Final Report: Enhanced Atmospheric Research at the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC)

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Abstract

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) was an international scientific expedition into the central Arctic sea ice to study the changing atmosphere-ice-ocean system and its key physical, chemical, and biological processes in a way that will support improved understanding and modeling of Arctic climate. The US Department of Energy's Atmospheric Research Measurement (ARM) Program operated its second ARM Mobile Facility (AMF2) as a major contribution to the expedition, and the Atmospheric System Research (ASR) program supported this project to maximize the success of DOE's involvement in MOSAiC. This project has enabled the successful collection of data through support of field operations plans, in-field operational implementation, oversight of real-time data quality, and representing DOE's interests within the broader international MOSAiC endeavor. The project has promoted scientific research by facilitating and leading a number of efforts to develop value-added products that will support research, including products related to aerosol properties, trace gases, cloud properties, snowfall, the surface energy budget, and a merged product designed for model assessment. These products and related analyses have also contributed to numerous scientific publications on related themes as well as direct model evaluation. Lastly, the project has engaged in a great deal of communication and outreach activities that help to publicize and promote both MOSAiC and DOE's specific contribution to a broad audience that includes the scientific community, program management, policy makers, and the general public.

Review of Project Activities

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) was an international scientific expedition into the central Arctic sea ice to study the changing atmosphere-ice-ocean system and its key physical, chemical, and biological processes. The expedition was designed to understand the many interacting processes that are contributing, and responding, to the rapidly declining Arctic sea ice. Overall, intensive cross-disciplinary field observations were designed to provide foundational knowledge that will enable thorough assessment of model performance in the Arctic, which will lead to improved predictive skill for representing Arctic processes on seasonal to climate scales. While the expedition comprised many different scientific disciplines and international contributions, the US Department of Energy's Atmospheric Research Measurement (ARM) Program operated its second ARM Mobile Facility (AMF2) as a major contribution to the expedition, focused on atmospheric processes. This final report summarizes a project supported by the DOE Atmospheric System Research (ASR) program to provide overall support for the implementation of ARM observations during the expedition, helping to facilitate its operational success, and enabling a broad use of ARM data across the MOSAiC and general research communities.

Over its entirety this project has successfully supported DOE's involvement in MOSAiC, including pre-field, in-field, and post-field support, general outreach, facilitation of data usage, and the derivation of value-added products to enable broader engagement in the use of DOE's MOSAiC data. Project activities are distinguished into different groupings below. From a personnel standpoint, the PI Shupe participated in MOSAiC field operations from mid-Sept 2019 to Jan 2020, and (via distinct funding) from May to Aug 2020. The project's post-doctoral researcher, with partial support from distinct funding, also participated in field activities for approximately 6 months of the expedition. While not supported by this project, the PI had additional team members onsite to support DOE scientific assessment at other times.

***Supporting Successful Operations*.** The PI has been intensely involved in the MOSAiC AMF2 deployment due to its complexity and the fact that ARM activities have been one component of a very large, international collaborative effort. Additionally, the PI is familiar with ARM instrumentation and how to best operate it in challenging Arctic conditions to achieve scientific success. The extensive interaction with AMF2 management and the ARM system has included the following:

- AMF2 Management. The PI engaged in a great deal of general coordination with AMF2 management from Los Alamos National Laboratory to support the design of field operations, prioritization of activities, integration of guest instruments, response to field challenges, day-to-day field implementation, data quality oversight and assessment, offloading of equipment, and much more. In particular, the PI worked with the operations team and instrument mentors to support operational decisions that ensure the best operation of equipment to achieve DOE and MOSAiC science objectives. These included: decisions on instrument installations on the sea ice, radar scan strategies, installations onboard the MOSAiC ship, assessment of the aerosol pollution monitor system, identification of real-time data/instrument issues, etc. Additionally, in the spirit of MOSAiC, there was a great deal of collaborative support including helping to reposition ARM equipment, providing polar bear guarding protection, and other support.
- Data Oversight. The PI maintained communication with members of the ARM data and instrument teams to support oversight and access to data. In the field this included helping to enable on-site scientific personnel access to ARM data and quicklooks, which built early interest

