Evaluation of Ice Nucleating Particles and Their Sources in the Central Arctic during MOSAiC

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Abstract

The Arctic is warming faster than any other region on Earth, causing glaciers to melt, frozen ground to thaw, and the Arctic Ocean's ice to shrink. These consequential changes induce feedback loops that exacerbate warming and affect weather and climate worldwide. Microscopic airborne particles called "aerosols" and clouds in the sky are crucial for regulating heat and light reaching the Arctic surface. However, the magnitude of their effects is not adequately quantified, especially in the central Arctic, where they impact temperatures directly over the sea ice. Unique aerosols called "ice nucleating particles" (iNPs), which play a significant role in cloud ice production, remain understudied. Understanding how ice forms in clouds is critical in the Arctic, as it affects cloud lifespan, interactions with heat and light, and precipitation.

In this project, we conducted the first-ever observations of INPs in the middle of the Arctic over a whole year, covering the entire period when sea ice grows and melts. Furthermore, these are the first observations of INPs in different size ranges throughout the year, anywhere in the world. We use DNA sequencing to evaluate the presence of various types of microorganisms, while INP measurements on seawater, sea ice, snow, and meltwater samples help assess potential local Arctic sources of INPs. The results from this work are currently being used to improve the accuracy of Arctic cloud formation in various models.

Summary

Introduction

The accelerated rate of warming in the Arctic is of great concern due to potential impacts, including the release of greenhouse gases from permafrost, melting glacial ice contributing to sea level rise, and declining sea ice cover leading to more open ocean. These processes induce feedback loops that contribute to amplified warming, affecting the global climate. Clouds play a crucial role in regulating the energy reaching the sea ice and snow surfaces, but the magnitude of their effects on surface temperature is not well constrained in the Arctic. Aerosols are also important contributors by serving as seeds for cloud formation, but even less is known about their overall impact and origin. In particular, aerosols that serve as ice nucleating particles (INPs) are vastly understudied, especially above the central Arctic Ocean. However, INPs likely play a significant role in Arctic mixed-phase cloud formation and the resulting impacts of such clouds on the surface energy budget.

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC), which took place from September 2019 to October 2020 on the German icebreaker *Polarstern*, drifted with the sea ice pack in the central Arctic, providing a unique opportunity to execute these novel INP measurements. The overarching goal of this project was to achieve an unprecedented characterization of INP abundance and sources to evaluate their capacity to modulate cloud ice formation over the central Arctic. Specifically, the three main objectives of the project were:

- **Objective 1:** Process size-resolved and total aerosol samples collected during MOSAiC for quantitative INP measurements and aerosol microbiological characterization to produce a high-quality dataset to be made available to the scientific community.
- **Objective 2:** Coordinate the collection of seawater, snow, and ice samples for the assessment of local INP sources to leverage aerosol INP measurements.
- **Objective 3:** Address a set of targeted scientific research questions based on current gaps in the understanding of INPs in the central Arctic:

1. How do seasonal changes in sea ice and air mass transport influence INP abundance and sources in the central Arctic?
2. Are marine and sea ice biological processes significant sources of atmospheric INPs compared to terrestrial sources?
3. Are open-water environments such as leads and melt ponds viable sources of INPs over the sea ice, and do such environments exchange INPs with the atmosphere?

Collaboration with several of the MOSAiC teams, including the Atmosphere, Ecosystems, Biogeochemistry, and Sea-ice teams, provided synergistic opportunities to evaluate aerosol-cloud interactions through coordination of sample collection and collaboration using holistic and multidisciplinary datasets. Results from the proposed work will leverage DOE ARM and ASR resources and inform models of all scales through improvement of understanding Arctic aerosol-cloud interactions from detailed observations at the atmosphere-ocean-sea ice interface.

Approaches used

Details about MOSAiC, sample collection, sample analysis, and findings have been reported by Creamean et al. (2019; 2022) but are briefly summarized here. DOE ARM funded our team to collect a continuous time series of size-resolved and total aerosol samples during MOSAiC. This included filter collections for offline INP measurements and DNA sequencing to determine the relative abundances of eukaryotes, bacteria, and fungi. The measurement efforts spanned an entire year to capture trends and variability throughout a full sea ice cycle and involved the deployment of three aerosol collectors (one size-resolved impactor and two open-face filter unit collection apparatuses) on *Polarstern*. Collection of seawater, sea ice, snow, and meltwater samples aimed to characterize potential local sources of INPs and microorganisms. This project involved processing these samples to address our stated research objectives.

