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Meltwater as a Local Source of Ice Nucleating Particles in the Central Arctic Summer

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Abstract Identifying sources of ice nucleating particles (INPs) in the central Arctic is important for understanding controls on the phase of Arctic mixed-phase clouds (AMPCs). We show meltwater samples collected from the Arctic pack ice in July 2020 contain biological INPs active at relatively warm temperatures ($T \geq -10$°C). We attribute the meltwater INPs to organisms and processes unique to a meltwater habitat. Concentrations of biological INPs active at $T \geq -10$°C on filters deployed downwind of meltwater sites showed an enhancement associated with surface proximity. We hypothesize that time over the melt-pond-covered pack ice may have influenced the higher concentrations of biological INPs on the aerosol filters. More work to resolve emission mechanisms from melt ponds is necessary for understanding the extent of this potential source, which may increase importance as melt seasons extend spatiotemporally.

Plain Language Summary Understanding what controls cloud properties in the Arctic is important for predicting weather and climate in the region. In this study, we found that, compared to seawater, meltwater on top of sea ice contains high concentrations of ice nucleating particles (INPs), which help form ice in clouds. The meltwater INPs were biological and could trigger ice formation at relatively warm temperatures (above −10°C). Air samples taken near meltwater areas had more of these particles compared to air from farther away, and the concentration of INPs in the air seemed linked to time spent over the ice rather than over open ocean. This suggests that the melting sea ice surface may be an important source of biological INPs. More research is needed to understand how these particles are emitted from meltwater and how big a role they play in the radiation budget as Arctic melt seasons grow longer and larger.

Key Points:

- Warm-temperature biological ice nucleating particles were found in Arctic meltwater (ponds and a lead) and downwind aerosol filters
- Ice nucleating particle concentrations were higher in meltwater than seawater, likely reflecting meltwater-specific biological processes
- Airborne warm-temperature ice nucleating particles were more concentrated near the ice surface than at 15 m

Supporting Information:

Supporting Information may be found in the online version of this article.

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1. Introduction

The Arctic is warming up to four times faster than the global average, underscoring the importance of resolving the Arctic's radiation budget for realistic projections of regional and global climate change (Rantanen et al., 2022). Arctic mixed-phase clouds (AMPCs) strongly influence the surface radiation budget (Hofer et al., 2024; Morrison et al., 2012; Shupe & Intrieri, 2004; Tan et al., 2016) and play a role in the timing of melt onset (Cox et al., 2016; Philipp et al., 2020). The ratio of cloud liquid to ice in AMPCs affects the radiation reaching the surface (Cesana & Storelvmo, 2017; Tan et al., 2022) and is sensitive to the atmospheric concentration of ice nucleating particles (INPs; Mauritsen et al., 2011; Morrison et al., 2005; Pinto, 1998; Solomon et al., 2018), especially those containing biological (proteinaceous) material capable of freezing at warm subzero temperatures (warm-INPs, $T > -15$°C; Kanji et al., 2017). The frequent occurrence of warm, low-altitude AMPCs with significant ice content during the summer (Creamean et al., 2022; Shupe, 2011; Shupe et al., 2006), alongside atmospheric patterns favoring local aerosol sources (Schmale et al., 2021), emphasizes the need to identify local sources of warm-INPs during this season.

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Observations of warm-INPs in the Arctic summer have been attributed to biological material from both terrestrial (Barry, 2024; Pereira Freitas et al., 2023; Wex et al., 2019; Šantl-Temkiv et al., 2019) or coastal marine sources (Creamean et al., 2019; Hartmann et al., 2021; Porter et al., 2022; Wex et al., 2019). However, due to limited observations, no studies have directly attributed sources to the pack ice, yet increases in biological INPs during the melt season in the central Arctic suggest that melting ice surfaces may be an additional source of INPs (Barry, 2024; Creamean et al., 2022; Hartmann et al., 2021). Meltwater is a low-salinity liquid consisting of melted snow and sea ice that forms on and under the sea ice, or in stratified water surfaces including leads in the pack ice and open spaces within ice ridges during the Arctic summer (Nomura et al., 2023; Perovich et al., 2021; Smith et al., 2023; Webster et al., 2022). This freshwater interface could act as a source of warm-INPs comprised of proteinaceous or organic material from organisms inhabiting the cryosphere and unique meltwater environments (Assmy et al., 2017; Boetius et al., 2015; Hauptmann et al., 2014; Krembs et al., 2002; Smith et al., 2023; Winder et al., 2023). Meltwater may influence the warm-INPs attributed to the marginal ice zone (MIZ; 15%–85% sea ice; Itkin et al., 2014) and surface microlayer (SML; Creamean et al., 2022; Hartmann et al., 2020, 2021) by vertical mixing of the stratified meltwater layer and upper ocean (Long & Perrie, 2012; Nomura et al., 2023). This potential source may become increasingly significant for the radiation budget as the meltwater surface area is projected to increase spatiotemporally as the Arctic warms (Rolph et al., 2020; Stroeve et al., 2014).

