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The Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC) Atmosphere Science Plan

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ARM
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Executive Summary

Arctic climate change is amplified relative to global change, and is embodied by a dramatic decline in the perennial sea-ice pack. These cryospheric transitions carry significant implications for regional resource development, geopolitics, and global climate patterns. Indeed, the changing arctic cryosphere is considered a grand challenge for global climate research. Arctic change, and its linkages with the global system, must be understood. Additionally, there is a growing stakeholder community that requires improved sea-ice forecasting for many applications. To make progress on these important issues requires developing a detailed, process-level understanding of the coupled climate system that can help to address the numerous deficiencies in numerical model representations of the Arctic. Such an understanding is only possible by making targeted, interdisciplinary measurements within the central arctic sea-ice environment.

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) initiative has been developed in response to these great challenges. It comprises three parts: 1) An intensive, icebreaker-based observatory that will freeze in, and drift with, the arctic sea ice for a full annual cycle making interdisciplinary measurements in the atmosphere, sea ice, upper ocean, and biosphere; 2) A distributed network of targeted, autonomous measurements to characterize spatial variability on model grid-box scales; and 3) Coordinated, multiscale analysis and modeling activities. MOSAiC is a major, international effort that will involve participation of many different agencies and entities. The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility is uniquely positioned to play a critical role in this initiative by providing a comprehensive instrument suite to characterize the atmosphere and its interactions with the sea-ice surface. ARM will deploy its second Mobile Facility (AMF2) and Mobile Aerosol Observing System (MAOS) at the MOSAiC central observatory as it drifts through the central Arctic for a 13-month campaign starting in September 2019.

Sea-ice is an integrator of energy fluxes in the coupled arctic climate system; thus, atmosphere-ice-ocean processes impacting the flow of energy through this system in all seasons are the primary target of MOSAiC. The broader, collaborative MOSAiC initiative will allow for many interdisciplinary studies along this theme. ARM's involvement will target specific areas related to the atmosphere and atmosphere-surface interactions that are critically under-observed in the Arctic, are leading contributors to model uncertainties in the region, and are programmatically important to DOE research and modeling programs. The guiding science themes for this project include: (1) The surface energy budget of sea ice; (2) Clouds and precipitation; (3) Aerosols; and (4) The atmospheric boundary layer. Many fundamental issues concerning these themes are lacking in observational constraints, particularly in the arctic winter and through consecutive seasons. For example, little is known about the energy budget of first-year sea ice, the annual cycle of central arctic aerosol concentrations, the spatial organization of cloud-precipitation systems relative to sea-ice heterogeneity, the winter boundary-layer evolution, or cloud-surface coupling processes over sea ice. The proposed ARM observations will be groundbreaking in many ways, and will ultimately have a dramatic impact on the arctic research community and its ability to represent coupled arctic processes in numerical models.

Acronyms and Abbreviations

ABL	atmospheric boundary layer
ACSM	aerosol chemical speciation monitor
AMF2	second ARM Mobile Facility
AOS	aerosol observing system
ARM	Atmospheric Radiation Measurement
ARSCL	Active Remote Sensing of Clouds
AWARE	ARM West Antarctic Radiation Experiment
AWI	Alfred Wegener Institute
BER	Office of Biological and Environmental Research
BSRWP	beam steerable radar wind profiler
CCN	cloud condensation nuclei
CCN100	single-column cloud condensation nucleus counter
CCN200	double-column cloud condensation nucleus counter
CESD	Climate and Environmental Sciences Division
COMBLE	Cold-air Outbreak in the Marine Boundary Layer Experiment
CPC	condensation particle counter
DOE	U.S. Department of Energy
ECOR	eddy correlation system
GNDRAD	ground radiation measurement suite
HSRL	high-spectral-resolution lidar
HTDMA	hygroscopic tandem differential mobility analyzer
IASC	International Arctic Science Committee
IPCC	Intergovernmental Panel on Climate Change
IR	infrared
KAZR	Ka-band ARM Zenith Radar
LW	longwave radiation
MAERI	marine atmospheric emitted radiance interferometer
MAOS	mobile aerosol observing system
MFRSR	multi-filter rotating shadowband radiometer
MMCG	merged moments on a Cartesian grid
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
MPL	micropulse lidar
MWACR	Marine W-band ARM Cloud Radar
MWR	microwave radiometer
MWRRET	microwave radiometer retrieval

MWR3C	3-channel microwave radiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
ONR	Office of Naval Research
P	pressure
PI	Principal Investigator
PSAP	particle soot absorption photometer
QCRAD	Quality-Controlled Radiation Value-Added Product
RH	relative humidity
SACR	Scanning ARM Cloud Radar
SEB	surface energy budget
SKIP	Self-Kontained Instrument Platform container
SKYRAD	sky-viewing radiation suite
SMPS	scanning mobility particle sizer
SP2	single-particle soot photometer
SW	shortwave radiation
T	temperature
TROPOS	Leibniz Institute for Tropospheric Research
u-CPS	ultrafine condensation particle counter
UHSAS	ultra-high-sensitivity aerosol spectrometer
VAP	value-added product
WACR	W-band ARM Cloud Radar
WMO	World Meteorological Organization
YOPP	Year of Polar Prediction

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1.0 Introduction

Earth's climate system is changing as a result of increased greenhouse gas concentrations and associated net warming effects. This warming is particularly pronounced in the Arctic, where temperatures are rising at more than twice the global rate (Hansen et al., 2010), and are expected to warm much more in coming decades. This so-called Arctic Amplification has been largely attributed to regional feedbacks associated with a changing cryosphere (e.g., Serreze and Barry 2011; Screen and Simmonds 2010), and makes the Arctic an ideal laboratory for studying the manifestation of global change.

An early and visible sign of global and arctic change is the dramatic decline in sea ice over recent decades (Comiso 2002; Stroeve et al., 2007). September annual minimum sea ice extent reached record minima in 2005, 2007, and 2012, with 2012 showing a 49% decrease relative to the 1979-2000 median (Overland and Wang 2013; Figure 1). In addition to being less spatially extensive, the ice pack is also becoming younger and thinner (Kwok and Rothrock 2009; Maslanik et al., 2011), and first-year ice now comprises 70% of the ice area (J. Maslanik, pers. comm. 2013). These changes invoke important feedback processes related to the surface reflectivity, sea ice drift and deformation, ice growth, productivity of ocean waters, sources of atmospheric moisture, and more.

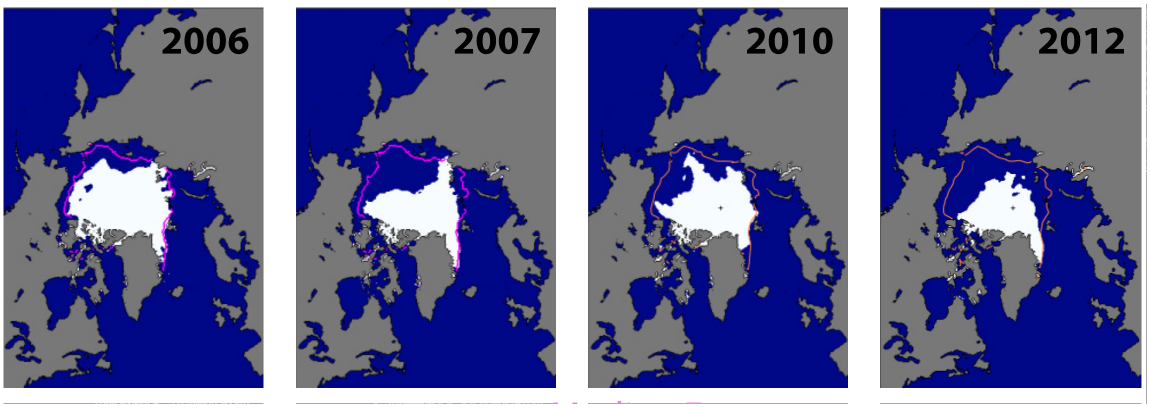

Figure 1. September minimum sea ice extent for four different years, compared to the 1979-2000 median (magenta contour). Images courtesy of the National Snow and Ice Data Center (nside.org).