As part of Objective 1, we processed a subset of the size-resolved samples (387 out of 1,380 collected) using our cold plate, and nearly all 101 total aerosol samples using the ice spectrometer (IS) for immersion mode INPs were processed. Heat and peroxide treatments were applied to 1/3 of the IS filter samples to obtain information on heat-labile (i.e., proteinaceous), bio-organic, and inorganic INPs. Both the size-resolved and total aerosol (plus treatment) data are available on the DOE ARM Data Archive (doi.org/10.5439/1798162 and doi.org/10.5439/1804484 for the size-resolved and total plus treatment INP data, respectively).

A second set of total aerosol filters was prepared for DNA sequencing, and the results were recently obtained. Aerosol DNA was concentrated and extracted following the methods in Uetake et al. (2020). After amplification, samples were purified, barcoded, and sequenced at the Colorado State University Next Generation Sequencing Core. Reads were demultiplexed and denoised to generate an amplicon sequence variant table, and taxonomy was assigned using the QIIME2 feature-classifier plugin (Barry et al., 2023; Bokulich et al., 2018). This work was conducted by graduate student Kevin Barry and is currently in preparation for publication.

Objective 2 was completed for all legs of the expedition. In addition to routine seawater from the underway system and CTD (conductivity, temperature, depth) rosette, sea ice core segments, and snow pit samples, meltwater samples from ponds and seawater samples from open leads were collected in late summer during inter-team coordinated on-ice intensive operational periods (IOPs). A subset of these "source" samples has been processed using the IS plus treatments. Graduate student Camille Mavis, with the assistance of undergraduate hourly student Maria Vazquez, is nearing completion in processing these samples in preparation for publication.

Findings

Objective 3 encompasses the primary scientific questions, some of which have already been addressed in recent publications, while others are currently being finalized for future publications. A seasonal pattern became apparent in the size-resolved INP observations (refer to Figure 1 and find more details in Creamean et al. (2022)). During the winter and spring, there were fewer INPs, and they generally originated from farther south. However, in the summer when the ice was melting, there were more INPs, likely due to biological activity in the local open water.

