The MOSAiC Expedition: A Year Drifting with the Arctic Sea Ice

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Highlights

- An international and interdisciplinary team made comprehensive observations of the atmosphere, sea ice, ocean, ecosystem, and biogeochemistry over an annual cycle in the Central Arctic.
- The MOSAiC year was characterized, above all, by a thin and dynamic sea ice pack, reflecting the impact of the multi-decadal warming trend in global air temperatures on the Arctic region.
- The unprecedented data set will foster cross-cutting, process-based research that will advance understanding, bolster observational techniques from the surface and satellites, and enable improved modeling and predictive capabilities.

The Arctic sea ice has a story to tell. It is a story of change and transformation on daily, seasonal, and decadal scales. It is a story of complex interactions and feedbacks, of processes that link the ice in myriad ways with the Arctic and global systems. It is a story that has been difficult to represent with numerical models. To better understand this story has been one of the primary objectives of the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC). MOSAiC is a scientific odyssey centered on a yearlong expedition into the heart of the Arctic, to explore the story of the changing sea ice, to unravel the interdependent processes involved, and to reveal the implications of this change.

Motivation

The changing Arctic has many societally-relevant implications. As the sea ice declines the Arctic is opening for expanded commerce, resource development, tourism, and shipping (Alvarez et al. 2020). Local communities and ecosystems are affected (e.g., Cooley et al. 2020). Arctic change may also be linked with large-scale circulation patterns that influence mid-latitude weather (Cohen et al. 2020) and global ocean structure (Sévellec et al. 2017). For all these implications, it is essential to understand the changing Arctic system at a level that can be represented in our predictive models. For example, to successfully operate in the Arctic requires reliable forecasts of sea ice on sub-seasonal to seasonal time scales. Moreover, higher-quality regional and global weather predictions rely on improved representation of hemispheric-scale interactions with a changing Arctic. To assess current and future ecosystem health necessitates models that realistically link physical and biological systems. Long-term societal planning requires coupled climate models that produce robust predictions of future changes. Importantly, all of these modeling priorities rely on accurate representation of processes and feedbacks that depict how the Earth system behaves and responds to perturbations. Essential processes cut across the Arctic system, linking the atmosphere, sea ice, ocean, and land through physical, chemical, and biological pathways.

The expedition

To address this need for cross-disciplinary, process-level understanding and thereby advance models, an international consortium of world-leading Arctic researchers, institutions, and funding agencies envisioned, planned, and executed the most comprehensive exploration of the central Arctic system to date. The MOSAiC expedition started in September 2019 as the German icebreaker *Polarstern* left Norway, traveled through the northern Laptev Sea, and moored itself inside the freezing sea ice pack (Fig. 1). Over the following weeks, racing the setting sun, the research team established an ice camp around the ship called the Central Observatory (CO), complete with paths, powerlines, sampling areas, and clusters of instruments. Simultaneously, a distributed network of quasi-autonomous systems was installed by the Russian icebreaker *Akademik Federov* at scales of 5-40 km in all directions surrounding the CO to assess spatial variability and scale. For the following 10 months this intensive constellation of research assets passively drifted with the sea ice across the central Arctic, following the Transpolar Drift, until reaching the ice edge in Fram Strait on 31 July 2020, nearly 1800 km from its starting position (Fig. 2). Thereafter, *Polarstern* was relocated further north, to continue this full-year endeavor through September 2020. Along the way, partner icebreakers supported periodic resupply and personnel rotations, scientific aircraft probed the atmosphere and surface in more detail, and an unprecedented collection of satellite observations for the region was assembled.

Fig. 1. *Polarstern* during polar night, with crack in the ice. (Photo: Matthew Shupe)

