 30 years can account for the observed reduction in sea ice extent and mass (Kwok and Untersteiner 2011). This excess is small relative to the uncertainties inherent in most fluxes in Figure 3, related to spatial/temporal variability and measurement error, as well as the potential trends in many of these terms.

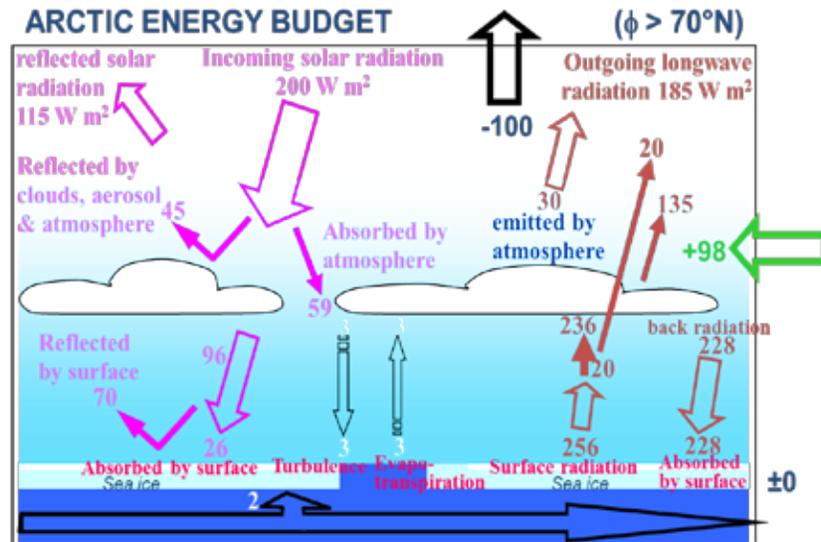


Figure 3. Estimates of regional annual mean arctic energy fluxes over a mostly ice-covered Arctic Ocean assuming a cylinder over the Arctic at $\sim 70^{\circ}$ N.

While it is clear that atmospheric energy fluxes are critically important for the energy budget of sea ice, many processes controlling these fluxes, and their interactions are poorly understood and represented in numerical models. This is particularly true in the sea ice environment due to a serious lack of process-level observations. Specific processes that control the flow of energy through the system are the target for the AMF2 deployment through intensive atmosphere and coupled-system observations in the central arctic ice pack. Primary research themes guiding ARM's involvement include: the surface energy budget, clouds and precipitation, aerosols, and boundary-layer structure. Each of these interrelated themes is briefly outlined here, starting with a list of relevant science questions and the overall science goal that the ARM measurements are particularly well positioned to address.

Surface Energy Budget

- Ø What is the annual evolution of the surface energy budget over young sea ice?
- Ø What key process interactions determine the surface energy budget?
- ✓ **GOAL: Comprehensive observations to close the surface energy budget and understand its variability in all seasons.**

The surface energy budget is one of the primary factors controlling the area and mass distributions of central arctic sea ice. It comprises large and variable downwelling longwave radiation, persistent radiative cooling from the surface, seasonal solar radiation, much of which is reflected by the bright surface, turbulent heat fluxes, and energy passing through the sea ice via transmission and conduction (e.g., Persson et al. 2002). To understand the net impact on sea-ice mass, it is important to understand how energy is partitioned into these different components as a function of time. Each term has important scales of variability in space and time related to solar cycles, surface changes, meteorology, and others. Similarly, the different components interact. For example, enhanced downwelling longwave radiation due to clouds can warm the surface and elicit a surface cooling response via enhanced radiative cooling, sensible heat, and/or conductive heat fluxes. The magnitudes of these responses to the initial forcing are determined by other environmental properties such as the surface-layer stability or snow depth. Additionally, key feedback processes, such as the ice-albedo feedback, are essential features of the arctic

system leading to amplified change. These feedbacks and process interactions, particularly over a distribution of thin sea ice, must be understood so they can be correctly represented in coupled models.

Clouds and Precipitation

- Ø **What factors determine arctic cloud phase partitioning?**
- Ø **What role do clouds and precipitation play in determining low-level atmospheric structure?**
- Ø **How does surface inhomogeneity influence the spatial structure of cloud-precipitation systems?**
- ✓ **GOAL: Full characterization of microphysical, macrophysical, and spatial structure of clouds and precipitation over a continuous year.**

Clouds have two competing effects on the radiative balance at the surface: (a) trapping longwave radiation leading to a net surface warming and (b) reflecting solar radiation leading to a net cooling. The balance of these effects depends on environmental conditions (sun angle, surface albedo, and temperature) and cloud properties (phase, microphysics). Phase in particular has been shown to be a primary driver of the surface radiation balance (Shupe and Intrieri 2004). Clouds are also a vehicle for precipitation, which is an essential aspect of atmospheric moisture and surface mass budgets. While some progress has been made on understanding the common arctic stratiform clouds, substantial work is still needed to develop a representative understanding of cloud-scale processes associated with phase partitioning that can be reproduced by models (Morrison et al. 2012). Moreover, relatively little is understood about the spatial organization and energetics of deeper precipitating cloud systems and their net impact on the surface. Changes in cloudiness as a result of broader arctic change can elicit different responses in the surface energy and mass budgets depending on when they occur. The ultimate role that clouds play in the observed regional changes in sea ice is yet to be determined, but requires a more detailed understanding of the processes through which clouds form, transform, and interact with the surface and atmosphere.

Aerosols

- Ø **How do aerosol physical, chemical, and optical properties over sea ice vary seasonally?**
- Ø **What sources and transport patterns cause variability in arctic aerosol?**
- Ø **What are the radiative and cloud-nucleating properties of the aerosol?**
- ✓ **GOAL: Produce the first annual cycle characterization of central arctic aerosol physical, chemical, optical, and cloud-active properties, including source attribution.**

Aerosols play two important roles in the climate system: 1) Direct impacts on atmospheric radiation; and 2) Indirect impacts on radiation and precipitation by influencing cloud formation and microphysical composition. Arctic aerosols are complex due to marked temporal and vertical variability, and disparate potential origins (e.g., Quinn et al. 2009). Chemical and physical properties dictate the ultimate impacts of aerosols on radiation and clouds, and these depend on source regions, which can range from locally produced marine biogenic species to long-range transport of biomass burning and anthropogenic particulate matter (Saha et al. 2010). The interplay of large-scale meteorology with the persistent, near-surface arctic inversion affects the mixing state, aging, and vertical structure of aerosol and its distribution across the Arctic. The role of black carbon in the arctic system is not well understood and likely changing with enhanced access to the Arctic. Overall, with so little known about central arctic

aerosols, there is the opportunity for significant advances in even the most basic level of understanding, which will provide major constraints on how central arctic aerosols are represented in models.