Despite their potential importance as local reservoirs of INPs, to the best of our knowledge, the concentrations and characteristics of INPs in Arctic meltwater ponds have been reported in only two prior studies, both based on the same data set (Hartmann et al., 2021; Zeppenfeld et al., 2019). Here, we present meltwater INP observations from the melt onset through pond development during the Multidisciplinary drifting Observatory for the Study of Arctic Climate 2019–2020 expedition (MOSAiC) aboard the German icebreaking research vessel *Polarstern*. *Polarstern* traveled passively with the sea ice from October 2019 to August 2020 via the Transpolar Drift with the aim to address knowledge gaps of Arctic coupled systems. Details on the expedition and observational program within the Central Observatory surrounding *Polarstern* are described in-depth in Fong et al. (2024), Nicolaus et al. (2022), Rabe et al. (2022), and Shupe et al. (2022). For comparison, INP observations are also presented for samples of bulk seawater (hereafter "seawater"), sea ice and snow (collectively referred to as "cryospheric samples"), and aerosol filters from two locations, on the ship and on the ice immediately downwind of meltwater ponds.

2. Materials and Methods

2.1. INP Sample Collection

Both meltwater and seawater samples were collected manually in 50 mL centrifuge tubes triple-rinsed with each sample type. Meltwater was sampled from the edge of melt ponds and one open lead resulting in nine total meltwater samples (Shupe et al., 2022; Figure 1 and Figure S1, Table S1 in Supporting Information S1). Seawater samples were collected approximately daily from a single tap of *Polarstern*'s flowthrough seawater system (11 m depth; within the upper ocean mixed layer (Fong et al., 2024; Schulz et al., 2024)); here, we report on the 14 seawater samples that fell within the meltwater sampling period (Table S2 in Supporting Information S1). Collection of cryospheric samples (seven ice cores, five surface snow from snow pits; Tables S3 and S4 in Supporting Information S1) is detailed in Fong et al. (2024), Nicolaus et al. (2022), and in Text S1 in Supporting Information S1.

On-ice aerosol samples were collected downwind of the sampled meltwater sources on pre-cleaned filters (Pallflex® Emfab™ 47 mm borosilicate glass microfiber, Text S2 in Supporting Information S1) 1 m above the surface by a miniaturized custom-built time-resolved aerosol particle sampler (TRAPS) (Creamean et al., 2018), sampling ambient air for 26–30 hr, corresponding to 341–1,077 standard liters (sL; 0°C and 101.325 kPa). Studies show negligible effects of ship combustion aerosols on immersion-freezing INPs relvent for this study (Barry et al., 2025; Irish et al., 2019; McCluskey et al., 2018a; Moore et al., 2024; Thomson et al., 2018; Welti et al., 2020). A total of 11 on-ice filters including 1 field blank were collected (Shupe et al., 2022; Figure S1, Table S1 in Supporting Information S1). Conversion to sL and the blank correction are described in Text S3 in Supporting Information S1. Additional INP data from total aerosol filters (Whatman Nuclepore polycarbonate) collected on board *Polarstern* in July were used to compare with our total aerosol filters collected on the ice (five on-ship filters, Table S5 in Supporting Information S1). The on-ship filter sampler was positioned at a height of 15 m above sea level and collected over 72-hr, averaging total filtered air volumes of 88,800 sL per sample.