This transitional Arctic has spurred a new generation of stakeholders and interest groups. The shrinking ice pack offers new opportunities for regional commercial interests, including cargo transportation and resource development, which require an ability to understand and forecast sea ice properties. Arctic ecosystems and communities are also affected by observed changes (e.g., Arrigo et al., 2008; Grebmeier et al., 2010). Additionally, repercussions of arctic change extend beyond arctic boundaries, potentially impacting lower-latitude weather. Decreased sea-ice coverage modifies ocean heat storage and release, impacting atmospheric thickness and large-scale circulation patterns (Overland and Wang 2010; Francis and Vavrus 2012). Such changes have been implicated in amplification of the Siberian High, leading to cold conditions and redistributed rainfall in East Asia (Honda et al., 2009; Wu et al., 2009), cold winters in Europe (Yang and Christensen 2012), and increased early winter snowfall in North America and Europe (Liu et al., 2012). Large-scale consequences of arctic sea ice decline have been linked to circulation and precipitation changes as far south as the tropics (Budikova 2009).

In spite of these implications of arctic change, significant deficiencies remain in our understanding of arctic climate processes. Recent model simulations of September sea-ice extent used for the Intergovernmental Panel for Climate Change (IPCC) 5th Assessment Report show results that are closer to observed trends than previous assessments (Stroeve et al., 2012), yet there continues to be an alarmingly large spread in model predictions that is not decreasing. The IPCC 4th Assessment Report (Solomon et al., 2007) shed some light on persistent model deficiencies and the limited progress in recent years, noting that “Arctic climate is characterized by a distinctive complexity due to numerous nonlinear interactions between and within the atmosphere, cryosphere, ocean, land, and ecosystems.” Natural variability in arctic systems, coupled with amplifying effects of interdependent feedbacks, makes detection and attribution of arctic change difficult. The report further notes the “serious problem” associated with a lack of observational data appropriate for developing process-level knowledge and assessing and developing models. Specific deficiencies are noted in understanding cloud, boundary-layer, sea-ice, and upper-ocean processes and their coupling. If not addressed, these deficiencies will continue to limit progress in characterizing arctic change and improving model predictions. As a result, Kattsov et al. (2010) have named understanding arctic sea-ice changes as one of the “grand challenges” in climate science and proclaimed that concerted efforts are needed to obtain meaningful predictions of arctic sea-ice conditions in coming decades. This grand challenge requires integrated and focused observational efforts coordinated with hierarchical regional climate modeling that aims to understand arctic sea ice, atmosphere, and ocean processes in a holistic, coupled manner (Maslowski et al., 2012).

2.0 MOSAiC Concept —An Overview

Motivated by this significant challenge, the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) initiative will be conducted in the central Arctic to specifically develop and further the required coupled-system knowledge. To achieve this goal, MOSAiC will entail year-round, coordinated, and comprehensive measurements, extending across the central arctic atmosphere-sea-ice-ocean system to provide a foundation for the needed process-level understanding of the changing arctic physical and biogeochemical systems. This foundation will serve as a means to improve models for hemispheric weather forecasting, assessment of ecosystem change, long-term arctic system prediction, and forecasting of sea ice. Acknowledging the central role of cryospheric change, the MOSAiC initiative is organized around the question: ***What are the causes and consequences of an evolving and diminished arctic sea-ice cover*?**

The design of MOSAiC fully integrates observational and modeling activities to ensure and facilitate improved model representations. Numerous workshops since 2011 have crystallized the high-priority modeling needs and deficiencies that can uniquely be addressed through MOSaiC. These form a basis for specific research questions that guide specific MOSAiC observational and modeling activities:

1. ***What are the seasonally-varying energy sources, mixing processes, and interfacial fluxes that affect the heat budget of young sea ice?***
2. ***How does sea ice move and deform over the annual cycle?***
3. ***What processes contribute to the formation, precipitation, and maintenance of arctic clouds and their interactions with aerosols and boundary-layer structure?***
4. ***How do interfacial exchange rates, biology, and chemistry couple to regulate ecosystems and the major elemental cycles in the high arctic sea ice?***

5. ***How do ongoing changes in the arctic ice-ocean-atmosphere system impact heat and mass transfers of importance to climate and ecosystems?***

MOSAiC will address these questions over model grid box scales and continuously over a full annual cycle to provide the type of representative information that is effective for promoting model development. MOSAiC is designed with a multi-tiered approach that includes the following:

1. A central observatory based on the German icebreaker *Polarstern* (Figure 2) will passively drift along the Transpolar Drift track for a full year, starting in newly forming sea ice of the northern Laptev Sea in September 2019. Observations made on the ship and at an adjacent ice camp will provide a comprehensive characterization of coupled-system processes associated with all stages of the sea-ice life cycle.

Figure 2. The *Polarstern* research icebreaker from the Alfred Wegener Institute.

2. Surrounding the central observatory will be a distributed network (Figure 3) of autonomous stations, unmanned observing systems, and episodic measurements for characterizing spatial variability and heterogeneity on model grid-box scales (+/- 15-40 km), and supporting upscaling of key process information.
3. Coordinated, multi-scale, observational and modeling activities will be employed for coupled-system analysis and synthesis.

The German Alfred Wegener Institute (AWI) is providing the *Polarstern* for 13 months with 45 berths available for science. AWI will facilitate logistical support for *Polarstern* and MOSAiC science via a "berth fee" levied on 26 available international berths. Support for resupply operations will be provided by China, Russia, and potentially Sweden. All of these experimental design elements have been described in great detail by an international team of investigators, led by the PI Shupe, in publicly released MOSAiC Science and Implementation Plans (www.mosaic-expedition.org; MOSAiC consortium 2016; 2017). These have undergone a public comment period and overarching review by the International Arctic Science Committee (IASC).

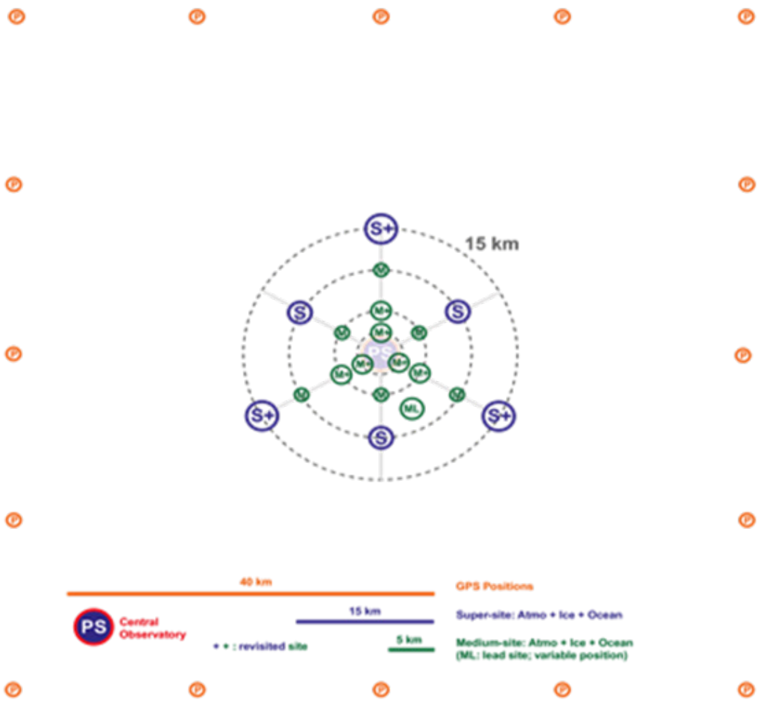

Figure 3. Schematic of the MOSAiC distributed network of observations surrounding the *Polarstern* (PS). Each colored circle is a different type of remote station or buoy.

3.0 MOSAiC Science and ARM's Role

Scientifically, there are many contributions to MOSAiC from as many as 15 different nations representing a wide range of institutions and agencies. The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility is a significant central participant. Scientific contributions from collaborating institutions will be briefly introduced here, followed by a more detailed introduction to ARM's specific role.

AWI and other German scientists will occupy 19 berths onboard *Polarstern* with particular focus on biological, biogeochemical, ocean-profiling, and sea-ice observations. The German contingency is providing numerous ocean and ice-profiling buoys, continuous acoustic measurements of ocean currents, some atmospheric profiling including support for radiosondes, routine helicopter mapping of ice/snow properties, numerous biological analyses, two coordinated aircraft campaigns, onsite scientific logistical support, and other activities.