in ARM data. It also involved working with the ARM data quality office to identify ways to improve operational quicklook plots to provide better real-time information for quality assessment. As part of this process, the PI identified numerous potential data issues that were subsequently addressed by ARM infrastructure (i.e., radar calibrations, radar clutter issues, irregularities in microwave radiometer data, problems with pollution identification). After the field operations, the PI also performed extensive quality assessments on a number of ARM data streams, often comparing with independent measurements, which led to various quality assessment responses by the appropriate instrument mentors. He also had routine dialog with the ARM data archive to ensure that all data gaps were either filled with data or documented appropriately otherwise. Lastly, via a multi-year process, the PI was able to work with ARM management and MOSAiC leadership to document a written agreement that officially (in the eyes of MOSAiC) recognizes, and approves, ARM's data management and archival plan.

- Representing DOE. One of the most important PI roles has been to advocate for, and represent, ARM's interests. This advocacy has relied upon pre-existing relationships with key partners and an ability to influence MOSAiC decision-making and leadership. The PI negotiated space for 3 full-year ARM technicians and 8 personnel during installation, which was difficult considering the high demand for space onboard the expedition. Onboard, the PI helped to solve numerous operational challenges by directly advocating for ARM's needs. The PI also advocated strongly for a special airborne evacuation of a small subset of onsite personnel, including one ARM site technician, who needed to get home in spite of COVID-19 limited logistical operations.

Promoting Scientific Research. Over the course of the project, a major focus has been on supporting the broader scientific impacts of DOE's investment in MOSAiC by advertising the value of ARM measurements, supporting targeted value-added data product development, engaging in analysis of data, linking ARM's MOSAiC efforts with other scientific activities, and otherwise helping to expand the user community for ARM data. Specific efforts include:

- Aerosol processes. Throughout the MOSAiC period the PI has engaged the ARM-ASR and MOSAiC communities regarding aerosol measurements and issues. One important topic is local pollution impacts on the measurements themselves, resulting in multiple coordinated efforts to identify pollution that will soon lead to a publication and data guide that will support broader community use of the MOSAiC aerosol measurements. Additionally, the PI has provided analysis using ARM data in support of publications on the first annual cycle of ice nucleating particle concentrations in the central Arctic (Creamean et al. 2022), a detailed assessment of an air mass intrusion into the Arctic bringing strongly enhanced aerosol concentrations (Dada et al. 2022), and the role of blowing snow in aerosol concentrations (Gong et al, in preparation).
- Trace gases. Numerous groups at MOSAiC measured a variety of trace gases, with some overlap. The PI is participating in a collaborative effort to combine the various data sources for a wide range of gases, provide comparative assessment of these sources, and ultimately resulting in a combined data set that uses the best available measurements to provide as complete a record as possible (Angot et al. 2022).
- Surface energy budget. ARM radiation observations are being combined with other surface energy budget measurements from the PI's group (through distinct funding) to produce a comprehensive surface energy budget product for MOSAiC. Development of this combined product has involved multiple ARM mentors and is resulting in a data publication (Cox et al.

2022) and the final, quality-controlled data set will be archived in summer 2022. Additionally, the PI has provided analysis, in part using ARM measurements, to support comparisons of satellite-derived surface radiation with ground-based measurements that will provide significant information on the scales and implications of spatial surface variability (Huang et al. 2022).