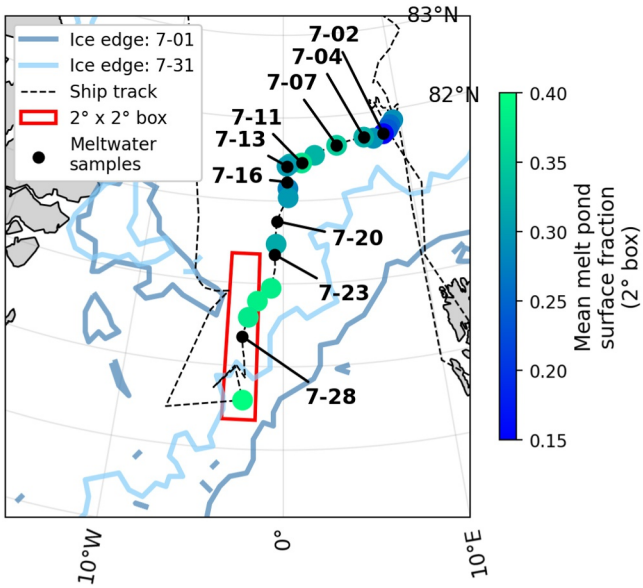

Figure 1. Meltwater sampling locations (black dots) along the *Polarstern* drift track (black dash); The average melt pond fraction (Niehaus et al., 2024) within a 2° × 2° domain (red box) centered around the *Polarstern* (colored dots); The sea ice edge (15% concentration) on 1 and 30 July 2020 (dark and light blue lines).

Details for these samples are available in Barry (2024). All samples were stored and transported frozen ($T \leq -20$°C) prior to INP analysis at Colorado State University (CSU).

2.2. INP and Supporting Measurements

Measurements of INPs within the meltwater, seawater, cryosphere, and water suspensions of particles from the aerosol filters (aerosol suspensions) were obtained using the CSU ice spectrometer (IS) and applying Equation 1 (Vali, 2019) to yield cumulative INP number as a function of temperature ($K(T)$) from fraction of frozen drops (f) and normalized to a unit volume (X) of water (mL) or filtered air (sL). Solutions for water and cryospheric samples were prepared for the IS by thawing at room temperature without further processing. Salinity measurements to account for freezing point depression of saline water were carried out with an Extech conductivity meter. Additional details on salinity measurements and calculations are provided Texts S2 and S3 in Supporting Information S1, respectively. Details for creating aerosol suspensions and the general IS configuration are described in Barry, Hill, Levin, et al. (2021) and Barry, Hill, Zentzsch, et al. (2021). Briefly, particles were removed from the filters and into suspension via rotation for 20 min in a Roto-Torque rotator (Cole Parmer) with 6 mL of 0.1-μm-filtered deionized water. For a select number of meltwater and aerosol samples, the heat-labile (likely proteinaceous) and heat-stable organic INP constituents were inferred by thermal (95°C) and hydrogen peroxide (H_2O_2) treatments (Hill et al., 2016; McLean, 1931; Ofoedu et al., 2021; Suski et al., 2018). Heating may not remove all ice nucleating material but is used to qualitatively asses the presence of ice nucleating proteins. Additional details on sampling and analysis methods for supporting meteorological, remote sensing, and back-trajectory data sets are provided in Text S4.

$$K(T) = -\frac{1}{X}\ln[f - (T)] \quad (1)$$

3. Results and Discussion

3.1. Meltwater Versus Seawater INPs

Figure 2a shows all meltwater samples contained INPs capable of freezing at $T > -10$°C, except for the earliest sample. Heat-treatments revealed high fractions of heat-labile INPs across the temperature range (Figures 2c and 2d and Figure S2 in Supporting Information S1), indicating the meltwater was predominately a reservoir of proteinaceous, likely biological INPs. H_2O_2-treatments showed trace contributions from inorganic (mineral) INPs.

After correcting for freezing-point depression, meltwater contained warm-INP concentrations about 10-fold greater than in the seawater, converging near $T = -25$°C (Figures 2a and 2b). This contrasts with previous studies reporting similar INP concentrations between melt ponds and ice-free ocean water (Hartmann et al., 2021; Zeppenfeld et al., 2019). This discrepancy may reflect differences in seawater sampling depth (1 m for previous studies and 11 m in present study). Enhanced stratification during the melt season can produce strong vertical gradients in meltwater fraction (Schulz et al., 2024), such that near-surface samples may already reflect a meltwater influence and obscure contrasts with the underlying ocean water.