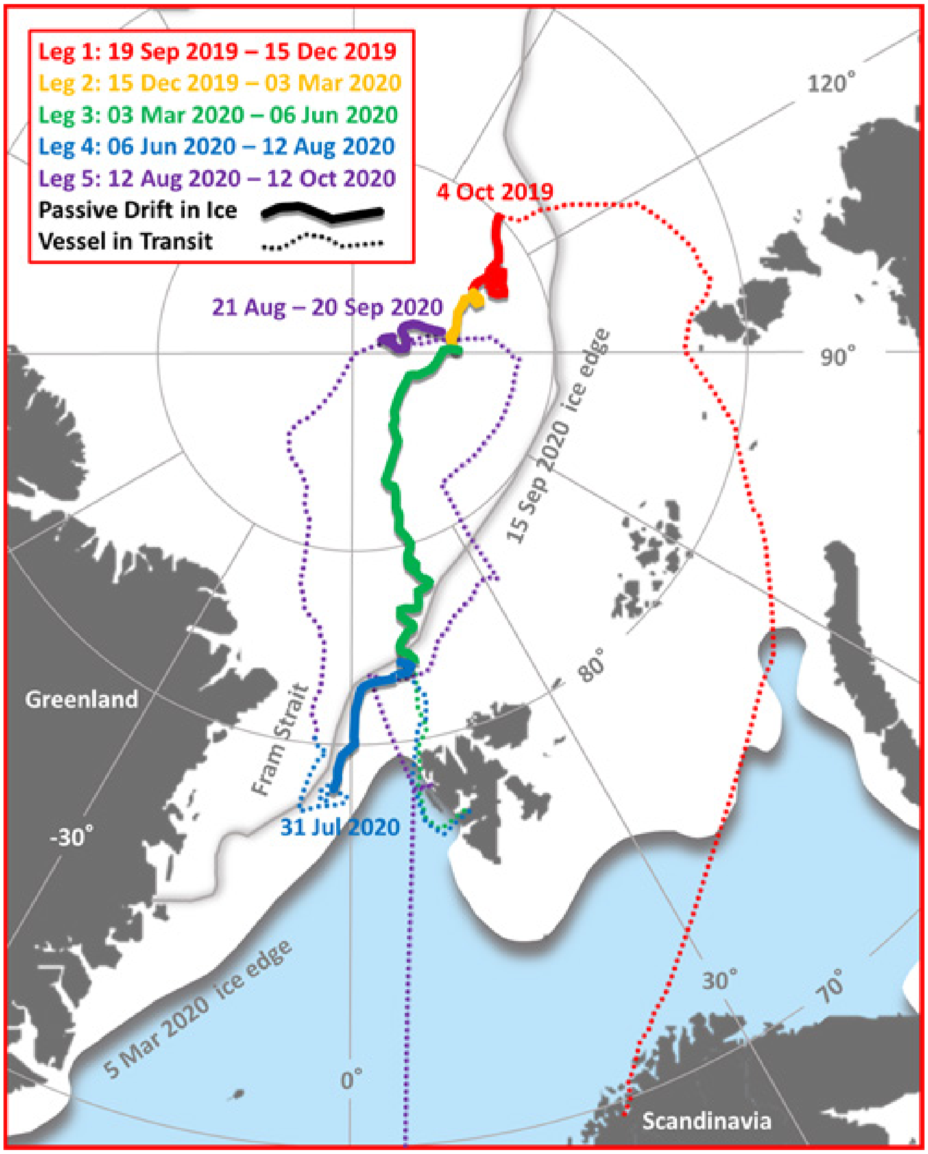

Fig. 2. The MOSAiC Expedition route, including the passive drift of the MOSAiC ice camp (solid) with dates of drift annotated, and in transit movements of *Polarstern* (dashed) delineated by legs (colors).

Modeled after Nansen's historic Fram expedition (Nansen 1897), the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment (Uttal et al. 2002), and the long-standing Russian North Pole drifting stations (Frolov et al. 2005), MOSAiC took the concept to a new level of sophistication, interdisciplinarity, and comprehensiveness. It captured a full year in the Arctic ice, linking continuous seasons and their transitions, including the rarely observed central Arctic winter. It represented a tremendously diverse and modern set of observations probing the atmosphere, sea ice, ocean, ecosystem, and biogeochemistry, all designed to enable cross-disciplinary process research. Lastly, it was designed to serve a broad user community, including important international modeling activities such as the World Meteorological Organization's Polar Prediction Project (Jung et al. 2016).

Navigating challenges to reveal opportunities

The quest to understand the story of the Arctic sea ice is not an easy one, and the MOSAiC expedition, like many in the past, was beset by challenges that at times threatened parts of the program. Yet, with these challenges came unprecedented opportunities for a deeper scientific understanding.