- Precipitation. The project has supported two efforts to derive and assess continuous snowfall rate estimates, both using multiple ARM precipitation gauges as well as ARM's cloud radar measurements. The first compares the snowfall precipitation accumulation to independent measurements of snow on the surface, and attempts to interpret discrepancies between these in terms of surface snow erosion and other processes (Wagner et al. 2022). The second provides a thorough assessment of snowfall and derives a consistent product for the winter accumulation season (Matrosov et al. 2022), along with a data product that is available on the ARM data archive.
- Cloud properties. The PI has applied his so-called ShupeTurner cloud microphysics retrieval product to ARM's observations from MOSAiC. This product is currently undergoing its final quality assessment and will be uploaded to the ARM data archive in summer 2022. Similarly, the ARM radar data is being used in other microphysics products, such as the Cloudnet product being implemented by partners from the TROPOS Institute in Germany. Lastly, the PI supported Israel Silber's ASR funded research to examine the atmospheric air mass transformation processes that support the occurrence of liquid-bearing clouds at MOSAiC (Silber and Shupe 2022).
- Broader engagement. Via this project the ARM MOSAiC efforts are also being linked with a number of other key Arctic activities. For example, the COMBLE experiment, which was also funded by DOE, took place at the same time as MOSAiC, offering nice opportunities for spatially comparative analysis. The PI has worked with COMBLE leadership to emphasize research possibilities of this nature (Geerts et al. 2022). Additionally, the PI has maintained strong links with the WMO-sponsored Year of Polar Prediction, which involves many international model centers focused on Arctic system prediction. As part of a collaboration with YOPP, our project team is working to develop so-called Merged Observatory Data Files (MODFs) that will provide MOSAiC data, from ARM and others, in a specialized merged format that is explicitly designed for model assessment in coordination with other YOPP participants. The MOSAiC MODF, along with generalized open-source software for producing MODF files at other observatories, is being developed by the post-doctoral researcher supported by this project, Michael Gallagher. The initial MODF includes information on atmospheric state, surface meteorology and energy budget, precipitation, and cloud properties, and will be finalized by fall 2022. In the future, the MODF framework will expand to include properties of the sea ice, snow, and upper ocean.
- Model assessment. The PI is supporting the use of the products mentioned above in a variety of model assessment activities. For example, the surface energy budget and cloud properties products are the foundation for a process-based model evaluation in collaboration with YOPP wherein the skill of 8 operational models was examined in detail (Solomon et al. 2022). One primary result is that the ability of models to produce accurate cloud properties impacts their ability to represent the surface energy budget over sea ice. These same products are contributing to a detailed model study and assessment related to a major warm air intrusion event that impacted the MOSAiC site in mid-April, also in collaboration with YOPP (Svensson et al., in preparation). Additionally, the surface energy budget information is being used to assess

model biases in a regional model that are dependent on the treatment of the sea ice in the model (Heinemann et al. 2022). Lastly, the precipitation information is contributing to a detailed model study of snow redistribution across the sea ice surface (Hames et al. 2022).

Communicating Results. Another important aspect of this project has been general communication about MOSAiC, and DOE's role in it, to a broad audience including other scientists, scientific management, policy makers, and the general public. From a technical standpoint, the PI has authored the Science Plan for ARMs involvement in MOSAiC (Shupe et al. 2018), authored the ARM field campaign report (Shupe et al. 2021), served as the chief author and editor of the overall MOSAiC Science Plan (https://mosaic-expedition.org/wp-content/uploads/2020/12/mosaic_scienceplan.pdf), and authored/co-authored overview publications highlighting the primary atmospheric (Shupe et al. 2022), sea ice and snow (Nicolaus et al. 2022), and ocean (Rabe et al. 2022) research conducted as part of MOSAiC.

Over the course of the project, the PI has given multiple 10's of presentations on MOSAiC to many different audiences. Overview presentations have been given to scientific audiences at ARM-ASR science meetings, the Arctic Science Summit Week, annual meetings of the American Geophysical Union and the European Geophysical Union, the International Symposium on Arctic Research, the Arctic Frontiers conference, the Arctic Connect conference, and others. Seminars have been given at Stockholm University, the University of Leipzig, the Geophysical Fluid Dynamics Laboratory, the Physical Sciences Laboratory, and the NCAR Polar Climate Working Group. Briefs have been provided to a CLIVAR panel and to the Interagency Arctic Research Policy Committee (4 times), as well as a full brief and scientific presentation to the DOE Biological and Environmental Research Advisory Committee (BERAC). Finally, the PI has given a large number of public lectures to entities like the Rotary Club, outreach to educational institutes ranging from K-12 through graduate school, engaged in multiple online educational networks, and provided a keynote lecture at the National Ocean Sciences Bowl. Through all of these outlets, DOE's investment in MOSAiC has been highlighted.