Boundary-Layer Structure

- ∅ What are the properties and effects of stably stratified turbulence in the lower atmosphere?
- ∅ What are the effects of a thinned ice cover on low atmospheric stability and heat fluxes?
- ∅ How do surface- and cloud-driven dynamics impact the low atmosphere structure?
- ✓ **GOAL: Annual cycle assessment of boundary-layer stability, the processes that erode it, and the resulting vertical structure.**

Two unique properties of the arctic atmosphere are a persistent temperature inversion and frequent stable stratification within the atmospheric boundary layer. These features can occur throughout the year, while stable boundary layers are particularly frequent and long-lived during the arctic night due to the lack of a diurnal cycle to force shallow convection (e.g., Zhang et al. 2011). Periodic destabilizing influences include cloud-driven dynamics, large-scale baroclinicity, and surface heterogeneities such as leads. Boundary-layer processes are the links that connect the local sea-ice system with the free troposphere, which is itself the primary conduit to the large-scale, global climate system. These processes, which may be changing as a result of thinning ice pack, control how energy and mass are transferred, interact with radiation and are important for cloud formation, impact the vertical atmospheric structure including the distribution of aerosol, impact momentum transfer to the surface, and modulate the surface energy budget. Moreover, these interactions are critical in the hemispheric linkages between arctic change and the global system. Formulations of boundary-layer turbulent processes used in numerical models rely on empirical relationships, yet often struggle to achieve a realistic balance between mixing and growth of surface stable layers.

2.0 Notable Events or Highlights

The MOSAiC year in the arctic sea ice was a tremendous experience for all involved, with unique and notable events throughout the year that provide important context for the measurements made and the science they will support. Each leg of the MOSAiC expedition brought its own interesting highlights. There are also several overall operational highlights for the AMF2.

2.1 Highlight by Leg

LEG 1 – Installation. In preparation for the start of MOSAiC, the AMF2 facility was installed over the course of a couple of weeks onboard *Polarstern*. The ARM installation (see Figure 1) included six sea container units on *Polarstern*'s bow, housing a wide range of remote sensors and a full Aerosol Observing System (AOS) for sampling aerosols and gases. ARM equipment was also installed on *Polarstern*'s P-deck, offering a clear view of the atmosphere in multiple directions. Once *Polarstern* arrived within the ice pack and selected the MOSAiC ice floe, installations were also set up on the sea ice. ARM had a presence at the Met City site with where precipitation and radiation instruments were installed at some distance from *Polarstern* (Figure 4). Most installations went exceedingly smoothly, considering the overall challenging and remote conditions. Moreover, the arctic winter descended quickly on the expedition, with 4 months of continual darkness starting in later October. During this first phase of the expedition there was a notable storm in the middle of November, bringing high winds and leading to

the first major fractures of the sea ice through the camp. As a result of these ice dynamics, the MOSAiC and ARM teams learned a great deal about how to support measurements on the ice in spite of a moving surface.



Figure 4. Leg 1 ARM team including the Principal Investigator (PI) pictured at Met City with ARM radiation and precipitation equipment as polar night has descended on MOSAiC. Photo: Matthew Shupe.

LEG 2 – Winter. In mid-December a new set of personnel came to support the expedition through the heart of the dark winter season. While at the MOSAiC ice floe, this crew did not see the sun, with sunlight only greeting them as they were on their voyage home in March. Leg 2 was relatively uneventful compared to the rest of the year. A late February storm represented the second-lowest pressure minimum observed during the year, with persistent high winds and a significant mid-winter warming of $\sim 10^{\circ}$ C relative to temperatures over the preceding month. Additionally, during these early months of 2020, the arctic region experienced record high positive values of the Arctic Oscillation Index, consistent with a strong polar vortex, the largest ozone hole observed to date in the Arctic, and anomalous winds near the surface that pushed the MOSAiC drift rapidly along its drifting course. See Figure 5 for a picture of ARM installations onboard *Polarstern*.



Figure 5. *Polarstern* bow with ARM laboratory containers and equipment visible, including installations above the bridge. Early March 2020. Photo: Michael Gutsche.

LEG 3 – Rising Sun. As the sun rose again after the arctic winter, Leg 3 began with an extended high-pressure, clear-sky period and the coldest near-surface temperatures observed for the year at $-42.3\text{ }^{\circ}\text{C}$. Within a few weeks the transition from complete darkness to 24 hours of sunlight was complete. The continued high Arctic Oscillation Index meant very fast drift with a lot of ice dynamics that threatened operations at times (Figure 6), even leading to one ARM instrument being damaged by ridging sea ice. In mid-April, a warm air intrusion represented a major shift from temperatures consistently below $-25\text{ }^{\circ}\text{C}$ to those consistently warmer than $-15\text{ }^{\circ}\text{C}$, and pushed the system towards the melt onset. This shift occurred as a result of a transition in the dominant large-scale circulation pattern and a breakdown of the influence of the polar vortex on the near-surface environment. Leg 3 was extended due to the COVID-19 pandemic and challenges with implementing the original resupply plan. As a result, *Polarstern* had to leave the ice to enable a rotation of crew, necessitating the removal of most equipment from the ice during the transition.



Figure 6. Met City, and ARM’s on-ice installations, cut off from *Polarstern* in April. Photo: Christopher Cox.

LEG 4 – Summer Melt. After rotating crew near Svalbard, *Polarstern* headed back to the MOSAiC ice floe, identifying a remnant and robust section of the floe on which to re-establish the Central Observatory. The melt season had started by this point, with significant snow melt leading to the formation of melt ponds on the surface (Figure 7). MOSAiC and ARM measurements at this time were able to document the atmospheric influences on variability of the surface energy budget, which controlled the speed and extent of melt. Key transitions during this leg included the complete melt of the snow, the formation of melt ponds, and the growth and drainage of melt ponds. Melt also revealed a great deal of sediment embedded within the sea ice, impacting the surface albedo. With persistent drift towards the south over the preceding months, the MOSAiC ice floe was much further south than initially planned, and by the end of July the ice floe reached the ice edge in the Fram Strait. With impeccable timing, all equipment was again de-installed from the sea ice and brought onboard *Polarstern* about one day prior to the complete disintegration of the original MOSAiC ice floe.