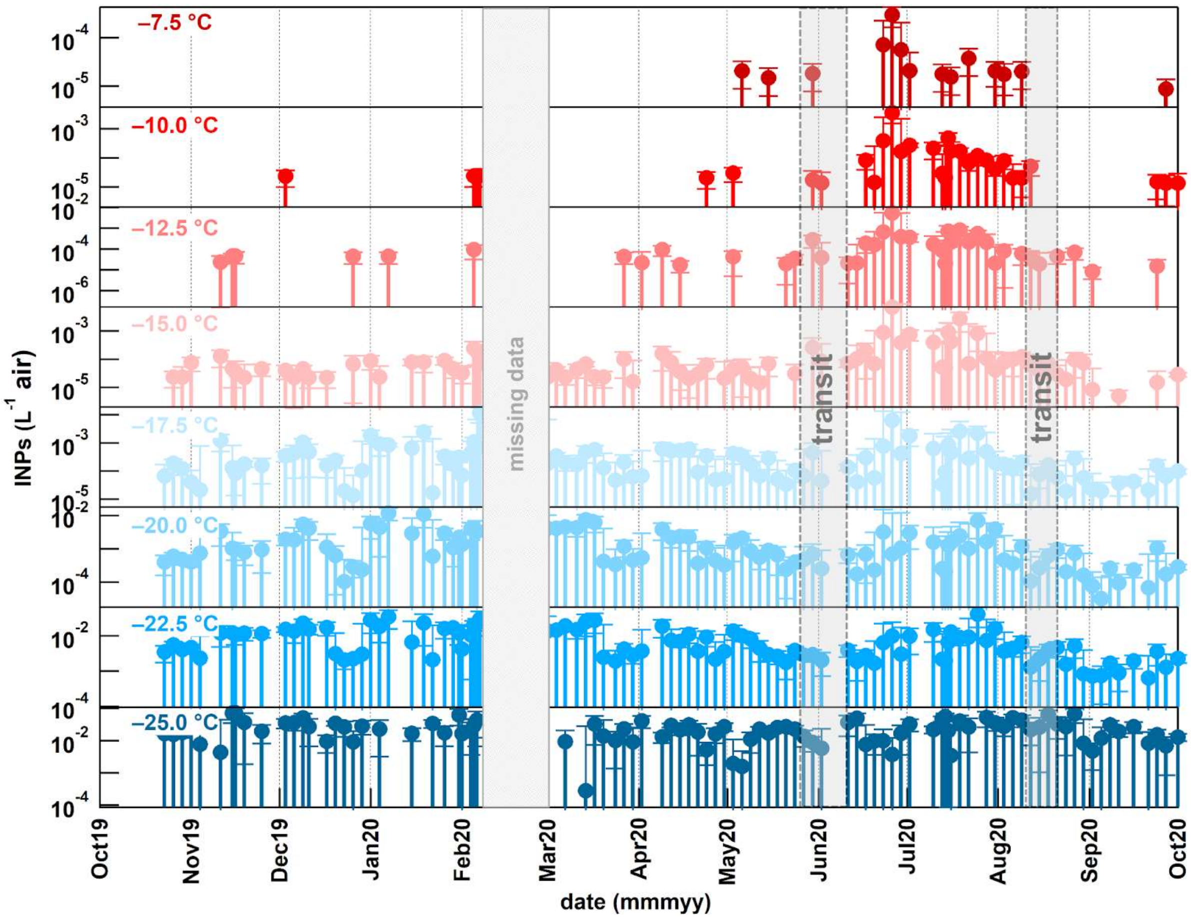

Figure 1. Time series of INP data from Creamean et al. (2022) at various cloud freezing temperatures.

As part of this project, Objective 3's scientific questions are being further addressed through DNA sequencing and the analysis of source sample INP results. These findings will be included in publications and theses that are currently in preparation by Barry and Mavis.

DNA analyses and treatments to distinguish INP types have been completed and are being used to compare coincident water and ice samples to assess local sources of microorganisms. The results indicate high levels of biological and organic aerosol INPs, and aerosol bacterial results suggest a mixture of terrestrial and marine taxa. In the summer (as shown in Figure 2), there are higher contributions from bacteria and/or fungi from known local sources and distant land sources.

