Polar primary aerosols across the ocean-sea ice-snow-atmosphere interface: from sources to impacts

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Abstract

Primary aerosols play a critical role in polar climate systems, influencing cloud formation, precipitation, radiative balance, and surface energy budgets. This paper provides a comprehensive synthesis of primary aerosol sources, transformation and removal processes, and broader atmospheric impacts in polar regions, emphasizing their links to ocean and sea ice biogeochemistry. These aerosols (including sea salt, primary organic aerosol, and primary biological aerosol particles) originate from marine and cryospheric environments and are emitted through physical processes, such as wave breaking, bubble bursting, and blowing snow. Emission sources include seawater, sea ice, snow, and freshwater from river discharge and glacial runoff. Once airborne, these particles can serve as a chemical reservoir, influencing atmospheric composition and reactivity, and as seeds for cloud droplet and ice crystal formation, influencing cloud microphysics and polar climate. Despite their importance, many of the processes governing primary aerosol emissions and transformations remain poorly constrained. The most pressing knowledge gaps pertain to emission processes, limited spatiotemporal observational coverage, instrumentation constraints, parameterization development, and the integration of interdisciplinary expertise. To improve our

understanding of primary aerosol drivers and their response to climate, future research efforts should prioritize strategically coordinated and cross-disciplinary process studies, advancements in measurement technologies and coverage, and close collaboration between modelers and observational scientists to inform and refine model parameterizations. As polar regions continue to undergo profound changes marked by increased precipitation, reduced sea and land ice, freshening oceans, and shifting ecosystem dynamics, characterizing present-day primary aerosol populations is vital. Improved understanding will be essential for anticipating future changes in aerosol-radiation and aerosol-cloud interactions and their implications for polar and global climate systems.

1. Introduction

Aerosols, which are liquid or solid particles suspended in the atmosphere, play a key role in climate. They can directly impact climate by absorbing or scattering incoming solar radiation, which subsequently warms the atmosphere or cools the surface, respectively, and conversely absorbing and re-emitting outgoing longwave radiation, which acts to warm the surface (IPCC, 2023). Light-absorbing aerosols can also deposit on snow and ice, darkening these surfaces and causing them to melt more rapidly (Abdul-Razzak, 2012). Certain types of aerosols are effective seeds for cloud droplet or ice crystal formation by serving as cloud condensation nuclei (CCN) or ice nucleating particles (INPs), respectively, which ultimately modify cloud properties, including phase, radiative effects, lifetime, and precipitation production (Brooks and Thornton, 2018). Yet, indirect effects of aerosols lead to some of the largest uncertainties in global radiative forcing estimates (IPCC, 2023), including uncertainties associated with naturally-sourced aerosol (Carslaw et al., 2013).

Clouds play a particularly important role in the rapidly-changing polar regions through their impacts on the energy budget and precipitation over frozen surfaces (e.g., McCoy et al., 2014; Tan and Storelvmo, 2019; Silber et al., 2021). However, these impacts are poorly quantified, due in part to uncertainties in aerosol sources, emission rates, and microphysical effects (Gettelman et al., 2020; Tan et al., 2022; Zhang et al., 2023). Polar clouds are sensitive to relatively small changes in aerosol (Mauritsen et al., 2011; Twohy et al., 2021), especially over the oceans, where clouds are more pristine than at lower latitudes (McCoy et al., 2014; Sterzinger et al., 2022).

In polar sea-ice environments, primary aerosols are emitted directly from the ocean (pelagic) or sea-ice (sympagic) surface in particulate form, whereas secondary aerosols are formed from gas-to-particle conversion and partitioning within the atmosphere (Cochran, et al., 2017). While both primary and secondary aerosols formed through new particle formation can serve as CCN, INPs are almost exclusively primary in nature (Kanji et al., 2017). These primary aerosols can be generated by waves and wind stress in open ocean near the marginal ice zone (MIZ), sea-ice leads and polynyas, snow cover on top of the sea ice, sea-ice meltwater (in the spring and summer), and glacial runoff and river water discharged into coastal ocean waters (May et al., 2016; Huang and Jaeglé, 2017; Irish et al., 2017; Frey et al., 2020; Figure 1). However, our understanding of many of these sources and emission mechanisms is limited in the Arctic and Antarctic.

In the polar regions, sea-ice loss is driving changing seawater microbiology (Post et al., 2013; Swadling et al., 2023), which may impact emissions of primary aerosol. Once lofted into the atmosphere, primary aerosols undergo heterogeneous chemical reactions that change their composition and cloud-forming abilities (Willis et al., 2023). Multiphase reactions involving bromine, chlorine, and iodine, produced from sea salt aerosols and the saline snowpack, alter the oxidative capacity of the atmosphere and

subsequent abundances of climate-relevant gasses (Simpson et al., 2015; Pratt, 2019). Therefore, understanding the sources, emission rates, quantities, chemical composition, and cloud-forming properties of primary aerosols in these natural environments is crucial for assessing polar ocean-sea ice-snow-atmosphere connections (Shepson et al., 2003; Willis et al., 2023), including cloud formation and subsequent impacts on the melt and formation of ice and snow.