LEG 5 – Freeze Up. The final leg of the expedition required taking *Polarstern* back north into the ice pack near the North Pole to finish out the year. A suitable ice floe was identified, and for the third time, a Central Observatory was established on the ice (Figure 8), this time to capture the energy transitions leading to freeze up of the surface. Freezing started to occur, but an early September storm brought warm air that halted the freeze up temporarily. Thereafter, melt ponds began to freeze over, and some of the season’s first snowfall helped to diminish the surface albedo and push the system permanently back towards freeze. By late September 2020, after nearly a full year in the arctic ice, all equipment was again packed onboard *Polarstern* and the journey home began.



Figure 7. A view of the MOSAiC ice floe during Leg 4, with the on-ice installations visible in the middle of the photograph, and the *Polarstern* in the background. Photo: Lianna Nixon.



Figure 8. Re-installing equipment on the ice during Leg 5. Photo: Michael Gallagher.

2.2 AMF2 Operations and Challenges

Operations of ARM equipment were generally robust and continuous, with relatively few failures or interruptions. Since most ARM instruments were installed onboard *Polarstern*, they did not suffer from the on-ice challenges related to ice dynamics, which periodically interrupted power. Additionally, most onboard instruments were able to continue operating even when *Polarstern* was underway during the transitions between Legs 3-4 and Legs 4-5. As a result, ARM's skilled onsite technicians maintained impressively continuous operations of most equipment for the duration of MOSAiC, in spite of the often extreme conditions. See summary in Table 1. A few key limitations to the data set did occur, including:

- The scanning X-band radar failed prior to full installation and was never operational.
- The 3-channel microwave radiometer struggled to operate and was not very continuous in time, although measurements from the 2-channel microwave radiometer were much more reliable.
- The micropulse lidar failed in the beginning of September, about 3 weeks prior to the end of field operations.
- The aerosol chemical speciation monitor suffered a number of issues that led to very low sensitivity in an already challenging arctic environment and it is not yet clear if there is any recoverable or useful information.
- Precipitation: One Altair shield for a precipitation gauge was destroyed by sea ice ridging; however, the instrument itself was recovered and still used.
- Met City instruments: The radiation and precipitation suites installed on the sea ice suffered a few periodic power outages as ice dynamics, or polar bears, would lead to interruption of line power from *Polarstern*.

In addition to generally robust operations in the field, ARM is serving as a model for how to collect, quality control, process, and archive data. Most of ARM's data is already publicly available in the ARM Data Center, while a great deal of collaborating MOSAiC data is not yet publicly released (all MOSAiC data must be publicly released by 1 January 2023). This open approach that ARM takes as a DOE user facility promotes the broad dissemination and use of the data for many applications and by many stakeholders, and is helping to grow the MOSAiC user community.

Table 1. ARM instruments deployed during MOSAiC. Unless otherwise noted, all instruments were installed onboard *Polarstern*. A general assessment of data quality is given (green: mostly good; yellow: use caution; red: data problems). All aerosol and gas measurements are marked yellow due to periodic contamination by local pollution, although most instruments operated well when not sampling pollution.

Instrument	Measurement and/or Derived Parameters
Radiosondes	Pressure, temperature, relative humidity, winds, 4-daily launched from ship (contribution to AWI-led effort)
Sky-viewing broadband radiometer suite	Downwelling broadband solar and terrestrial radiation, direct and diffuse solar partitioning, sky infrared temperature, deployed on sea ice
Sky-viewing broadband radiometer suite	Downwelling broadband solar and terrestrial radiation, two systems

Instrument	Measurement and/or Derived Parameters
Surface-viewing broadband radiometer suite	Upwelling broadband solar and terrestrial radiation, infrared surface temperature, deployed on sea ice
Multifilter rotating shadowband radiometer	Upwelling irradiance at 6 wavelengths, deployed on sea ice
Marine atmospheric emitted radiance interferometer	Spectral infrared radiation (sky, surface), trace gas and cloud properties
Sun photometer	Solar irradiance & sky radiance at 6 wavelengths, fixed pointing zenith
Beam-steerable radar wind profiler	Wind profiles, typically below 4 km
Doppler lidar	Wind profiles, vertical velocity, turbulent dissipation rate, below 1 km
Ceilometer	Backscatter, cloud base height
Micropulse lidar	Backscatter, depolarization; profiles of cloud and aerosol properties
High-spectral-resolution lidar	Backscatter, depolarization; profiles of cloud and aerosol properties
Ka-band ARM Zenith Radar	Doppler radar moments and spectra, profiles of cloud properties
Marine W-band ARM Cloud Radar	Doppler radar moments and spectra, profiles of cloud properties
Ka-band Scanning ARM Radar	Doppler radar moments, spatial cloud distribution and properties
X-band Scanning ARM Radar	Doppler radar moments, spatial cloud distribution and properties
Total sky imager	Visible hemispheric sky images, cloud coverage
Microwave radiometer, 2-channel	Sky brightness temperature; integrated water vapor & liquid water path
Microwave radiometer, 3-channel	Sky brightness temperature; integrated water vapor & liquid water path
Present weather detector	Precipitation occurrence and intensity, on ship and on sea ice
Laser disdrometer	Precipitation and particle size distribution, on ship and on sea ice
Weighing bucket rain gauge	Precipitation occurrence and mass, on sea ice
Siphon rain gauge	Precipitation occurrence and mass, on ship
Condensation particle counter	Two systems: Total particle concentration >10 nm and >3 nm
Scanning mobility particle sizer	Particle size distribution 10-500 nm
Ultra-high-sensitivity aerosol spectrometer	Particle size distribution 50-1000 nm
Humidified tandem differential mobility analyzer	Mass, size, and particle size distribution as a function of relative humidity, hygroscopicity
Cloud condensation nucleus counter	CCN concentration, supersaturation of 0.4% and scanning from 0-0.8%
Aerosol chemical speciation monitor	Mass spectrum, particle composition
Single-particle soot photometer	Black carbon mass concentration
Nephelometer	Light scattering at dry relative humidity at 3 wavelengths
Particle soot absorption photometer	Light absorption at 3 wavelengths

Instrument	Measurement and/or Derived Parameters
Total aerosol filter sampler	Aerosol loadings for offline ice nucleating particle analysis, offline DNA sequencing (Guest instrument: Colorado State Univ.)
Davis rotating-drum unit for monitoring	Size-resolved aerosol loadings for offline ice nucleating particle analysis, 3 bins 0.15-12 μm (Guest instrument: Colorado State Univ.)
Davis rotating-drum unit for monitoring	Size-resolved aerosol loadings, offline single-particle morphology and elemental composition (Guest instrument: Univ. Michigan)
Ozone monitor	Ozone concentration
Trace gas monitor	Carbon monoxide, nitrous oxide, and water vapor concentration

3.0 Results

Scientific research using ARM's observations from MOSAiC is just starting, but early insights into the data suggest exciting and interesting future outcomes. A few examples are provided here.