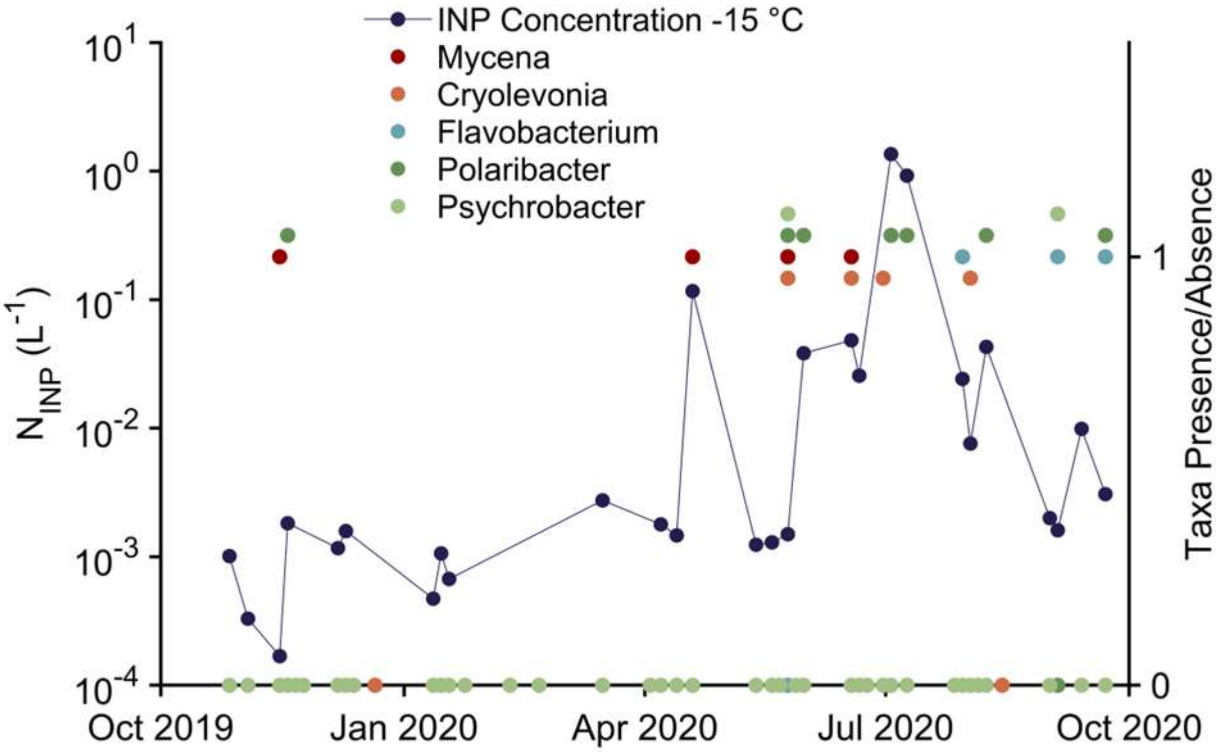

Figure 2. Time series of INP concentration at –15 ºC and the presence (1) absence (0) of taxa mycena (terrestrial fungi), cryolevonia (permafrost and sea ice), flavobacterium (soil and freshwater), polaribacter (high latitude ocean water), and psychrobacter (seawater, ice, permafrost).

Results from the analysis of source samples reveal that the concentration of INPs in melt ponds is ten times higher than in the seawater within the ocean mixed layer, suggesting that freshly melted snow and ice are potentially significant sources of INPs in the Arctic summer (see Figure 3). To gain insight into the parameters required to link the melt pond fraction to INP concentration, an analysis is being conducted on INPs in ice cores and snow to determine if the melt pond environment promotes increased primary biological production, thereby generating INPs.

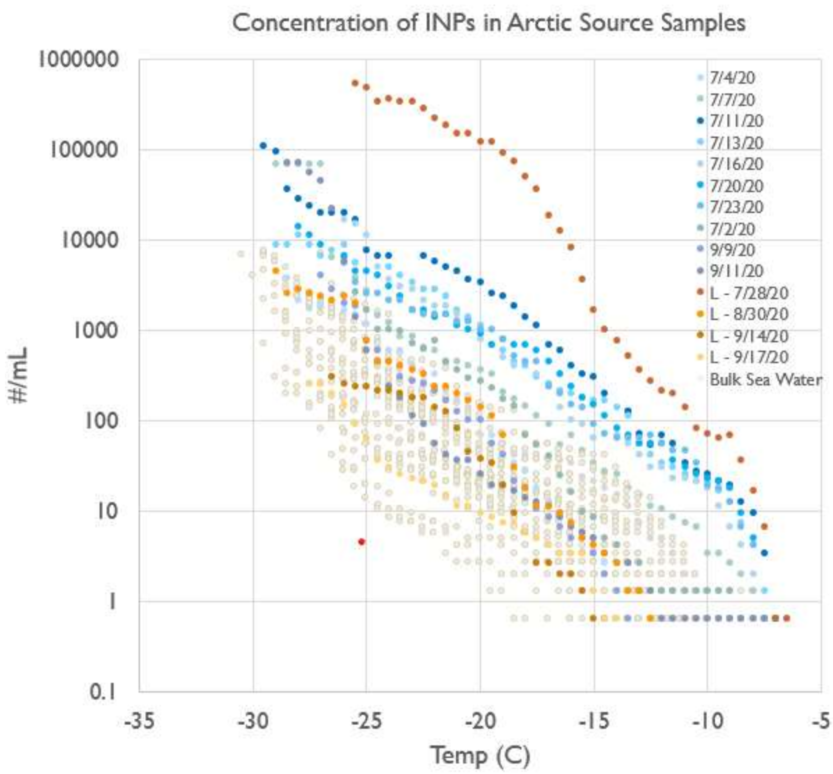

Figure 3. INP spectra from melt pond samples (blues), open lead samples (orange), and bulk seawater samples (beige).

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