Internationally there are explicit contributions from Norway, Finland, China, Russia, the United Kingdom, and proposed contributions from Japan, Korea, Sweden, Belgium, the Netherlands, France, Spain, Denmark, and others. These international partners are providing support for vast research including biogeochemical processes, sea-ice properties, snow morphology, aerosol chemical composition, ocean mixing, lead processes, and many others. Internationally, MOSAiC is also strongly linked with the Year of Polar Prediction (YOPP), which is organized by the World Meteorological Organization (WMO). Various YOPP activities will be ongoing from 2017 until beyond the end of MOSAiC, involving operational modeling centers with a host of regional and global model activities that interface with enhanced arctic observation campaigns during the time.

The U.S. has been central to the initial conception and organization of MOSAiC and has provided co-leadership for the endeavor from the beginning. In addition to DOE ARM, multiple other U.S. agencies are involved, including the National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), and National Aeronautics and Space Administration (NASA). These agencies are contributing to surface flux measurements made across the MOSAiC distributed network, measurements of ice optical properties, biogeochemical processes linking ice and ocean, spatial distribution of snow depth, coordination with satellite measurements, process model studies, and quasi-operational coupled-system and sea-ice forecasting. In addition to these direct MOSAiC contributions, multiple aircraft activities are being proposed to coordinated with MOSAiC, potentially supported by NASA, NSF, and the Office of Naval Research (ONR), focusing on various themes related to clouds, radiation, aerosols, arctic cyclones, surface interactions, and long-range advection.

ARM's Participation in MOSAiC. MOSAiC is a major experimental endeavor for which the science drivers dictate the need for operating a sophisticated suite of instruments in an extreme and remote environment for a continuous year. Given that atmospheric processes are at the heart of arctic change, are strongly coupled with the rest of the system, and are a leading contributor to model deficiencies (Tjernström et al., 2008), atmospheric measurements are one of the most important elements of MOSAiC. ARM is particularly well suited to provide the diverse and detailed atmospheric measurements that are needed through the deployment of its second ARM Mobile Facility (AMF2) and Mobile Aerosol Observing System (MAOS) on and around the drifting *Polarstern* during MOSAiC. ARM is uniquely positioned to efficiently provide these measurements due to the comprehensive nature of its facilities and its extensive experience operating in extreme environments (Alaska, Colorado mountains, Antarctica) and from ships. Moreover, the timing and location of MOSAiC bring the opportunity for ARM to coordinate this MOSAiC deployment with other ARM and DOE activities, including the operational ARM measurements occurring at Barrow (known officially as Utqiagvik) and Oliktok Point, Alaska and the recently announced deployment of the first ARM Mobile Facility in the North Atlantic region during the same time period as MOSAiC for the Cold-air Outbreak in the Marine Boundary Layer Experiment (COMBLE). Lastly, these observational activities directly feed into DOE's Arctic-related modeling objectives.

4.0 Science Goals

The involvement of ARM in MOSAiC is guided by a collection of scientific foci that comprise an important contribution to the overall MOSAiC effort. To understand these science drivers, it is informative to consider the fluxes of energy through the arctic system that impact the changing arctic sea ice. Figure 4 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 ~1 Wm^{-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 4, related to spatial/temporal variability and measurement error.

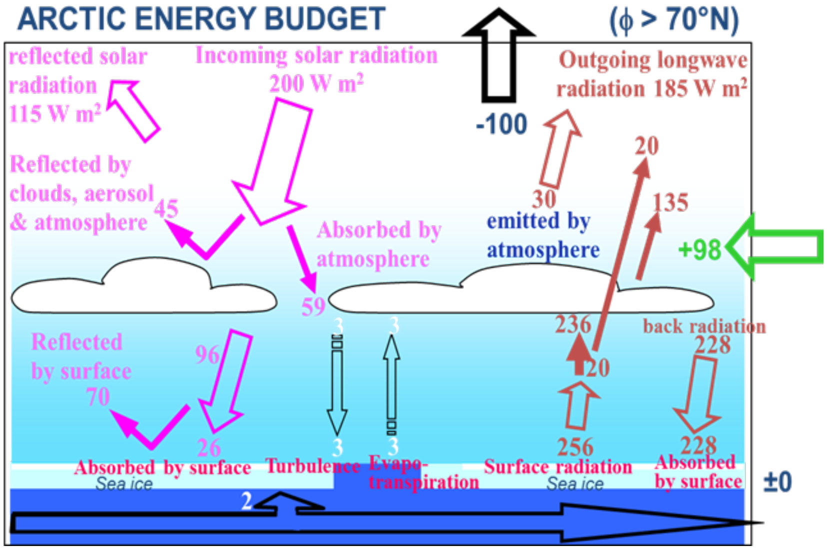

Figure 4. Estimates of regional annual mean arctic energy fluxes over a mostly ice-covered Arctic Ocean assuming a cylinder over the Arctic at approximately 70°N.

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 what we aim to address with the MOSAiC ARM deployment through intensive atmosphere and coupled-system observations in the central arctic ice pack. Primary research themes guiding this project include: the surface energy budget, clouds/precipitation, aerosols, and boundary-layer structure. Each of these inter-related 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.

4.1 Surface Energy Budget

What is the annual evolution of the surface energy budget over young sea ice?

What are the key process interactions determining the surface energy budget?

GOAL: Comprehensive observations to close the surface energy budget and understand its variability in all seasons.

The surface energy budget (SEB) is one of the primary factors controlling the area and mass distributions of central arctic sea ice. It is comprised of 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. 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 other factors. 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. Additionally, there are key feedback processes, such as the ice-albedo feedback, that 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.

4.2 Clouds and Precipitation

What factors determine arctic cloud phase partitioning?

What role do clouds and precipitation play in determining low-level atmospheric structure?

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 in 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.

4.3 Aerosols

How do aerosol physical, chemical, and optical properties over sea-ice vary seasonally?

What sources and transport patterns are responsible for variability in arctic aerosol?

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

4.4 Boundary-Layer Structure

What are the properties and effects of stably stratified turbulence in the atmospheric boundary layer (ABL)?

What are the effects of a thinned ice cover on ABL stability and heat fluxes?

How do surface- and cloud-driven dynamics impact the ABL 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 ABL. These features can occur throughout the year, while stable ABLs 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. ABL 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, and modulate the surface energy budget. Moreover, these interactions are critical in the hemispheric linkages between arctic change and the global system. Formulations of ABL 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.

5.0 Measurement Requirements

Necessary measurements to address the Science Goals given in Section 4 are outlined here, broadly distinguished into the four primary science thematic areas.

Surface Energy Budget. All components of the energy balance at the surface are essential: These include broadband shortwave and longwave radiation, and surface turbulence sensible and latent heat fluxes. The radiation measurements should include upwelling and downwelling as well as direct and diffuse components. Surface turbulent heat fluxes should be measured using eddy-correlation and bulk approaches. If possible, the subsurface heat flux through snow and ice (conductive flux) should also be estimated (flux plates and/or thermistor strings) to gain near closure at the surface. All surface energy flux measurements should be made on the sea-ice adjacent to the *Polarstern* (~500m distant) to minimize impacts from the ship itself. It is important to ensure a clean view for upward-looking radiometers, an undisturbed ice/snow surface below downward-looking radiometers, and minimal turbulent flow distortion for turbulent heat flux measurements.

Clouds and Precipitation. Measurements should be made to continuously characterize the macrophysical, microphysical, turbulent, and radiative properties of clouds, along with the occurrence, spatial distribution, and rate of precipitation. A core set of cloud measurements includes vertically pointing, cloud radars (ideally in both Ka- and W-bands) paired with depolarization lidar, multi-channel microwave radiometer, spectral infrared interferometer, and radiosonde profiles to give a very detailed view of cloud occurrence, phase microphysical properties, vertical motions, and turbulence. Radiation measurements in narrow bands can additionally be useful for constraining the cloud optical depth. The spatial distribution of clouds and precipitation within multiple 10s of km from *Polarstern* should be observed using scanning, dual-frequency radar (X- and Ka-bands). Scanning radars of this nature have never been operated over the arctic sea ice and will offer the opportunity to examine the spatial distribution of clouds relative to features likes leads in the ice. Paired with the active radar sensors, it is essential to have multiple surface measurements of precipitation to characterize the occurrence, mass, and rate of snowfall. Due to the significant challenge of measuring snowfall, multiple systems/approaches are important.