Aerosol variability. Relatively few observations exist of aerosols over the central arctic ice pack, particularly in the winter season. Early observations of particle number concentrations from the MOSAiC autumn transition into winter (Figure 9) demonstrate a very wide range and highlight some of the interesting features and challenges associated with aerosol measurements in this environment. First, there were numerous periods when the total particle concentration from the condensation particle counter (CPC) exceeded 10^4 cm^{-3} . These periods were influenced directly by local emissions from the *Polarstern* itself during unfavorable winds. At times a back-pressure purge was applied to the aerosol inlet, preventing samples of ship emissions (red bars in Figure 9), but there were also plenty of these periods that were not purged (e.g., 13-17 October). Currently several groups are working to identify and characterize the impacts of ship pollution on the aerosol data sets.

In addition to these measurement challenges, the timeseries reveals some very interesting temporal variability. Typically, the timeseries, when not impacted by ship emissions, shows particle concentrations ranging from 50-2000 cm^{-3} ; this is a common range for the arctic atmosphere. However, there are periods, such as 18 October, 25-27 October, and 1-2 November, when the particle concentration dipped well below 10 cm^{-3} . These exceedingly clean conditions are likely due to long air mass trajectories within the Arctic with few local sources of additional aerosol but a steady sink of aerosol due to wet and dry deposition. Under these conditions, it is likely that aerosol availability limits cloud formation (e.g., Mauritsen et al. 2011), with potential implications for the surface energy budget at this important time of year.

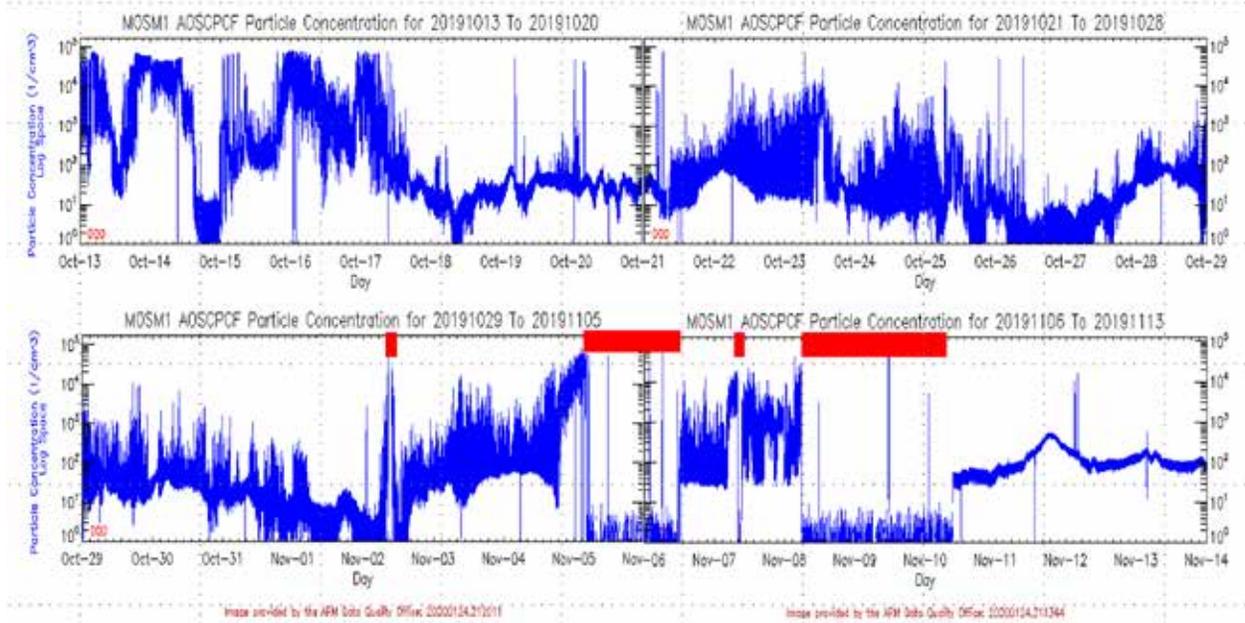


Figure 9. Quicklook plots produced by the ARM Data Quality Office for 13 October to 13 November 2019 of unfiltered particle concentrations from the CPC onboard *Polarstern*.

A number of other aerosol-related studies are underway with ARM- and DOE-supported measurements from MOSAiC. These include filter-based offline analysis of particle composition, the first annual cycle of near-surface ice nucleating particle concentrations, a detailed assessment of the impact of local pollution on aerosol timeseries, temporal variability in cloud condensation nucleus concentrations, and more. One paper has been submitted by colleagues at the Leibniz Institute for Tropospheric Research (TROPOS) that examines aerosols from wildfires with potential impacts on clouds (Engelmann et al. 2021). In addition to these current research efforts, there is a great deal of potential within the ARM measurements to better understand the origins of arctic atmospheric particles and how aerosol concentrations are influenced by air mass processes, boundary-layer dynamics, cloud interactions, and other factors.

Clouds and Cloud-Surface Interactions. ARM measurements are very well suited to examine detailed cloud properties and processes, and their interactions with the surface through radiation and dynamics. The ARM Ka-band Zenith Radar (KAZR) data has been incorporated into the Cloudnet cloud retrieval package to provide a time series of vertical classifications of cloud type, cloud microphysics, and numerous other properties (see Figure 10). These cloud properties are useful for examining processes and for evaluating models.

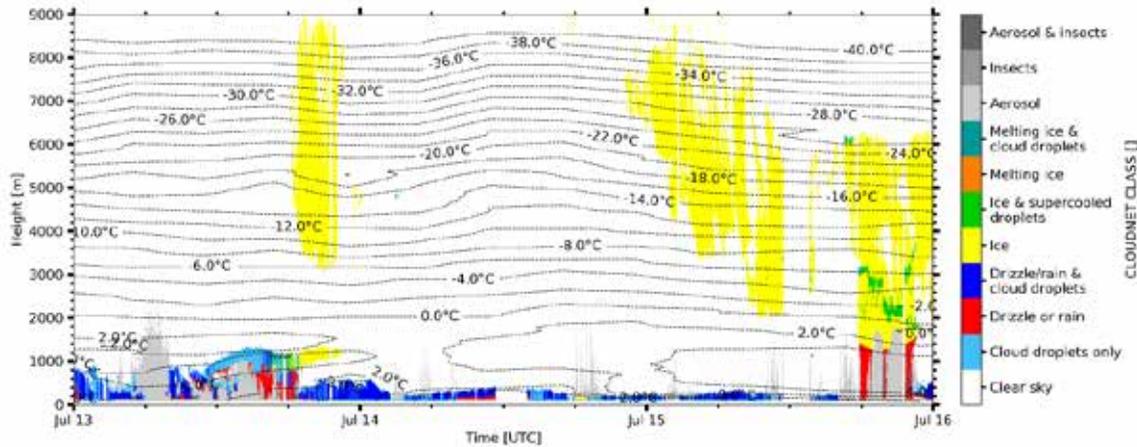


Figure 10. Retrieval of the cloud type classification during 13-16 July using the Cloudnet algorithm applied by TROPOS. This classification uses the ARM KAZR data in addition to other data from collaborating institutions.