Challenges started with simply finding an ice floe to moor the ship and conduct observations, as the ice in the target region was thinner than expected and transected with foreboding ridges. In the end a floe was selected with a heavily ridged inner core, which originally formed on the Siberian Shelf (Krumpen et al. 2020), to provide stability over a years' drift. This floe was wrapped with thinner ice, some newly forming, to offer insight into the new, thinner Arctic ice pack. Yet even before on-ice installations were complete, ice dynamics started to pose a huge challenge that would persist for most of the year: frequent and dramatic cracks in the ice. Leads opened and ridges formed, limiting access and power to instrument sites, and forcing relocation of installations. On many occasions the heightened dynamics hindered the ability to measure the processes responsible for these very dynamics! Early on it became clear that MOSAiC was to have a front row seat to observe an evolving, highly dynamic ice pack.

As the calendar turned to early 2020, a stagnant circulation pattern over the central Arctic led to record-high positive values of the Arctic Oscillation Index with warm air moving over the sea ice pack from north-central Siberia (see essay *Surface Air Temperature*) and record ozone loss in the lower stratosphere (Wohltmann et al. 2020). While representing a unique opportunity to witness this unprecedented, and unexpected, circulation pattern, the pattern also pushed *Polarstern* across the central Arctic faster than anticipated, about three times as fast as Nansen's historic expedition along a similar route. During the progressing spring, further ice dynamics eventually destroyed much of the original CO domain.

After a brief exit from the ice from late May to early June due to another major challenge—the global coronavirus pandemic—*Polarstern* rejoined its network of autonomous measurements and moored to a new position on the MOSAiC floe to observe summer melt (Fig. 3). An earlier-than-expected entry into Fram Strait and a retreating ice edge foretold a rapid melt and impending end. However, a fortunate lull in ice dynamics enabled a consistent and comprehensive assessment of the melt, the associated formation of freshwater lenses, and their impacts on vertical exchange and structure of the atmosphere-ice-ocean system. The remarkable stability of the floe's ridged core enabled the unique opportunity to follow this floe to the very end of its lifecycle a few kilometers from the open ocean. Measurements continued to the last possible moment, ending with a spectacular disintegration of the floe as equipment was lifted onboard.

Fig. 3. *Polarstern* and the second Central Observatory. (Photo: Markus Rex)

To bring MOSAiC full circle, and achieve the full year in ice, *Polarstern* ventured back northward through areas of thinner-than-average sea ice (see essay *Sea Ice*). After establishing a new camp on 21 August 2020 (Fig. 4), the expedition was again confronted with ice dynamics fracturing the very ice being studied. But now the sea ice started a transition toward freeze-up. In these waning days, the expedition quantified the loss of energy from the upper ocean, and the subtle changes in surface reflectance as melt ponds froze over and were dusted with the season's first snows. All of these processes worked together to send the ice back into the autumn freeze, reminiscent of conditions when the expedition began a year earlier.

Fig. 4. Part of the MOSAiC ice camp in September 2020, with tethered balloon, meteorological tower, and other installations on the ice. (Photo: Marcel Nicolaus)

Groundwork for the future

Through MOSAiC we have learned much about studying the new Arctic. The thinning ice pushes us to adjust how we observe this Arctic system and to consider new approaches for interdisciplinary and autonomous measurements. The expedition built tremendous capacity, exposing scores of early career scientists to the challenges of field research. MOSAiC also demonstrated the strength of international collaboration by bringing together funding from 20 nations and participants from at least 37 nations. During all stages of the planning, field expedition, scientific analysis, and outreach, the MOSAiC consortium, through intense cooperation and mutual support has accomplished much more collectively than would have been possible through individual disciplinary or national efforts.

At this early stage, it is not known what all will be learned from the MOSAiC year; the pieces have not yet been assembled and synthesized. But it is obvious that the sea ice has revealed a great deal of its story over the course of this scientific adventure. It is a story of thinner and more dynamic ice, with likely impacts on upper ocean mixing, the exchange of gases, aerosols, and moisture with the atmosphere and clouds, the seasonal cycle of productivity, and the evolution of surface reflectance, to name a few key processes. MOSAiC was in an opportune place and time to experience this story, and to collect the data with which to explore it. These data, the legacy of MOSAiC, are now starting to become publicly available and will be entirely so by 1 January 2023. In the years to come, the scientific community will embark on a further journey to harness this wealth of new information toward advancing knowledge, enhancing observational techniques, improving model predictions, and broadening global awareness of the changing Arctic.

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