Aerosols. Very few measurements of aerosols exist over the arctic sea ice, particularly in the winter season, such that any measurements made will contribute to an unprecedented data set in this region. Aerosol measurements should characterize number concentrations, size distributions, and chemical and optical properties, and cloud activity. All of these measurements will be made through an inlet by instrumentation operated onboard *Polarstern*. While vertical information on aerosols is highly desired, the most feasible approach to vertical profile information is via collocated radiometer and lidar observations. In addition to aerosol properties, gas-phase tracers and chemical markers at the surface will provide information on the origin and chemical environment for aerosols. Providing further information on particle origin and particle concentrations at two size ranges (>2.5 nm and >10 nm) will allow for tracking variations in newer, small particles, which may help constrain the importance of local aerosol sources.

Atmospheric Boundary Layer. Vertically resolved and continuous thermodynamic and dynamic properties of the atmosphere are essential for characterizing and understanding the role of the atmospheric boundary layer. This information includes routine profiling of temperature, moisture, and winds. Thermodynamic measurements can be made through a combination of radiosoundings (ideally 4 per day) with additional higher-frequency information provided by spectral infrared interferometer and microwave radiometer. Similarly, the radiosonde wind measurements can be complemented with higher-frequency measurements from wind profiling radar, and possibly Doppler lidar. These remote-sensing systems may also contribute information on the turbulent structure of the atmosphere.

6.0 Instruments

To meet the outlined measurement requirements, the project has requested the AMF2 and the MAOS. These resources will be deployed on and around the *Polarstern* icebreaker when it is frozen into the ice pack of the central Arctic Ocean in September 2019 and drifts with the ice through October of 2020. A specific discussion of the required ARM instrumentation is provided here and summarized in Tables 1 and 2. Following this discussion of ARM instruments is a short narrative on collaborating instruments that will be operated by other partners in MOSAiC but will help serve the scientific goals outlined in this plan.

Table 1. AMF2 instruments, measurements, scientific justifications, and priorities for inclusion in the project. All instruments will be installed on *Polarstern* other than those labeled with a *, which should preferable be installed on the adjacent sea ice. Priority Code: Required, High priority, should be included if possible, Reduced priority and/or further evaluation is needed; Do not need.

Instrument	**Measurement**	**Science Justification**
Balloon-borne sounding system (radiosonde)	Twice-daily profiles of P, T, RH, winds	Thermodynamic profiles, ABL structure, link with clouds and surface
Microwave radiometer, 3 channel (MWR3C)	Liquid water path, water vapor path	Thermodynamic and cloud property characterization.
Microwave radiometer (MWR)	Liquid water path, water vapor path	Thermodynamic and cloud property characterization
High-spectral-resolution lidar (HSRL)	Backscatter, depol ratio, cloud micro properties	Cloud property characterization; aerosol profile info
Micropulse lidar (MPL)	Backscatter, depol ratio, cloud micro properties	Similar to HSRL.
Doppler lidar	Air motions, turbulence	Wind, turbulence in ABL, cloud-atmosphere interactions
Total sky imager (TSI)	Visible hemispheric sky pictures	Visual documentation of cloud/sky coverage
Scanning W-band ARM Cloud Radar (SWACR)	Radar moments; Scanning; cloud micro/dynamical properties	(Similar to Ka-SACR; not needed)
Marine W-band ARM Cloud Radar (M-WACR)	Vertical radar moments and spectra; motion stabilized	Cloud/precip characterization; cloud-ABL dynamics; dual-frequency synergy with KAZR
Ka-band Scanning ARM Cloud Radar (Ka-SACR)	Scanning radar moments; Joint with X-SACR;	Cloud/precip characterization and spatial organization.
X-band Scanning ARM Cloud Radar (X-SACR)	Scanning radar moments; Joint with Ka-SACR; Polarimetry.	Cloud/precip characterization and spatial organization.
Ka-band ARM Zenith Radar (KAZR)	Vertical radar moments and spectra	Cloud/precip characterization; cloud-ABL dynamics; dual frequency synergy with M-WACR
Vaisala ceilometer	Cloud base, backscatter	Robust cloud presence and height
Beam steerable radar wind profiler, 1290-MHz	Wind profiles	BL wind structure (sub-optimal system for arctic operations)
Infrared sounder spectrometer for IR spectral technology (ASSIST)	IR spectral radiance at zenith or other angles	Cloud property characterization; cloud radiative properties
Atmospheric emitted radiance interferometer (AERI)	IR spectral radiance at zenith or other angles	Cloud property characterization; cloud radiative properties
IR all-sky camera	IR radiation, spatial	Sky radiative heterogeneity
Multifilter rotating shadowband radiometer (MFRSR)*	Solar irradiance at multiple wavelengths	Atmospheric/aerosol optical depth
Upwelling radiation (GNDRAD)*	Upwelling broadband LW, SW fluxes	Surface radiation/energy budget, albedo characterization

Instrument	Measurement	Science Justification
Downwelling radiation (SKYRAD)*	Downwelling broadband LW, SW fluxes	Surface radiation/energy budget, cloud radiative properties
Eddy correlation system (ECOR)*	Surface turbulent fluxes, carbon dioxide.	Surface energy balance; turbulent momentum, heat, CO_2 fluxes
Surface energy balance System (SEBS)*	Up/down SW/LW radiation, soil moisture	(little added value beyond GNDRAD, SKYRAD)
Video disdrometer (VDIS), 2D*	Precip DSD and fall speed	Precipitation mass/rate
Rain gauge, weighing bucket*	Precipitation rate	Precipitation mass/rate (difficult to operate in cold temperatures)
Met. instrumentation*	Near-sfc P, T, RH, winds	Meteorological state for context
Inertial navigation system	Platform pitch, roll, heave	Informational, context

To start the discussion of ARM instrumentation it is first important to acknowledge a couple of key aspects that make this deployment particularly challenging and that may influence instrumental decisions. First, due to remoteness, space limitations on *Polarstern*, limited access, and the high cost of operations, it is important to critically evaluate all instrumentation. While the communications capabilities onboard *Polarstern* in 2019-2020 are not yet clear, it is likely that communications will be very limited (mostly text with potential for small attachments) and much less than the typical level of communications experienced by the ARM facility and instrument mentors. Additionally, visits to the *Polarstern* will only be possible during periodic crew changes, which will occur approximately every two months. For these reasons, operations may be more isolated than typical for ARM deployments, putting extra emphasis on instruments operating robustly and stably over long periods with limited mentor access to real-time data. As a result, it is important that ARM technicians have the skills to address most of the critical operational issues that may arise, and that the number of instruments is in line with the number of onsite ARM technicians. Additionally, all instruments should be individually evaluated and scientifically justified. A prioritization of instruments is included as color coding in Tables 1-2. Some instruments are not justified and should not be deployed. Lastly, the project will include the deployment of some instruments on the *Polarstern* itself as well as some instruments on the sea ice adjacent to the ship. Those on the ice are meant to avoid measurement contamination due to the ship and other infrastructure. The location for deployment of individual instruments is also indicated in Tables 1 and 2.

On-ship Installations. *Polarstern* is a large research icebreaker with substantial space for scientific equipment. ARM installation locations will be on the bow (D- and C-Deck) and above the bridge (P-Deck). All of these locations are shown in Figure 5, while the C-Deck is directly above the D-Deck. While the specific detailed plan is still being finalized, initial plans are for four ARM lab containers on C-Deck (ARM-OPS, ARM-KAZR, ARM-AOS, ARM-MAOS), one ARM lab container on D-Deck (ARM-GP), and one ARM lab container on P-Deck (ARM-SACR). This plan may be adapted as needed through coordination with AWI and the MOSAiC leadership.