Detailed cloud measurements from autumn 2019 (Figure 11) reveal the complexity of cloud types observed over MOSAiC, including classic shallow mixed-phase clouds (i.e., days 321-323) and deep storms with significant precipitation (i.e., days 336-340), among many others. The complementary nature of ARM measurements enables a straightforward assessment of cloud phase and a clear identification of the presence of supercooled liquid water (e.g., Shupe 2007). Consistent with previous arctic observations made at ARM’s North Slope of Alaska site and elsewhere, a clear bimodal state of surface longwave radiation is driven by the presence, or absence, of these liquid-containing clouds. When liquid is present, the net surface longwave radiation is small (i.e., downwelling nearly matches upwelling). However, when liquid-containing clouds are absent, the atmospheric emitted radiation is significantly decreased relative to surface cooling, and there is a deficit of 40 to 60 W/m² of longwave radiation at the surface (i.e., Figure 11d). Detailed cloud observations of this type will be the foundation for numerous large-eddy simulation model studies to examine the formation, evolution, and impacts of arctic mixed-phase clouds.

MOSAiC’s detailed observations provide additional insight into how these cloud-driven radiative states impact other surface energetic terms. Initial relationships (Figure 12) show that in response to cloud radiative warming in winter, the surface sensible heat flux responds by cooling the surface by ~10 W/m². The remaining energy goes into increasing the surface temperature by an average of 7 °C, which impacts near-surface stratification, while also diminishing the upward conduction of heat from the warm ocean to the ice surface. Based on measurements at multiple sites, it is clear that snow depth modifies these processes locally, and importantly modulates the amount of heat conducted through the sea ice. Overall, these cloud-driven processes modify the temperature structure of the sea ice (not shown), while inhibitions of conductive heat flux diminish the heat lost at the bottom of the ice, which is responsible for ice growth. Many of these surface energetic process relationships, such as that between net longwave radiation and sensible heat flux, are being used to perform a process-based assessment of many arctic regional and global models in coordination with the World Meteorological Organization Polar Prediction Project’s Year of Polar Prediction.

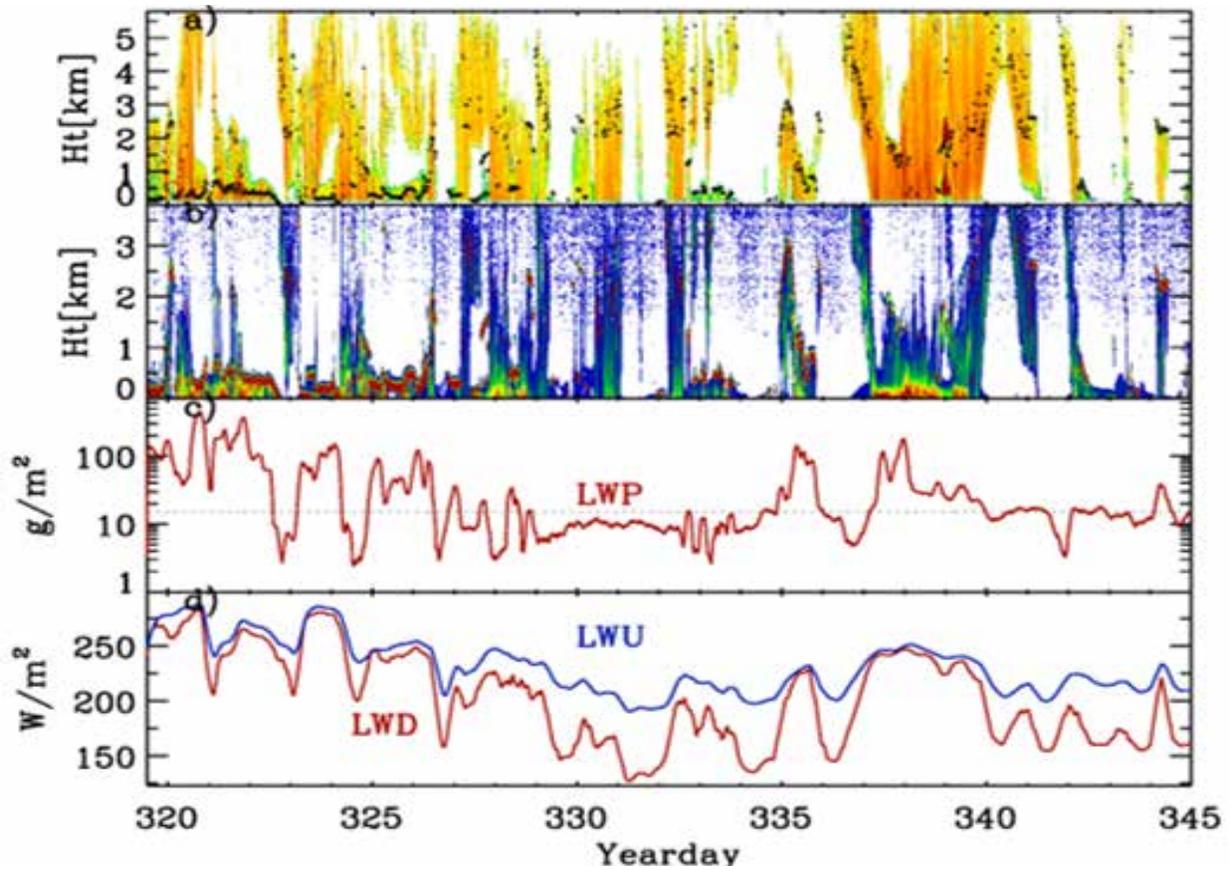


Figure 11. Observations from October into November of 2019, including a) cloud radar reflectivity, b) lidar backscatter, c) liquid water path derived from microwave radiometers, and d) surface downwelling (red) and upwelling (blue) longwave radiation.