Additionally, the PI has been heavily involved in various media activities and outlets that serve to publicize MOSAiC and DOE's participation in it. These outlets are too numerous to list here but include national and international print, radio, television, and online outlets (some of which are listed at https://www.arm.gov/research/campaigns/amf2019mosaic/media). Of particular relevance here, however, are direct links with DOE-led communications efforts. The PI has supported numerous DOE and ARM communications activities including press releases, news items, field blogs, photo documentation, science stories, social media posts, and other DOE communications.

Professional Development. A post-doctoral scientist, Michael Gallagher, was funded by the project and has been heavily involved in many aspects of MOSAiC. Through joint funding with another project, he was also able to go to the MOSAiC expedition during two of its legs, gaining special insight into the data collection process that has supported him in working with datastreams and developing products that enable a wide range of analyses. Being in the field also provided him with important perspectives on the interesting science questions that can be addressed using ARM data, including things like the impact of storms on the atmospheric structure and sea ice. Dr. Gallagher has gladly accepted the role of working with ARM and other MOSAiC data, and particularly in developing data products that engage a broader user group into MOSAiC analysis. In this role, he is developing important connections and relationships that are already serving him as he develops his future career path in climate research. Some of the software tools he has produced for developing joint products have garnered some interest from members of ARM infrastructure.

Publications and Products

This project has supported the development of numerous products that will enable broader use of ARM data in scientific research. These products and their status are briefly summarized in the following Table.

Name	**Details**	**Availability; related citation**
Surface energy budget product	Surface radiation, turbulent heat flux, conductive heat flux, near-surface meteorology	Final product anticipated summer 2022 (Cox et al. 2022)
ShupeTurner cloud microphysics product	Cloud phase type and microphysical properties of liquid and ice	Final product anticipated summer 2022
Radar-based snowfall estimates	Continuous estimates of snowfall rate from radar reflectivity	Available on ARM Archive (Matrosov et al. 2022)
Trace gas combined product	Continuous, quality-controlled trace gas concentrations	Final product anticipated during 2022 (Angot et al. 2022)
Merged Observatory Data File	Combined file including atmospheric meteorology, surface energy budget, precipitation, and cloud properties	Final product anticipated fall 2022 (Gallagher et al.)

In addition to these products, the following publications that describe data products and/or scientific analyses have been supported by this project.

Angot, H., B. Blomquist, D. Howard, S. Archer, L. Bariteau, I. Beck, M. Boyer, Z. Brasseur, D. Helmig, J. Hueber, H.W. Jacobi, T. Jokinen, T. Laurila, K. Posman, L. Quelever, M. D. Shupe, and J. Schmale, 2022: Year-round trace gas measurements in the Central Arctic during the MOSAiC expedition. Scientific Data, submitted.

Cox, CJ, M, Gallagher, MD, Shupe, POG, Persson, A, Solomon, T, Ayers, B, Blomquist, IM, Brooks, D, Costa, A, Grachev, D, Gottas, DJ Hutchings, J, Leach, SM Morris, J, Osborn, L, Riihimaki, T, Uttal, 2022: Continuous observations of the surface energy budget and meteorology over Arctic Ocean sea ice during MOSAiC. Scientific Data, submitted.

Creamean, J. M., K. Barry, T. C. J. Hill, C. Hume, P. DeMott, M. D. Shupe, S. Dahlke, S. Willmes, J. Schmale, I. Beck, C. J. M. Hoppe, A. Fong, E. Chamberlain, J. Bowman, R. Scharien, O. Persson, 2022: First annual cycle observations of aerosols that seed ice formation in central Arctic clouds. Nature Communications, submitted.

Dada, L., H. Angot, I. Beck, A. Baccarini, L.L.J. Quelever, M. Boyer, T. Laurila, Z. Brasseur, G. Jozef, G. de Boer, M. D. Shupe, S. Henning, S. Bucci, M. Duetsch, A. Stohl, T. Petaja, K. R. Daellenbach, T. Jokinen, and J. Schmale, 2022: A Central Arctic extreme aerosol event triggered by a warm air-mass intrusion. Nature Communications. Submitted.