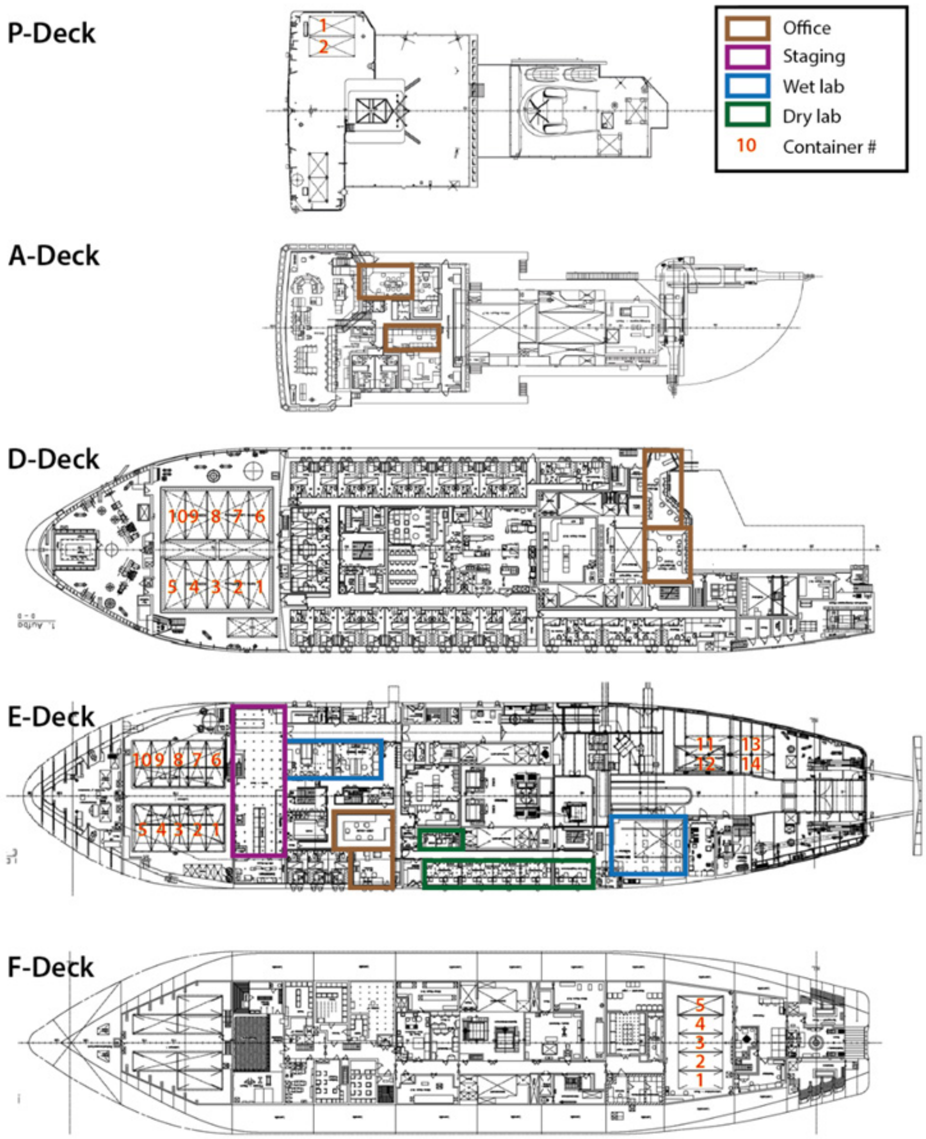

Figure 5. Deck plans for *Polarstern*. C-Deck is comprised of lab containers stacked on top of the containers on D-Deck.

The installation will include a scanning X/Ka-band radar system; the first scanning cloud radar deployed in the Arctic. This system will be important for characterizing the spatial organization of clouds and precipitation. To minimize obstruction in the radar's view, it will be installed as high as possible on the P- Deck, although the specific installation is still under discussion and will need to take into account the space available for both radar pedestal and SACR lab container. In particular, the decision needs to be made about the specific pedestal to use (heavy or light). It is anticipated that the scanning radar will only be operated when the ship is stationary within the ice pack, with no ship motion. Radar scan strategies will be devised via consultation between the MOSAiC science team and ARM Radar Science Committee. Ensuring the calibration of all radar systems is critical and may be challenging to accomplish on a ship.

Additional remote-sensing instruments will be installed along the handrail on the P-Deck or in/on lab containers on the C-Deck. These include the following equipment. Vertically pointing cloud radar systems (KAZR, MWACR) are essential for routine identification and characterization of cloud properties. Of these systems the KAZR is highest priority, but having both Ka- and W-bands offers the potential for enhanced cloud retrievals. Vertically pointing, depolarization lidar systems (HSRL, MPL) are also essential for observing cloud properties as well as atmospheric backscatter associated with aerosols. Of these systems the HSRL is most important, while having both systems would help to assure a continuous lidar data set for the full campaign. A ceilometer will also support robust observations of cloud occurrence and height. The visible Total Sky Imager, and an infrared equivalent if available, provides information on the spatial distribution of sky cover over the site. Depending on the possible view, it may be desirable to install these instruments on a lab container that will be on the sea ice (see below). Passive microwave (MWR, MWR3C) and spectral infrared (MAERI) measurements are important for deriving layer integrated cloud liquid water path, atmospheric water vapor path, cloud microphysical properties, and some atmospheric gas and thermodynamic profile information. A sun photometer will provide important information on the atmospheric optical depth. An infrared thermometer will point down at the surface to monitor surface temperature. Finally, wind profiles will be measured with a 1290-MHz BSRWP. While it was initially questionable if the 1290-MHz system would be sufficient in the dry arctic atmosphere, this system performed quite reasonably in the Antarctic during the ARM West Antarctic Radiation Experiment (AWARE), so it is likely to perform reasonably in the Arctic.

Ideally a 4-times-daily radiosonde program will be implemented as a backbone for atmospheric profiling. AWI typically conducts radiosoundings onboard *Polarstern* and there is a full balloon-launching facility adjacent to the helicopter deck. AWI will oversee the radiosonde program but implement this in coordination with ARM. Initial agreements between AMF2 and AWI personnel are that each institution will fund the equivalent of two radiosondes per day. AWI personnel will implement three of the daily soundings, while ARM personnel will implement one daily sounding. All radiosondes will be launched from the ship and the radiosonde equipment will be the standard equipment that is permanently mounted on *Polarstern*. This equipment is being upgraded to the Vaisala MW-41 system with RS-41 radiosondes, which is consistent with ARM's systems.

The MAOS was requested in place of the standard AMF2 AOS in order to obtain both aerosol physical and chemical properties. One or two aerosol lab containers will be installed on C-Deck with sampling inlets drawing low-level ambient air. These labs will house the following instruments. The radiative properties of near-surface aerosols will be measured using a PSAP, an ambient nephelometer, and a wet nephelometer. Aerosol total number concentration is an essential parameter and will be measured by a CPC and u-CPC, the second of which is important for distinguishing new particles from older particles. The aerosol size distribution, which provides information on the life cycle of aerosols, will be measured using a combination of SMPS and UHSAS. An HTDMA will provide information on the size distribution as a function of the relative humidity. The concentration of aerosols that can impact cloud formation will be measured by a CCN counter, which could be a single-column CCN100 but is preferably a two-column CCN200 to allow for a measurement at constant relative humidity as well as scanning in humidity.

Aerosol chemical composition will be measured using an ACSM, providing information on the source and history of aerosol particles. Black carbon will be measured with an SP2. Lastly, some key atmospheric gases (O_3, CO, N_2O, NO_x) will be measured to support a characterization of important chemical processes occurring in the atmospheric system. Aerosol measurements may be a challenge onboard *Polarstern* since its own power generation will produce exhaust that could contaminate aerosol measurements. Special consideration of the aerosol inlet(s) may be needed and it may also be necessary to modify operations based on wind directions and/or pollution monitoring. Post-experiment quality assurance and analysis will require careful attention to pollution records. Additionally, it will be important to consider calibration of aerosol equipment used during MOSAiC with potential aerosol measurements made by others (e.g., SP2).

Table 2. List of MAOS instruments, measurements, and justifications, similar to Table 1.