There are several reasons to expect higher INP concentrations in meltwater versus in seawater, as well as increases over time. First, the differences in marine and cryospheric ecosystems manifest in distinct microbiological communities (Assmy et al., 2013; Boetius et al., 2015; Hatam et al., 2016; Hauptmann et al., 2014; Møller et al., 2013) between Arctic seawater and meltwater (Smith et al., 2023; Xu et al., 2020). Second, organisms once living in sea ice brines may release exo-polymeric substances (EPS) as protectants against osmotic or photo-stress when transitioning to a shallow, freshwater environment (Krembs & Deming, 2008; Krembs et al., 2002; Mundy

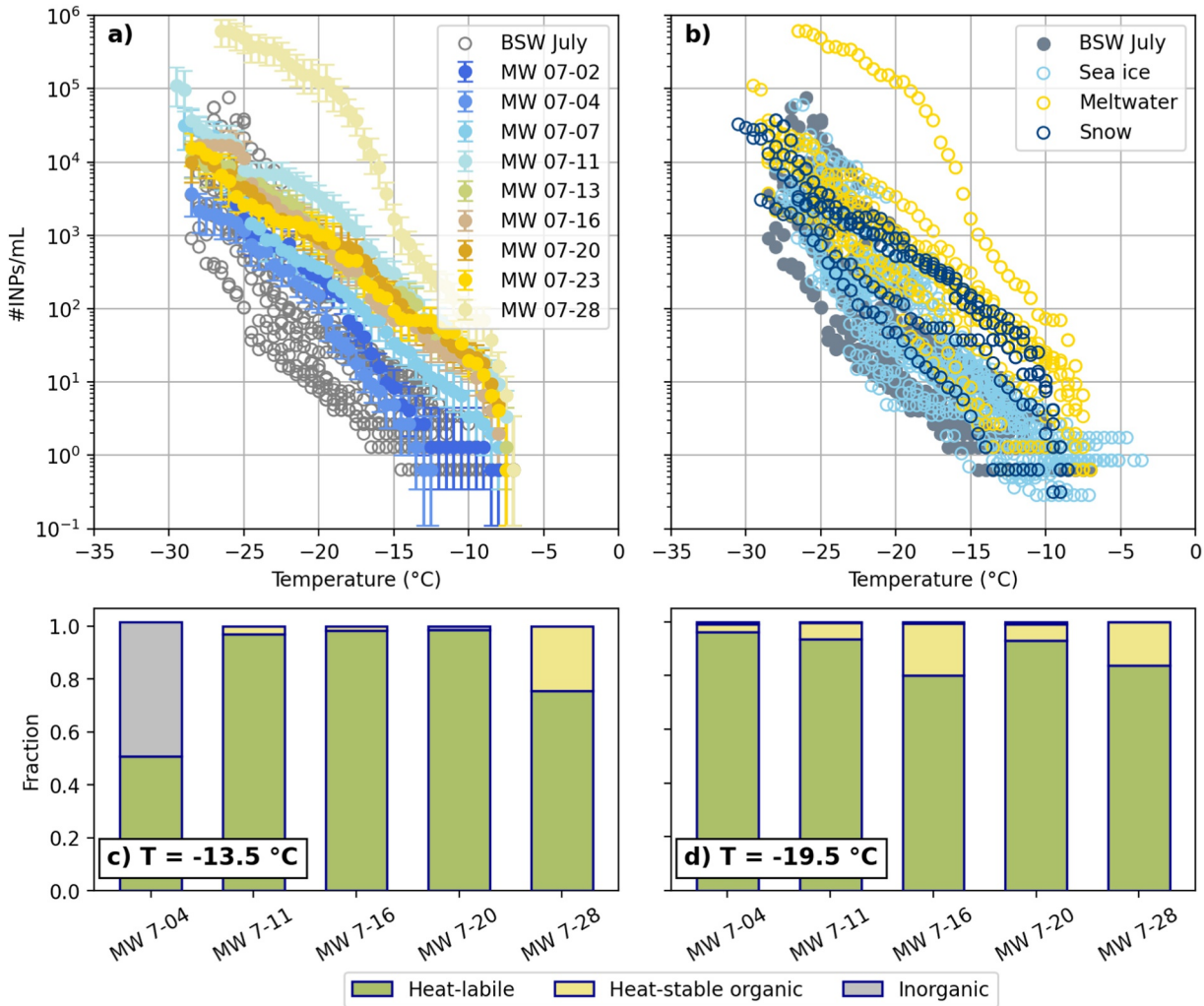

Figure 2. Cumulative INP concentration versus temperature for (a) July seawater ("BSW"; gray) and meltwater (colored). 95% confidence intervals are shown for the meltwater samples. (b) July BSW (gray), sea ice (light blue), meltwater (yellow), and snow (dark blue). Relative fraction of heat-labile, heat-stable organic, and inorganic INPs at (c) $T = -13.5$°C and (d) $T = -19.5$°C for select meltwater samples. Note, −13.5°C was the highest common temperature in which heat stable (organic and inorganic) INPs were detected across treated samples, a value necessary for computing the comparative fractions for each composition type and suggesting that the INPs were predominantly biological above this temperature.

et al., 2011). Salinity reductions estimated between our meltwater samples (Table S1 in Supporting Information S1) and sea water (32 g/kg; isotonic with brine at melting temperature) are greater than observations that yielded significant cell losses (Chamberlain et al., 2022; Garrison & Buck, 1986). Osmotic lysis may generate smaller biological material that is more readily aerosolized (Amiraux et al., 2017; Leck et al., 2002; Wilson et al., 2015) and promote consumption by bacteria, whose cells may also be associated with INPs (Creamean et al., 2019). The composition of dissolved organic matter in lead meltwater in late summer during MOSAiC was dominated by locally produced and photochemically degraded material (Kong et al., 2024) and the activity was dominated by consumption of organic material originating from the ice-associated habitat (Chamberlain et al., 2025; Smith et al., 2023). These findings suggest the biological material in meltwater is dominated by input from cryospheric organisms which undergo degradation and bacterial consumption.

Even after controlling for colligative properties, Irish et al. (2017) found a strong negative and no significant correlation between freezing temperatures of Arctic seawater INPs and salinity and bacterial abundance, respectively. This suggests that while INPs are associated with melting ice, fresh meltwater may not be a source of intact cells. Wilson et al. (2015) observed most ice nucleating material was smaller than whole cells (0.02–0.2 μm) associated with phytoplankton exudates. McCluskey et al. (2018b) similarly reported enhanced INPs in