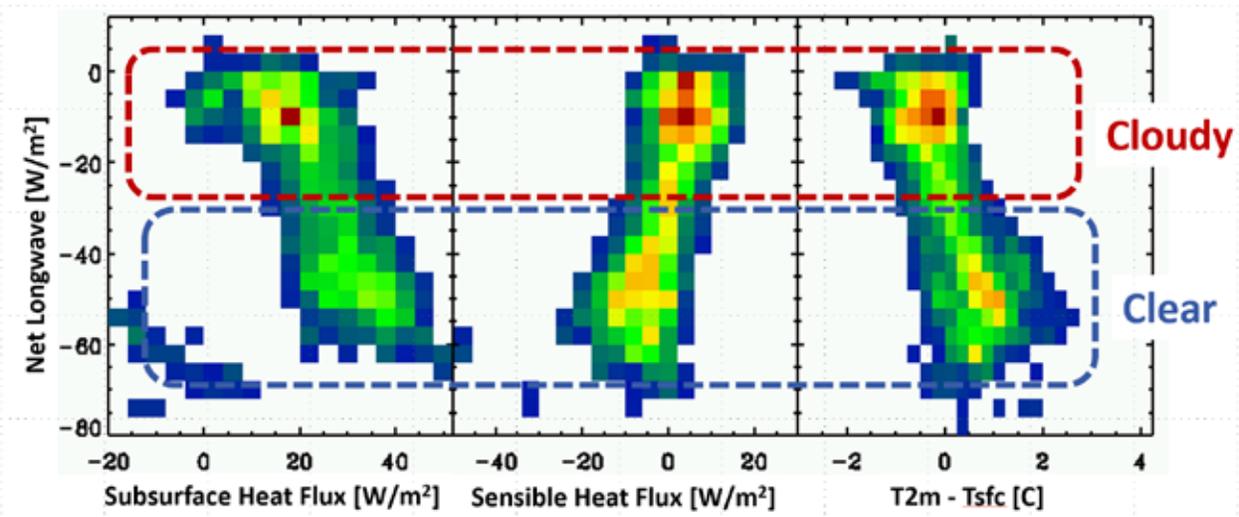


Figure 12. Relationships between net surface longwave radiative flux and the subsurface conductive heat flux, sensible heat flux, and near-surface temperature gradient. The two states including cloud liquid water (“Cloudy”) and not including cloud liquid water (“Clear”) are highlighted.

Precipitation. Measurements of snowfall are difficult due to the slow fall speeds of snowflakes relative to the effects of horizontal winds, as well as the complicating effects of blowing snow relative to falling snow. To help constrain snowfall at MOSAiC, ARM deployed numerous sensors for measuring snow, including laser disdrometers, present weather detectors (PWD), and a Pluvio2 weighing gauge, both onboard *Polarstern* and at Met City on the sea ice. Additionally, ARM’s KAZR radar can be used to derive snowfall via reflectivity-based retrievals (e.g., Matrosov 2007). Through a partnership with the Swiss Federal Institute for Forest, Snow, and Landscape Research, an assessment of ARM’s various snowfall estimates was conducted through comparison with estimates of the surface snow water equivalent (SWE) derived from physical samples, manual measurements of density, and transects of snow depth. The analysis incorporated additional measurements of near-surface winds and particle concentrations to assess the potential role of blowing snow and snow redistribution on the comparisons of snowfall over the winter accumulation season.

Results of this snow analysis (Figure 13; Wagner et al. 2021), when also considering erosion of snow from the surface, suggest that the PWD that was mounted onboard the *Polarstern* was potentially the most accurate measure of snowfall reaching the surface, in part because this sensor was installed at a relatively high altitude that likely limited the adverse impacts of blowing snow. Additionally, the radar-based retrieval of snowfall also proved to be quite reliable, likely also because of the higher altitude of derived snowfall. Beyond a simple assessment of methods, this study also provided an important, process-based perspective on snow over the MOSAiC winter that included documenting the impact of storms on snow accumulation, blowing snow and erosion of the surface, compaction, and other processes. For example, it is estimated that at certain times of the year at least 50% of the atmospheric snowfall is eroded away over time, which has an important implication on the potential insulative effects on the sea ice. Beyond this observational analysis, these results have also contributed to a model-based paper that examines the spatial distribution and re-distribution of snow on sea ice (Hames et al. 2021).

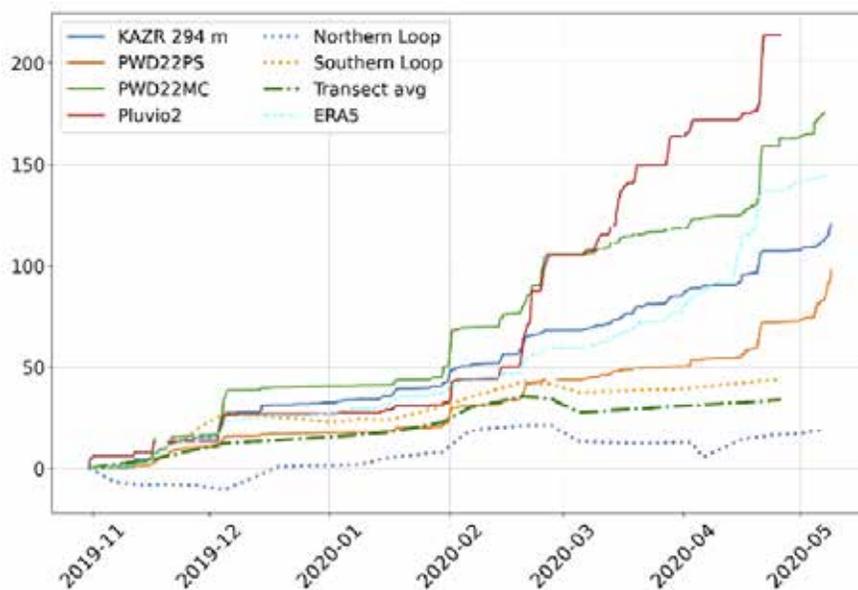


Figure 13. Cumulative snowfall, in mm of SWE, from multiple ARM sensors, derived from the ARM KAZR, snow depth measurements along multiple transects on the sea ice, and from the ERA5 reanalysis product. Note that the transect SWE values can be affected by erosion of snow during wind events, particularly in the spring. Figure from Wagner et al. (2021).