Instrument	**Measurement**	**Science Justification**
CCN200 (dual col.)	CCN concentration	Baseline characterization of CCN
Condensation particle counter (CPC)	Aerosol number concentration > 10nm	Baseline characterization of total aerosol concentrations
Ultrafine condensation particle counter (UCPC)	Aerosol number concentration > 2.5 nm	Small-particle concentration, new-particle formation, and source attribution
Hygroscopic tandem differential mobility analyzer (HTDMA)	Aerosol mass, size, and # distribution as g(RH), particle growth factor	Baseline characterization of aerosol size distribution; aerosol hygroscopicity
Ultra-high-sensitivity aerosol spectrometer (UHSAS)	Aerosol size distribution, 50–1000 nm	Baseline characterization of size distribution
Scanning mobility particle sizer (SMPS)	Aerosol size distribution, 15-450 nm	Baseline characterization of size distribution
Nephelometer	Aerosol light scattering coefficient at dry RH, 3 wavelengths	Aerosol scattering, radiative effects
Wet nephelometer	Aerosol light scattering coeff as f(RH), 3 wavelengths	Aerosol scattering, radiative effects
Humidigraph	Aerosol light scattering coefficient as f(RH)	Aerosol scattering, radiative effects
Particle soot absorption photometer (PSAP)	Aerosol light absorption at 3 wavelengths	Aerosol absorption, radiative effects
Photo-acoustic soot spectrometer	Aerosol light absorption at 3 wavelengths	Aerosol absorption, radiative effects (low sensitivity in the Arctic)
Aethelometer	Aerosol light absorption at 7 wavelengths	Aerosol absorption, radiative effects (Redundant with PSAP)
Aerosol chemical speciation monitor (ACSM)	Aerosol mass spectrum measurements	Characterization of aerosol composition
Single-particle soot photometer (SP2)	Black carbon mass concentration	Role of black carbon
Photon transfer reaction mass spectrometer	Volatile organic compounds	Characterization of aerosol composition (some similar info to ACSM)
PILS-IC-WSOC	Water soluble organic carbon	Characterization of aerosol composition (labor intensive, similar info to ACSM)
NO_x, NO_y, CO, O_3	Gas concentrations	Airmass source, age, transport
Vaisala WXT520	P, T, RH, winds	Context
Sodar	Vertical wind	Context
Cimel sunphotometer	Aerosol optical depth	(Similar info to MFRSR)

On-Ice Installations. To support operations on the sea ice adjacent to the *Polarstern* will require a lightweight lab container, similar to the SKIP container operated during AWARE, to serve as a base of operations. Some equipment may be installed on top of this container, while others will be installed within the vicinity. The full collection of upwelling and downwelling, shortwave and longwave, direct and diffuse radiation will be measured using the suite of instruments associated with the GNDRAD and SKYRAD systems. These radiation measurements are of extremely high importance; special care must be taken to ensure continuous, robust operations and to limit the build-up of rime on the instrumentation. An MFRSR will augment these radiation measurements in specific spectral bands for deriving atmospheric optical depth. Surface turbulent heat fluxes will be measured with an ECOR system mounted on a short tower. Precipitation measurements will be a great challenge in the extreme arctic conditions, requiring multiple different instruments and approaches. A precipitation station will include the optical rain gauge, present weather detector, Pluvio2 or Geonor weighing gauge, and Parsivel laser disdrometer. For all installations on the ice, care should be taken to minimize contamination of the measurements, while also ensuring that equipment can be moved relatively quickly if ice conditions change.

Guest Instruments. In addition to the ARM instruments outlined in Tables 1 and 2, there is the potential for adding guest instruments to the ARM suite. Such guest instruments have been operated in the past with other ARM deployments and will follow the standard ARM field campaign request process. Potential guest instruments will be discussed with the appropriate scientific and AMF2 leadership. It will be important that any such guest instruments do not significantly detract from the ability of the facility to obtain the core proposed measurements.

Data Products. To best use the instruments outlined above, the project has requested several standard ARM value-added products (VAPs) to facilitate higher-order usage of the measurements. These include enhanced radar data products (KAZR-ARSCL, WACR-ARSCL, MicroARSCL, MMCG for SACR data) in addition to the QCRAD radiation product, and MWRRET microwave retrieval. Instrument mentors and others in the ARM community may request additional products and those should be considered when possible.

Partner Activities. MOSAiC is a large, internationally collaborative project. Thus, complementing the ARM observations will be many important scientific contributions from other nations, agencies, and institutions. Those that are particularly supportive of the science goals outlined in Section 4 are briefly listed here. The intention with outlining these specific activities is to ensure that the ARM observational activities are well aligned with these other collaborative activities to support strong leveraging and the ability for value-added science beyond what is possible from ARM measurements alone. Principal Investigator (PI) Shupe will actively work with ARM personnel and collaborating partners to support the necessary coordination.

- Soundings: The Alfred Wegener Institute will provide facilities and support for routine radiosondes. It has been agreed that AWI and DOE will jointly support a four-times-daily radiosonde program, with each institution providing resources for two soundings per day. For manpower, AWI will have two personnel dedicated to routine radiosounding as well as on-ice tethered balloon operations. DOE will provide manpower to support one sounding per day.
- Tethered balloons: AWI and the German TROPOS institute will operate tethered balloons from the sea ice adjacent to *Polarstern*. While multiple measurements are likely, the ability to profile some basic aerosol properties is of most interest here. Additionally, it may be possible to deploy an ARM radar calibration sphere from the larger TROPOS tethered balloon when it is operated in the spring of 2020.
- Atmospheric profiling: The German TROPOS institute will operate its OceanNet container on *Polarstern*, which features a Raman lidar and additional microwave measurements. These will provide supporting information on the thermodynamic profile.

- Wind profiling: While only pending as of February 2018, there are plans for the University of Trier and the University of Leeds to operate Doppler lidars at MOSAiC. These systems will provide wind profile information, below clouds, that nicely complements ARM's radar wind profiler measurements. If there are multiple Doppler lidars available, it may be desirable to operate one of these from the roof of the atmospheric lab container on the sea ice.
- Surface fluxes: The National Science Foundation has funded the University of Colorado to install 1-2 meteorological towers on the sea ice, extending up to 15-30m height. These will allow for multiple levels of flux measurements that complement the ARM ECOR observations. Additionally, this project will install single-level flux stations, similar to the ARM ECOR and radiation measurements, at 3 or more nodes that are ~15km away from *Polarstern*. These will provide spatial context for ARM measurements.
- Precipitation: A number of other investigators are interested in surface precipitation measurements, although these are currently only proposed measurements. If they are funded, a coordination plan will be developed.
- Aerosol: There is an active community of aerosol scientists (University of Helsinki, Paul Scherrer Institute, University of Colorado, British Antarctic Survey, etc.) eager to participate in MOSAiC. They intend to largely provide measurements that complement ARM's. Specifically, they will look into more detail of the chemical composition, new particle formation, cloud activity, and other properties. Additionally, these scientists plan a number of filter samplers for offline and laboratory analysis of aerosols. This team of aerosol scientists will operate largely independent of ARM and have an additional lab container onboard to house their equipment.
- Unmanned aircraft: While not yet funded, multiple teams are interested in unmanned aircraft measurements around MOSAiC. The specific approach, payload, and measurement foci are not yet clear for these activities.

7.0 Logistics

MOSAiC will be a challenging experiment for ARM in a number of ways. This section outlines some of the practical details related to this project, including the timeline of key events, experimental logistics, communications, and personnel considerations.

Timeline. Logistics for MOSAiC will be overseen and coordinated by the Alfred Wegener Institute since it is providing the icebreaker *Polarstern* as the primary research vessel. The intention for the MOSAiC experiment is to have a full year of observations from within the Arctic ice pack, extending from the beginning of October 2019 through the end of September 2020. An approximate timeline for activities is given in Figure 6. Mobilization of all equipment onto *Polarstern* will occur in mid-September 2019, likely in the port of Tromso, Norway. At that time equipment from prior activities will be off loaded, MOSAiC equipment will be on loaded, and there will be a few days in port for setting up equipment on *Polarstern*. The exact timing of these activities is not yet finalized, but one objective for PI Shupe is to continue pushing for additional days in port to enable ARM personnel to set up as much equipment as possible.