this size range within Pacific SML concurrent with surface-active molecules, following the decay of a phytoplankton bloom in a mesocosm experiment. Together, these findings suggest the greater concentration of INPs within the meltwater samples in this study may not be associated with higher counts of intact cells, but with cell fragments or EPS. Viruses may also act as INPs but have not yet been observed in Arctic melt ponds (Atanasova et al., 2025; Hill et al., 2023). Galgani et al. (2016) showed the dissolved organic matter in Arctic SML samples had increased fractions of freshly dissolved amino acids along the gradient from oceanic to meltwater, in addition to distinct gel types between the seawater and meltwater, suggesting a continuous source of unique proteinaceous material from melting snow and sea ice in melt ponds from EPS or photo-dissolution.

Meltwater samples collected during August and September of MOSAiC showed temporal increases in bacterial abundance and salinity within the same pond (Figure S3 in Supporting Information S1), suggesting an increasing seawater influence through vertical and horizontal mixing. Only melt pond ice was collected for INP analysis during these months; the spectra are shown in Figure S4 in Supporting Information S1 and not included in the analysis with our bulk melt water samples. The salinities of the meltwater presented in this study were $\leq$2.44 g/kg (Table S1 in Supporting Information S1), suggesting the temporal increase in biological INPs was not driven by a seawater influence but instead the increased pooling of biological material from the snow and sea ice. As expected, there was no clear relationship between salinity and meltwater INP concentration. While Xu et al. (2020) observed the seawater and melt ponds had generally distinct eukaryotic communities during MOSAiC, similarities between seawater and an open pond (melted-through sea ice) suggest an exchange between these habitats. Notably, the distinct lead meltwater sample from July 28 was collected within the biologically active MIZ (Barber et al., 2015; Figure 1), where INP concentrations in seawater are enhanced relative to seawater from the open ocean or pack ice (Creamean et al., 2022; Hartmann et al., 2021; Zeppenfeld et al., 2019), especially at temperatures <-15°C which could represent a unique biological INP active at cold temperatures. This, and the low salinity of this sample (1.54 g/kg) suggests the INPs observed could reflect biological enrichment associated with the MIZ environment, rather than direct mixing with seawater.