Boundary-Layer Processes. Multiple groups are engaged in studies of the atmospheric boundary layer and its interactions with the surface, including studies that use ARM measurements as well as measurements from collaborating projects. These studies include the use of both uncrewed aircraft systems and tethered balloons (both from collaborating projects) to examine detailed boundary-layer structure, its relation to cloudiness, its impact on atmospheric turbulent mixing, and its influence on surface energy fluxes. Additionally, an international team is developing a comprehensive view of boundary-layer winds during MOSAiC. This effort will incorporate ARM's beam-steerable radar wind profiler and Doppler lidar, both of which performed better than expected in this environment, where signals are typically weak. These wind measurements will help to examine processes such as the formation of low-level jets, and can also be coupled to surface momentum flux estimates to quantify the atmospheric forcing of ice motion. Looking in more detail at this surface interaction, one research team is leveraging ARM observations to study how this atmospheric forcing affects mesoscale sea ice dynamics, including the relation between divergence in the atmosphere and ice pack. Lastly, ARM boundary-layer measurements are contributing to preliminary modeling studies of the low-atmosphere structure, both during the very stable conditions experienced at times in winter, and during spring and summer when leads in the ice can modify surface turbulent heat exchange and might have implications for atmospheric mixing and moisture.

4.0 Public Outreach

For many reasons, MOSAiC has been a tremendous opportunity for public outreach through numerous channels and to many communities. The Arctic itself is an extreme and photogenic location, with amazing natural scenes, adventurous experiences, and exciting science, all of which is appealing and compelling to a broad audience. Additionally, the international nature of MOSAiC also broadened the base of interest. As such a large, international project, there was a lot of emphasis on outreach including dedicated outreach coordination efforts through a collaboration between the expedition's lead institution (AWI) and PI Shupe's team at the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado and the National Oceanic and Atmospheric Administration (NOAA). These various avenues for outreach fall into the following categories.

4.1 Web Presence

The main MOSAiC web page (<http://www.mosaic-expedition.org>) was initially built and maintained by PI Shupe, but was eventually handed off to AWI for further development and management. This web page provides extensive details about the project and had a nice map feature during the field year where the public could follow the progress of *Polarstern* as it drifted across the Arctic, including daily updates on field conditions, an updated blog posting, and relevant photos. An additional web site was established at the University of Colorado (<http://mosaic.colorado.edu>), primarily as a source of information on MOSAiC-related education and outreach activities. MOSAiC activities have also been featured prominently on the ARM web page via many articles and photo collections that highlighted numerous MOSAiC participants and their science, including (partial list):

- <https://www.arm.gov/news/features/post/52304>
- <https://www.arm.gov/news/blog/post/54709>
- <https://www.arm.gov/news/blog/post/58450>

- <https://www.arm.gov/news/blog/post/58781>
- <https://www.arm.gov/news/blog/post/59439>
- <https://arm.gov/news/facility/post/65360>
- <https://www.arm.gov/news/blog/post/66691>
- <https://www.arm.gov/news/blog/post/66754>
- <https://www.arm.gov/news/blog/post/66785>
- <https://www.arm.gov/news/facility/post/68016>

In addition, PI Shupe contributed more than 60 entries to a field blog entitled “Postcards from a Frozen Icebreaker” (<https://blogs.agu.org/thefield/2019/10/16/postcards-from-a-frozen-icebreaker-part-1/>) hosted by the American Geophysical Union that followed MOSAiC activities in the field during Legs 1 and 4.

4.2 Press Conferences

MOSAiC has been the focus of multiple press conferences or press workshops, including important exposure for the ARM role in MOSAiC. These include MOSAiC-specific press conferences at the 2019 and 2020 American Geophysical Union fall meetings, a press conference at the launch of MOSAiC in Tromsø, Norway on 20 September 2019, and a virtual press conference for U.S. journalists at the end of the MOSAiC field operations on 12 October 2020.

4.3 Media

The ARM MOSAiC team has engaged many media outlets and platforms over the course of the project, providing dozens of interviews leading to coverage in the New York Times, the Associated Press, National Public Radio, Washington Post, Arctic Today, E&E News, Scientific American, Science, Nature News, Inside Climate News, National Geographic, the British Broadcasting Corporation, Carbon Brief, Gizmodo, Vice News, Al Jazeera English, China Global Television Network, Westwood One Radio, Colorado Public Radio, and many other international and national print, radio, television, and podcast outlets.

4.4 Video

Multiple documentaries have been produced about MOSAiC. An onboard production team obtained a great deal of high-quality footage that has been the foundation for a full-length MOSAiC documentary released in Germany in late 2020. A related English-language documentary has also been developed by Wild Blue Media (United Kingdom) and is being released to many international markets during 2021, including in the United States (anticipated September 2021). In addition to these conventional documentaries, the CIRES team has also produced two 27-min planetarium films. These films are being released to the international network of planetaria for use (free of charge), as well as being released in 360-degree and flat-screen versions online (the first show is now available: <https://www.youtube.com/watch?v=nAq9szCpWpY>). The COVID-19 pandemic has delayed the premiers of these planetarium shows, but initial plans are underway for releases in Boulder, Colorado in fall 2021 and in Washington, D.C. in early 2022. These planetarium shows will also support outreach efforts of individual MOSAiC scientists in their own communities.

4.5 Education

The CIRES team engaged in multiple high-impact educational efforts. Shupe and a colleague Anne Gold co-developed a Massive Open Online Course entitled “Frozen in the Ice – Exploring the Arctic” that featured a collection of recorded educational videos cutting across six relevant scientific themes all linked to MOSAiC, including clouds, radiation, and many other processes of specific interest for DOE. The course, with 50 modules, has had more than 16,000 unique visitors and 2,850 participants enrolled thus far. Additionally, the CIRES team developed educational curricula for K-12 classrooms, hosted workshops for teachers at the American Geophysical Union (AGU) Fall Meeting, facilitated many interactions between MOSAiC scientists and classrooms, and sent out a weekly newsletter called “MOSAiC Mondays” to a large mail list of teachers who incorporated MOSAiC-themed curriculum into their teaching. Lastly, the CIRES team has served to coordinate dialog across the MOSAiC consortium by facilitating a “Broader Impacts Network” that supports the sharing of outreach content.

4.6 Public Outreach

The ARM-MOSAiC investigator team has given numerous presentations to different communities on the science and experience of MOSAiC, and these routinely describes the role that DOE has played in MOSAiC. These include presentations to multiple high school groups, a multi-part engagement with the online “Reach the World/Exploring by the Seat of Your Pants” group that services many K-12 classrooms nationally and internationally, public presentations at many venues, lectures at University of Colorado post-graduate classes, a panel discussion at the Futurium museum, a keynote presentation for the National Ocean Sciences Bowl competition, and many others.

5.0 MOSAiC Publications

Since it is now only six months since the end of the MOSAiC field campaign, only a few submitted publications thus far feature ARM data. However, the data is being used in many studies that will lead to eventual publications. Additionally, many presentations have highlighted ARM data from MOSAiC.