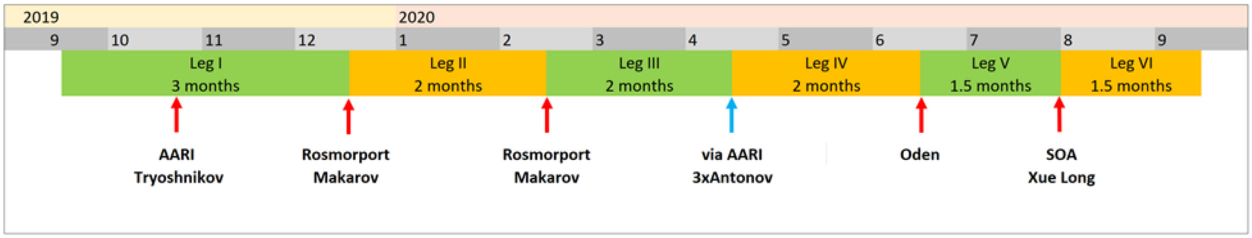

Figure 6. Approximate timeline of major operations during MOSAiC. Note that the exact dates have not yet been determined. Additionally, the final leg will likely persist until the end of September 2020 prior to returning to Germany.

In mid-late September, the plan is for *Polarstern* to leave Tromso and rendezvous with an escort icebreaker, likely the Russian *Akademik Treshnikov*, before heading into the ice pack. The location of initial installation will likely be near the Marginal Ice Zone, demarking the ice that has made it through the 2019 melt season. By this time of year, that ice will be growing again and will go on to become at least second-year ice over the course of the 2019-2020 year. Logistic and scientific professionals will choose an ideal ice floe near 84 N, 120 E to serve as the installation location for *Polarstern*. At that point, the escort vessel will top off the *Polarstern*'s fuel supply and help to install a distributed network of observations around the primary ship. This escort vessel will likely be within ~20 km of *Polarstern* for 1- 2 weeks. The intention is to find the install location near the end of September, such that primary observations can be set up and start in early October 2019.

From October 2019 through the end of September 2020, the *Polarstern* will drift with the sea ice along what is referred to as the Transpolar Drift. Extensive ice drift modeling, using observed ice motion over the past 12 years, has led to the approximate drift path and timing indicated in Figure 7. This is simply for guidance; the actual drift will likely be different from this. Over the course of the year-long drift there will be resupply missions using additional icebreakers that serve to bring fuel, food, and exchange personnel. The intention is to have crew changes approximately every 2-3 months (see Figure 6), although a final schedule is still to be determined. Crew changes using resupply vessels will require extra time for these vessels to reach and return from *Polarstern*. ARM personnel can be exchanged during each general crew exchange. During these exchanges there may also be the opportunity for resupply of instrument parts and materials, but every effort should be made to have necessary equipment on site from the beginning.

In late September or early October 2020, the end of MOSAiC science operations will be declared. All scientific equipment will be pulled from the ice and secured on *Polarstern* for the return voyage. At this time of year, the ice will be relatively thin, allowing *Polarstern* to exit the ice under its own power. It will voyage back to its home port in Bremerhaven, Germany. Sometime in October 2020, all equipment can then be offloaded.

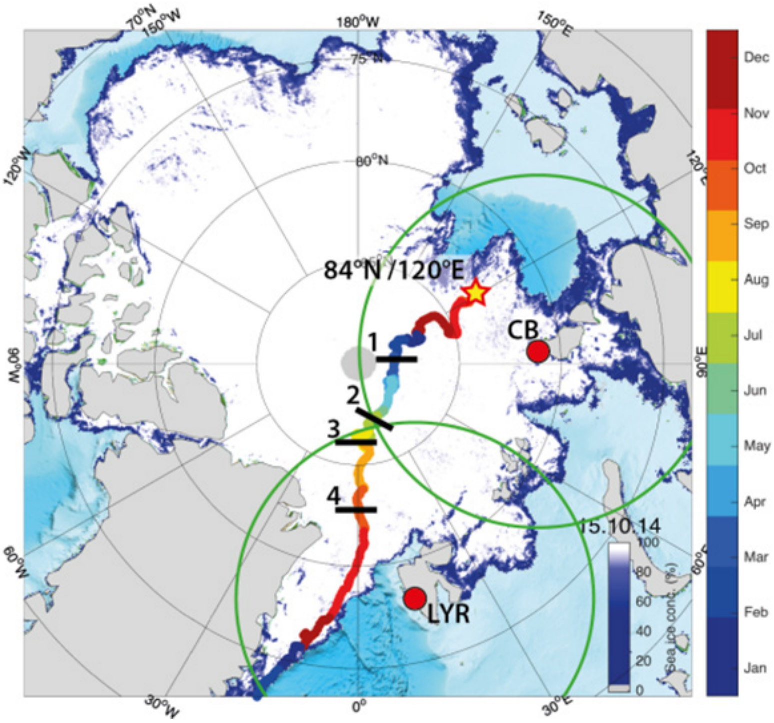

Figure 7. Modeled potential drift trajectory for the *Polarstern* during MOSAiC, starting at the yellow star. The color of the track indicates time of year. This trajectory is estimated and the actual trajectory will likely differ.

Experimental Logistics. ARM equipment will be installed on and near the *Polarstern*. Figure 8 shows the specific positions on the ship where the instruments outlined in Section 6 will be installed. All of this equipment will be installed near and/or adjacent to instruments from MOSAiC collaborators, including additional lab containers. Lab containers installed on C-Deck towards the bow of the ship will be stacked on top of containers on D-Deck. Access to these containers will be enabled by decking infrastructure established by *Polarstern* between containers. Ship's crew will assist with major operations such as cranes to move equipment, establishing power connections, and other aspects of baseline operations onboard.

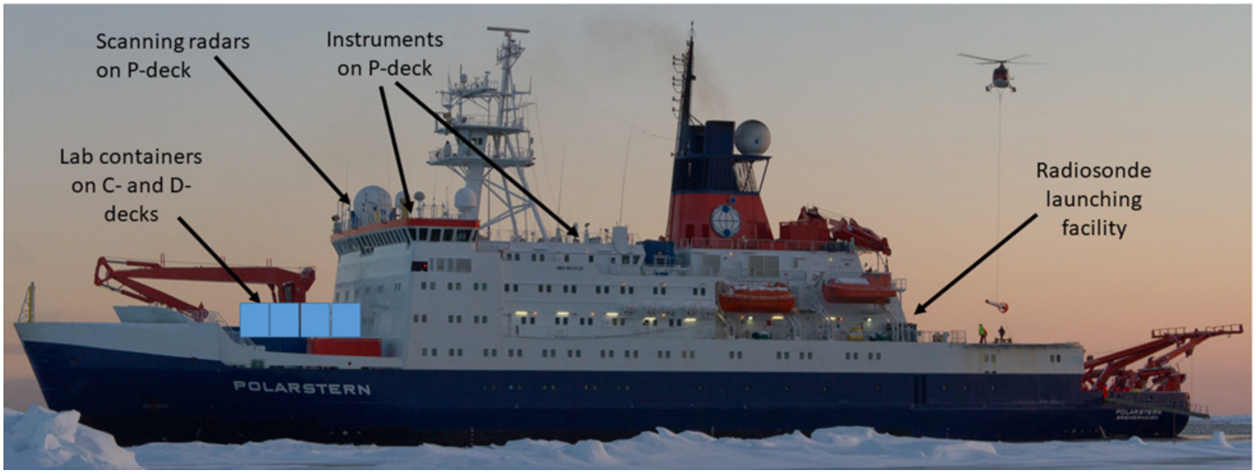

Figure 8. *Polarstern* with annotations designating installation locations for ARM Facility equipment.