3.2. Meltwater Versus Cryosphere INPs

The distinct influences of snow versus sea ice on the meltwater INPs is considered in Figure 2b. The INPs in the meltwater and snow samples had remarkable alignment between $T = -13.5$ and -20°C, suggesting a shared INP population (Figure S5a in Supporting Information S1). The ice cores (top 10 cm segment) showed variability in INP concentration and had lower warm-INP concentrations compared to the snow and meltwater samples (Figure S5b in Supporting Information S1). For surface melt ponds (as opposed to under ice meltwater, which was not sampled), the snowpack on top of the sea ice is first to melt, becoming the initial component of a melt pond in which the snow biology may have more time to establish itself as the dominant ice nucleating species (Perovich et al., 2021). Nomura et al. (2023) found that a meltwater layer in a lead sampled in late summer during MOSAiC was predominantly sea ice melt, suggesting that the composition of meltwater on sea ice and leads may undergo a shift from a snowpack to sea ice influence. Furthermore, the different concentrations of biological INPs within ice cores and meltwater may be due to the physiology and morphology of microbes living in ice versus those released into and potentially disintegrating in meltwater (Chamberlain et al., 2022).

3.3. Emissions From Melt Ponds

While melt ponds were confirmed as a reservoir of INPs in this study, whether they influence airborne concentrations of INPs depends upon emission mechanisms and magnitudes of associated fluxes. Specific emission mechanisms from relatively shallow melt ponds have not been identified in part due to a lack of observations. It is so far assumed that generation of aerosol from a liquid surface involves bubbles, in which material from the water and SML is ejected into the air upon bubble-bursting. This mechanism may preferentially emit biological particles due to the scavenging of surface-active material on the surface of the rising bubble (Bigg & Leck, 2008; Dubitsky et al., 2023). This process is also suggested by observations of EPS in Arctic and North Atlantic primary aerosols (Facchini et al., 2008; Hawkins & Russell, 2010; Leck & Bigg, 2005). INP enrichment in the SML versus the underlying water in melt ponds suggests surface-active biogenic compounds may enrich the near-surface aerosols in INPs relative to the underlying water source (Hartmann et al., 2021; Wilson et al., 2015; Zeppenfeld et al., 2019).