5.1 Journal Articles/Manuscripts

Three scientific manuscripts have been submitted that use ARM data from MOSAiC:

1. Engelmann, R, A Ansmann, K Ohneiser, H Griesche, M Radenz, J Hofer, D Althausen, I Veselovskii, C Jimenez, R Wiesen, H Baars, J Buhl, H Gebauer, M Haarig, P Seifert, U Wandinger, and A Macke. 2021. “Profiling of wildfire smoke in the troposphere and stratosphere, of Arctic haze, and of embedded cloud layers over the North Pole region during MOSAiC 2019-2021: An introductory.” *Atmospheric Chemistry and Physics*, submitted.
2. Wagner, D, MD Shupe, OG Persson, T Uttal, M Frey, A Kirchgaessner, M Schneebeli, M Jaggi, AR Macfarlane, P Itkin, S Arndt, S Hendricks, D Krampe, R Ricker, J Regnery, N Kolabutin, E Shimanshuck, M Oggier, I Raphael, and M Lehning. 2021. “Snowfall and snow accumulation processes during the MOSAiC winter and spring season.” *The Cryosphere*, submitted.

3. Hames, O, M Jafari, DN Wagner, I Raphael, D Clemens-Sewall, C Polashenski, MD Shupe, M Schneebeli, and M Lehning. 2021. “Modelling the small-scale deposition of snow onto structured Arctic sea ice during a MOSAiC storm.” *Geoscientific Model Development*, submitted.

The first of these uses ARM radar measurements to derive ice cloud properties in support of research into smoke aerosols and ice clouds. The second uses multiple ARM precipitation measurements as well as ARM radar measurements to derive multiple estimates of snowfall for comparison with surface snow accumulation. The third builds upon the second, using some of the same data, and then incorporates a model to represent the spatial distribution, and redistribution, of snow on the surface. In addition to these papers, ARM data is heavily featured in an overview manuscript that is being prepared for the MOSAiC atmosphere program that should be submitted by July 2021.

Shupe, M, and coauthors. 2021. “Overview of the MOSAiC Expedition – Atmosphere.” *Elementa*, to be submitted.

5.2 Meeting Abstracts/Presentations/Posters

Presentations including ARM measurements from MOSAiC have been given at many meetings and conferences to date, demonstrating the wide reach and potential impact of these measurements. A partial list of presentations includes:

Barry, W, T Hill, J Creamean, P DeMott, and the MOSAiC field team. 2021. Tracking ice nucleating particles in the central Arctic during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) experiment. Arctic Science Summit Week, virtual online, 24-26 March.

Creamean, J, T Hill, K Barry, and P DeMott. 2020. Evaluation of ice nucleating particles and their sources in the central Arctic during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) experiments. AGU Fall Meeting, virtual online, 1-17 December.

Creamean, J, T Hill, K Barry, P DeMott, and the MOSAiC field team. 2021. Evaluation of ice nucleating particles and their sources in the central Arctic during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) experiment. American Meteorological Society annual meeting, virtual online, 11-14 January.

Creamean, J, T Hill, K Barry, P DeMott, and the MOSAiC field team. 2021. Evaluation of ice nucleating particles and their sources in the central Arctic during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) experiment. Arctic Frontiers meeting, virtual online, 1-4 February.

Persson, O, M Shupe, G de Boer, D Perovich, J Haapala, J Graeser, A Solomon, C Cox, and J Hutchings. 2020. Structure of Arctic cyclones during MOSAiC and their surface impacts. AGU Fall Meeting, virtual online, 1-17 December.

Shupe, M. 2020. Challenges and opportunities of a year in the Arctic sea ice. Interagency Arctic Research Policy Committee – General community. 8 October.

Shupe, M. 2020. Challenges and opportunities of a year in the Arctic sea ice. Interagency Arctic Research Policy Committee – Joint committee meeting. 19 October.

Shupe, M. 2020. Challenges and opportunities of a year in the Arctic sea ice. DOE Biological and Environmental Research Advisory Committee. 23 October.

Shupe, M, O Persson, C Cox, M Gallagher, T Uttal, D Costa, J Osborn, SM Morris, A Solomon, and DK Perovich. 2020. Cloud influences on the surface energy budget at MOSAiC. AGU Fall Meeting, virtual online, 1-17 December.

Shupe, M, O Persson, C Cox, M Gallagher, T Uttal, D Costa, J Osborn, S Morris, A Solomon, and D Perovich. 2021. Cloud influences on the surface energy budget at MOSAiC. Arctic Frontiers, Tromso, Norway, 1-4 February.

Shupe, M. 2021. Atmosphere Observations during MOSAiC. National Center for Atmospheric Research (NCAR), Polar Climate Working Group. 10 February.

Shupe, M. 2021. Challenges and opportunities of a year in the Arctic sea ice. US Climate Variability and Predictability (CLIVAR) Program, Process Study and Model Improvement (PSMI) panel. 23 February.

Shupe, M, M Rex, and the MOSAiC ATMOS team. 2021. Atmospheric processes in the Central Arctic during MOSAiC. Arctic Science Summit Week (ASSW), Lisbon, Portugal, 20-26 March.

Shupe, M. 2021. MOSAiC and its data. Interagency Arctic Research Policy Committee – Atmosphere team. 27 April.

Shupe, MD, M Rex, and the MOSAiC ATMOS team, 2021. Atmospheric processes in the Central Arctic during MOSAiC (EGU21-10447). European Geophysical Union virtual, 19-30 April.

Shupe, MD. 2021. A Year in the Arctic Sea Ice. National Ocean Sciences Bowl. 7 May.

Uin, J, SR Springston, and TB Watson. 2021. ARM aerosol and trace gas measurements during the MOSAiC expedition. AGU Fall Meeting, virtual online, 1-17 December.

Wagner, D, M Shupe, O Persson, M Frey, A Kirchgaessner, I Raphael, D Clemens-Sewall, C Polashenski, J Regnery, S Hendricks, M Oggier, G Liston, M Schneebeli, and M Lehning. 2020. Working towards a reliable snowfall estimate on Central Arctic sea ice. AGU Fall Meeting, virtual online, 1-17 December.

Wagner, DN, MD Shupe, O Persson, T Uttal, M Frey, A Kirchgaessner, M Schneebeli, M Jaggi, AR Macfarlane, P Itkin, S Arndt, S Hendricks, D Krampe, J Regnery, R Ricker, N Kolabutin, E Shimanchuck, M Oggier, I Raphael, and M Lehning. 2021. Snow and snow accumulation processes during MOSAiC (EGU21-12692). EGU virtual, 19-30 April.

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