Some equipment will be installed adjacent to the *Polarstern* on the sea ice. These installations will be established when conditions are identified as safe for doing so. The starting of the drift will intentionally be located next to a large ice floe that has made it through the previous melt season; thus, this ice floe should be thick and stable enough for the intended on-ice installations. A schematic of the near-ship ice camp is shown in Figure 9. “Met City” will be at the end of a power line extending out from the *Polarstern* by about 500m. This is the location for the lightweight lab container. Surrounding Met City will be the various on-ice instrument installations including ARM’s radiation, precipitation, and eddy-correlation measurements. Collaborating measurements will also be made near Met City. Power will be supplied by the powerline from the ship; however, a power buffer could be considered to help support operations through possible interruptions of power due to shifting ice conditions. Safety on ice is of utmost importance, particularly with regard to harsh weather conditions, polar bears, and variable sea-ice conditions. As a result, all operations on the ice will be subject to safety protocols and coordinated schedules. A limited number of groups will be allowed on the ice at a given time, and access of ARM personnel to the ice will be determined in coordination with onsite scientific and logistics personnel. The ultimate authority for access to the ice rests with the *Polarstern* captain, while AWI will also provide logistics personnel that will support on-ice operations and safety. ARM personnel should be well equipped with appropriate extreme cold weather gear to ensure their safety in conditions that can reach -45 C with potentially high winds.

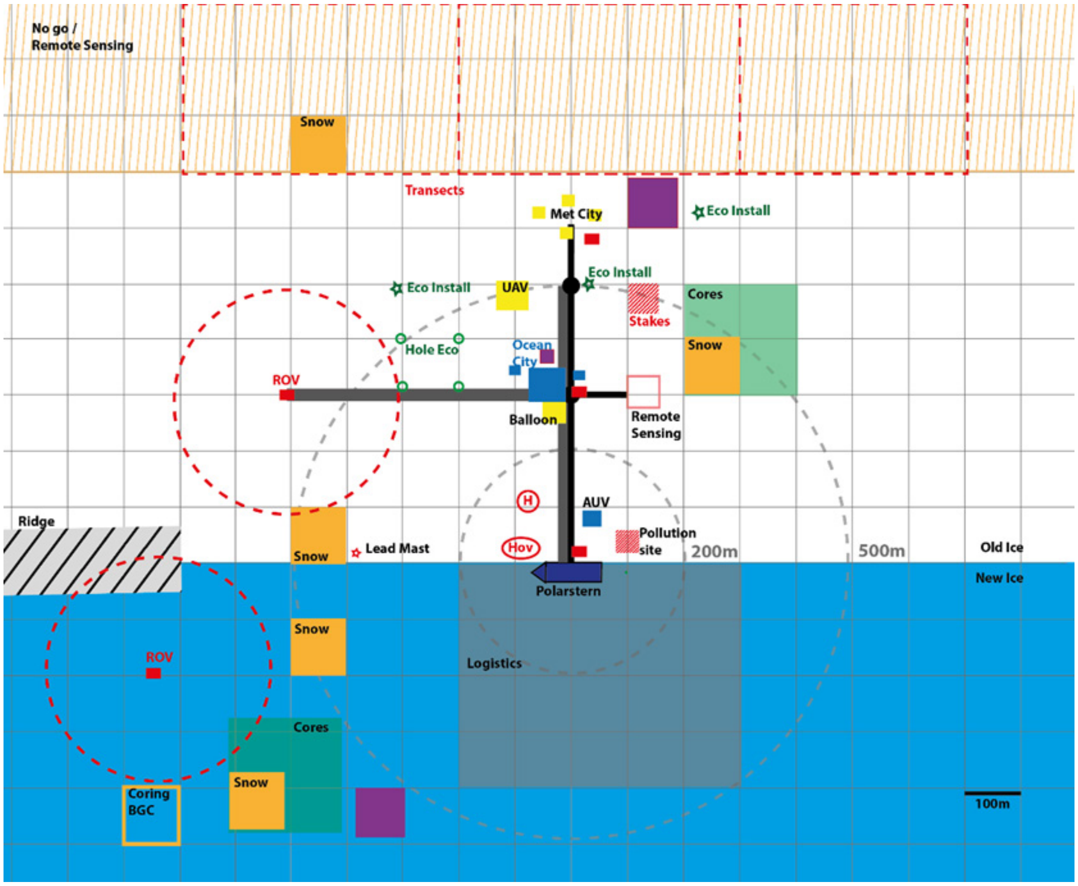

Figure 9. Schematic of the ice camp adjacent to the *Polarstern*. The white color indicates thicker ice, while the blue color indicates thinner ice. Different sectors are designated for different on-ice activities. ARM facilities would all be installed near “Met City.”

Communications onboard *Polarstern* have typically been limited, and shared across a full crew of approximately 90 people. While it is difficult to project what communications will be possible in 2019, it is important to plan for very limited communications. For these reasons, operations during MOSAiC will likely be more isolated than typical for ARM deployments, which puts extra emphasis on instruments operating robustly and stably over long periods with little mentor access to real-time data. Thus, onsite ARM technicians should have the skills to address most of the critical diagnostic and operational issues.

Personnel Considerations. ARM personnel will live onboard *Polarstern*, as part of a total of 90 people. Approximately 45 people will be ship's crew while 45 will be scientific personnel. As part of the berth fee for participation in MOSAiC, ARM personnel will have berth space on the ship, meals, and access to the other facilities of the ship. The ship has medical facilities as well as recreation and leisure activities. When selecting ARM technicians, the particular challenges of this experiment should be kept in mind, including the extreme conditions, isolation, extended darkness, etc. In addition, due to remoteness with limited access for personnel and limited communications, the science team is requesting special consideration for the skills and capabilities of onsite ARM technicians. Of particular concern is the operation of the more complex instrumentation including radars, lidars, and aerosol instruments. Ideally the site technicians will collectively have advanced knowledge of these systems that will support their robust operations.

The science team, led by PI Shupe, will actively assess the status of ARM observations relative to the stated science goals (Section 4). PI Shupe will participate on the first leg to support ARM setup operations where possible, to provide input on initial installations, and to serve as a liaison with AWI, the *Polarstern*, and other MOSAiC science projects. Prior to, and during, this leg, he will work with ARM staff to establish a methodology for real-time assessment of data, including quicklook plots and other health status summaries. Shupe will work to get this near-real-time information hosted on the *Polarstern's* public network to support data assessment, daily operations, and scientific coordination. On following legs, representatives of Shupe's team will be onboard *Polarstern*, although funded to support a distinct project. These representatives will spend a portion of their time evaluating the ARM data. The science team acknowledges that it has no supervisory role over ARM technicians. Feedback from Shupe and the science team will be provided when appropriate via the AMF2 manager; an appropriate communications protocol for doing so will be established prior to the field work.

8.0 Relevancy to DOE/BER

A major thrust of the DOE Biological and Environmental Research (BER) Climate and Earth Science Division (CESD) mission is to advance the predictive understanding of Earth's climate system. To improve predictive skill requires developing an improved process-level physical understanding of the climate system that can be captured in numerical models. The aims and objectives of MOSAiC, and the atmosphere-surface research conducted using the ARM deployment, are strongly in line with this high-level mission and many of the specific goals and objectives of CESD.

Change is occurring in the Arctic more extremely and rapidly than elsewhere. Due to numerous feedbacks the Arctic is highly sensitive to global climate change and it is likely that the global system is particularly sensitive to arctic change, which impacts the poleward transport of heat among other large-scale processes. Furthermore, arctic changes are generally not well represented in climate models, and attribution of those changes is not yet clear. Thus, the Arctic is a critical region to study in order to understand and represent the Earth's changing climate. CESD understands this fact and has prioritized the Arctic as a region of interest, specifically noting the importance of the changing cryosphere.

By going to the central Arctic, MOSAiC is focusing on one of the leading signs of climate change and some of the leading sources of uncertainty in climate models. The ARM observations will help to develop a process-level understanding of the interactions between the arctic atmosphere and sea ice. Targeted processes involve the boundary layer, precipitation, clouds, aerosols, their interactions with each other and the surface, all of which are explicitly prioritized by CESD. Moreover, in coordination with the full MOSAiC concept, the ARM observations will also contribute towards understanding interactions with the ocean and biogeochemistry of the central Arctic. By targeting these interactions, the campaign will develop the information needed to evaluate, constrain, and improve the representation of the arctic atmosphere, sea ice, and their coupling processes in numerical models.

The campaign will be a significant challenge. Yet it is a challenge that the climate research community must rise to meet. CESD-ARM facilities offer an unparalleled perspective on atmospheric processes that is a critical element for MOSAiC. This project is a perfect opportunity to use these facilities to significantly advance the frontiers of climate sciences.

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