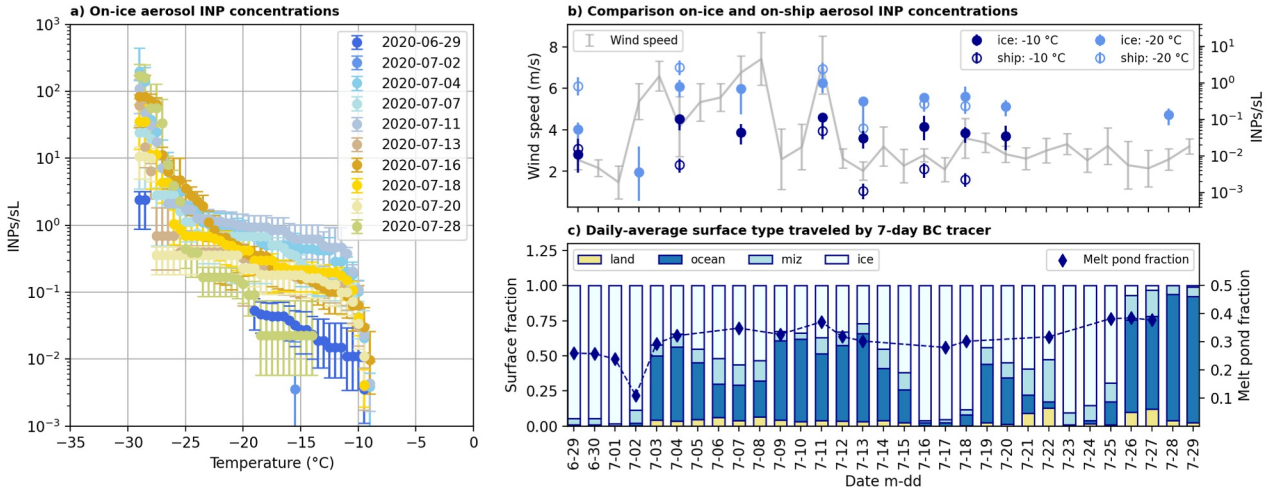

Figure 3. (a) Cumulative INP concentration versus temperature for on-ice aerosol filter samples. (b) INP concentration of on-ice (closed circles) and on-ship (open circles) aerosol filters at $T = -10$°C (dark blue) and $T = -20$°C (light blue); daily-averaged wind speed with ±1 standard deviation (gray line). (c) Relative residence time of the FLEXPART simulated 1-day, 100-m black carbon tracer over surface types.

While many studies have investigated wind-driven bubble-bursting processes for fresh versus saline water (Axson et al., 2016; Frossard et al., 2014; Harb & Foroutan, 2022; Sofieva et al., 2022; Zinke et al., 2022), more work is needed regarding bubble formation and size distributions across a range of wind speed and salinity conditions to understand the preferential emission processes from melt ponds and open leads.

Wind-independent bubble mechanisms have been suggested for low-fetch surfaces in low-wind conditions (Norris et al., 2011), which are supported by observations of enhanced film droplet generation at wind speeds <5 m/s (Leck et al., 2002). The processes relevant for melt ponds included: the release of trapped bubbles during sea ice melt (Drake, 1968; Nilsson & Rannik, 2001), gas bubbles produced by microbes in the meltwater (Norris et al., 2011), melting snowflakes on the surface (Blanchard & Woodcock, 1957), ripples generated by wind or movement of the sea ice, and the rising of bubbles originating from density gradients between a colder thin surface layer and the warmer underlying water (Galgani et al., 2016). Additionally, a high supersaturation of dissolved gases within the meltwater could increase the efficiency of aerosolization (Stramska et al., 1990).

3.4. Airborne INPs

On-ice aerosol filters frequently showed an INP mode active at $T \geq -10$°C except for the samples from July 2 to 28 (Figure 3a), and heat-labile INPs were observed for heat-treated samples (Figure S6b in Supporting Information S1). Similar spectral shapes were observed for the on-ship aerosol samples (Figure S6a in Supporting Information S1). These results align with observations during a coincident period of MOSAiC of enhanced warm-INPs and fractions of fluorescing (biological) aerosols (Beck et al., 2024; Creamean et al., 2022). The presence of INPs active at $T \geq -10$°C in meltwater samples thus provides a necessary condition for that INP reservoir to serve as a source for airborne INPs, potentially contributing to the aforementioned enhancement of warm-INPs during MOSAiC and relevant for the warm and low-lying AMPCs observed during that period (Creamean et al., 2022).

Lower INP concentrations and absence of warm-INPs on the July 2 on-ice filter (no on-ship data available) may have resulted from below-cloud scavenging during precipitation (Figure S7b in Supporting Information S1). INP sampling during other July precipitation events was limited and July 2 had the most accumulated rain and snow (Figure S8 in Supporting Information S1). Additionally, melt pond fraction within 2° × 2° around the *Polarstern* decreased by 15% from June 29 to July 2nd (Figure 3c), attributed to ice-lids formed in sub-freezing temperatures and lateral pond drainage (Webster et al., 2022), potentially suppressing meltwater contributions to airborne warm-INPs. On July 28, sampling was done within the MIZ with low, southerly winds from the ice-free ocean (Figures 1 and 3b, and Figure S7i in Supporting Information S1). The on-ice filter had comparable INP concentrations at $T = -20$°C, but lacked warm-INPs (Figure 3b), consistent with marine aerosol sources (McCluskey et al., 2018c; Schnell & Vali, 1976). Although chlorophyll-*a* in seawater (proxy for primary production by phytoplankton) peaked in July 2020 (Creamean et al., 2022), INPs do not correlate directly with chlorophyll-*a*

(Creamean et al., 2019; Irish et al., 2017; McCluskey et al., 2017). The heat-treated INP spectrum from July 28 resembled marine-organic types observed in North Atlantic air masses (Figure S6b in Supporting Information S1, McCluskey et al., 2018c).