Geerts, B., S. E. Giangrande, G. M. McFarquhar, L. Xue, S. J. Abel, J. M. Comstock, S. Crewell, P. J. DeMott, K. Ebell, P. Field, T. C. J. Hill, A. Hunzinger, M. P. Jensen, K. L. Johnson, T. W. Juliano, P. Kollias, B. Kosovic, C. Lackner, E. Luke, C. Lupkes, A. A. Matthews, R. Neggers, M. Ovchinnikov, H. Powers, M. D. Shupe, T. Spengler, B. E. Swanson, M. Tjernstrom, A. K. Theisen, N. A. Wales, Y. Wang, M. Wendisch, P. Wu, 2022: The COMBLE campaign: A study of marine boundary-layer clouds in Arctic cold-air outbreaks. Bulletin of the American Meteorological Society. doi:10.1175/BAMS-D-21-0044.1.

Hames, O., M. Jafari, D. N. Wagner, I. Raphael, D. Clemens-Sewall, C. Polashenski, M. D. Shupe, M. Schneebeli, and M. Lehning, 2022: Modelling the small-scale deposition of snow onto structured Arctic sea ice during a MOSAiC storm using snowBedFoam 1.0. Geoscientific Model Development. Submitted.

Heinemann, G., L. Schefczyk, S. Willmes, M.D. Shupe, 2022: Verification of regional climate model simulations of near-surface variables for the MOSAiC winter period. Elementa: Science of the Anthropocene, Submitted.

Huang, Y, P. C. Taylor, F. G. Rose, D. A. Rutan, M. D. Shupe, and M. Webster, 2022: Towards a more realistic representation of surface albedo in NASA CERES satellite products: a comparison with the MOSAiC field campaign. Elementa: Science of the Anthropocene, submitted.

Matrosov, S. Y., M. D. Shupe, and T. Uttal, 2022: High temporal resolution estimates of Arctic and snowfall rates emphasizing gauge and radar-based retrievals from the MOSAiC expedition. Elementa: Science of the Anthropocene, 10(1), doi: 10.1525/elementa.2021.00101.

Nicolaus, M., D. K. Perovich, G. Spreen, M. A. Granskog, L. v. Albedyll, P. Anhaus, M. Angelopoulos, S. Arndt, H. J. Belter, V. Bessonov, G. Birnbaum, J. B. Brauchle, R. Calmer, E. Cardellach, B. Cheng, D. Clemens-Sewall, R. Dadic, E. Damm, G. de Boer, O. Demir, D. Divine, A. Fong, S. Fons, N. Fuchs, C. Gabarró, S. Gerland, R. Gradinger, H. F. Goessling, J. Haapala, C. Haas, J. Hamilton, H.-R. Hannula, S. Hendricks, A. Herber, C. Heuzé, M. Hoppmann, K. V. Høyland, M. Huntemann, J. K. Hutchings, B. Hwang, P. Itking, M. Jaggi, A. Jutila, L. Kaleschke, C. Katlein, N. Kolabutin, D. Krampe, S. S. Kristensen, T. Krumpen, N. Kurtz, A. Lampert, B. A. Lange, R. Lei, B. Light, F. Linhardt, G. Liston, B. Loose, A. R. Macfarlane, M. Mahmud, I. O. Matero, S. Maus, A. Morgenstern, R. Naderpour, V. Nandan, A. Niubom, M. Oggier, N. Oppelt, F. Pätzold, T. Petrovsky, R. Pirazzini, C. Polashenski, B. Rabe, I. A. Raphael, J. Regnery, M. Rex, R. Ricker, K. Riemann-Campe, A. Rinke, J. Rohde, E. Salganik, R. K. Scharien, M. Schiller, M. Schneebeli, M. Semmling, I. Sheikin, E. Shimanchuk, M. D. Shupe, M. M. Smith, V. Smolyanitsky, V. Sokolov, J. Sokolova, T. P. Stanton, J. Stroeve, A. Tavri, L. Thielke, A. Timofeeva, R. T. Tonboe, M. Tsamados, D. N. Wagner, D. Watkins, M. Webster, M. Wendisch, 2022: Overview of the MOSAiC expedition: Snow and Sea Ice. Elementa: Science of the Anthropocene, 10(1), doi:10.1525/elementa.2021.000046.

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