INP concentrations measured on filters deployed 1 m above the ice surface (Figure 3b; "ice") were consistently higher at $T = -10$°C compared to those measured at 15 m on the ship (Figure 3b; "ship"). At $T = -20$°C, INP concentrations at the various ice sites were either comparable to or lower than those at the ship site. Although the on-ice filters sampled smaller volumes of air, their elevated INP concentrations at warmer temperatures suggest potential proximity-driven enrichment to a surface-based INP source.

There is evidence of a correlation between wind speed and on-ice INP concentrations, particularly at $T = -15$°C and -20°C, suggesting there may have been a specific INP population more readily emitted via wind-driven processes from the meltwater or enriched at the water surface, though our interpretation is limited by a small sample size ($n = 9$; Figure S9 in Supporting Information S1). While wind speed has been shown to drive total aerosol concentrations (Saliba et al., 2019), it alone cannot explain the variability in observed INP concentrations. Similar weak or absent relationships between INPs, wind speed, and aerosol properties have been reported in other marine INP studies (Gantt et al., 2011; Li et al., 2022; Moore et al., 2024; Van Pinxteren et al., 2017). The on-ice filter samples collected from July 13 to 20 coincided with lower wind speeds, and on July 16 and 18, air masses showed almost no residence time fraction from over the open ocean while airborne INP concentrations remained relatively constant (Figure 3b). This suggests that wind-driven contributions to the on-ice INPs originated over the pack ice and its associated melt ponds rather than open water, and that air-mass history (over pack ice or open ocean) plays a critical role. The July 28 sample further supports this: despite sampling within the MIZ and high INP concentrations in the melt water (Figures 1 and 2a), air masses did not traverse the pack ice, and no warm-INPs were detected (Figure 3).

4. Conclusions

Our results showcase meltwater as a reservoir of biological, warm-INPs in the central Arctic, distinct from mixed-layer seawater, likely due to the unique biological composition of the cryosphere and the processes associated with an environmental transition from low-light brine to exposed freshwater upon melting. It is likely that the INPs in melt ponds are associated with stress-induced EPS and related proteinaceous gels as opposed to intact cells. These substances are surface-active and enriched at the top layer of the meltwater, subject to scavenging by rising bubbles in the ponds and emitted into the near-surface aerosol population. Exact emission mechanisms are unknown, yet wind-driven bubble-bursting and other forms of bubble generation are possible within melt ponds, suggesting this reservoir can be a source of airborne INPs.

The on-ice aerosol filters deployed downwind of meltwater features and 1 m above the surface revealed elevated heat-labile (biological), warm-INPs relative to those collected 15 m above the surface on-board *Polarstern*. This observation, and the overall consistency in INP concentrations from the on-ice filters despite variability in wind speed and open-ocean fraction, support the interpretation that the on-ice filters were more influenced by a pack-ice-associated source. The results of our INP analysis of meltwater and on-ice aerosol filter samples suggest that meltwater may be a source of INPs capable of influencing the low-lying AMPCs that are ubiquitous in the Arctic. While this study focuses on INPs below 15 m, future work should investigate their vertical distribution, as fractions of warm-INPs reaching cloud base may influence AMPC and fog dynamics in the low-aerosol Arctic boundary layer. As climate changes and the spatiotemporal extent of meltwater increases, more biological activity and freshwater may increase locally-sourced INPs.

This study also reveals the complexities underlying meltwater as a source of INPs: multifaceted biological processes and unresolved emission mechanisms. Further work should target this complexity by investigating (a) what is being emitted and (b) under what processes and conditions. Measurements of aerosol flux and bubble size distributions over ponds and meltwater layers atop leads under varying wind speed conditions will help inform our understanding of emissions from this source (Gaman et al., 2004). In addition, in situ melt pond observations are needed to investigate potential wind-independent bubble generation from melting ice, biological respiration or photosynthesis, or turbulence that is either buoyancy-driven or caused by movement of the ice. To inform our understanding of the extent of this potential source, future work should interpret in situ melt pond observations with remote-sensing and model output of meltwater areal fraction or fetch (Niehaus et al., 2024; Wang et al., 2024) and novel satellite-observations of biogenically-sourced aerosols from EarthCARE and PACE.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The data underlying this study are openly available in DOE ARM Data Archive at https://doi.org/10.5439/2523674. Post-processing codes used to generate the figures and analyses in this study are available on Zenodo (Mavis, 2026).

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