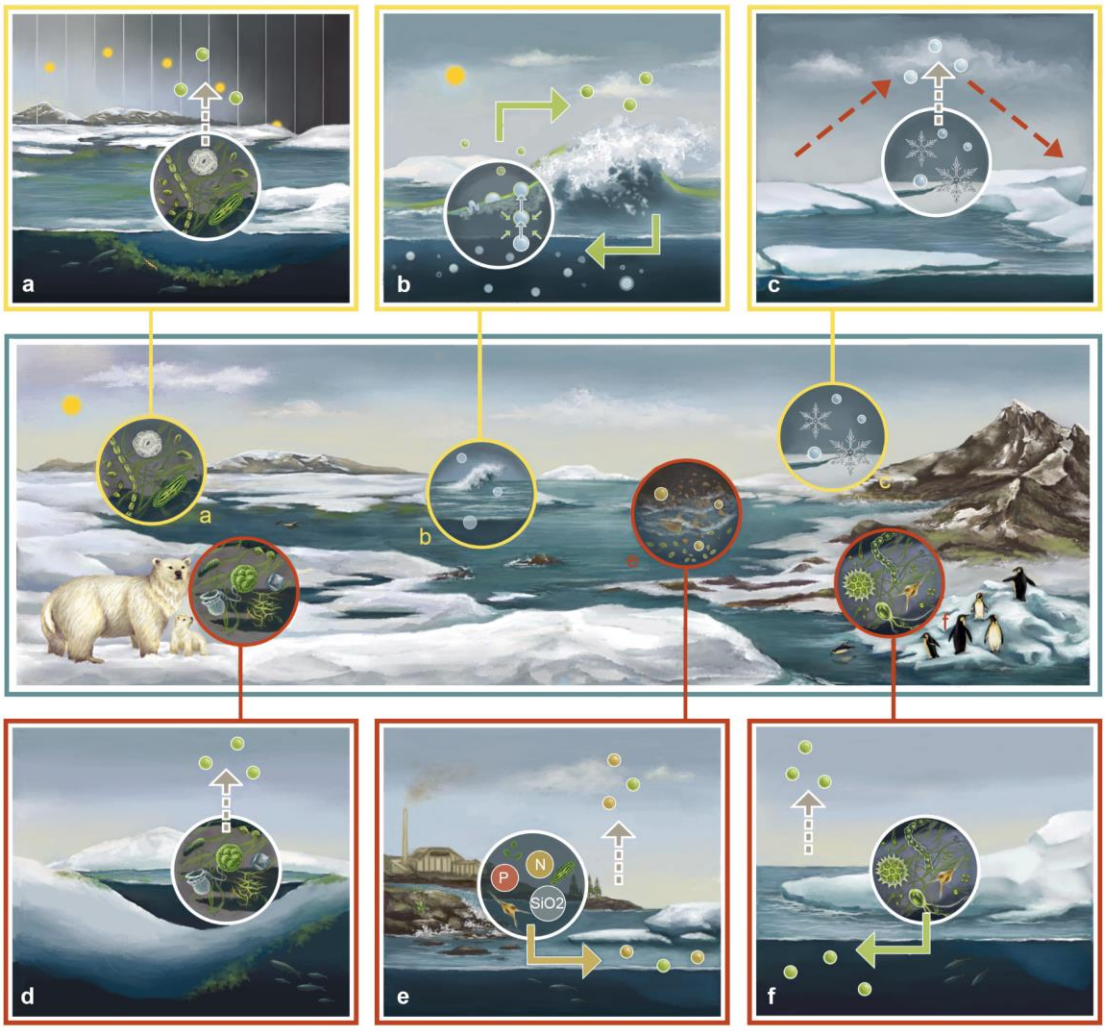

Figure 1. Conceptual framework of key primary aerosol sources and emission processes in polar sea-ice regions. Center panel: Conceptual overview of primary aerosol sources and emission processes in the polar environment. Key processes are magnified in sub-panels and color-coded to reflect the current level of scientific understanding: yellow represents not well understood processes and red denotes particularly poorly constrained mechanisms. Top row sub-panels: a) seasonal cycle of primary biological aerosol emissions; b) bubble bursting and wave breaking as mechanisms for sea spray aerosol production, incorporating material from both the bulk seawater and the sea surface microlayer (SML); c) aerosol emissions from open leads and blowing snow during the polar winter, spring, and fall. Bottom row sub-panels: d) potential emissions from melt ponds during seasonal melt; e) introduction of primary materials into the coastal ocean via river runoff and processing of terrestrial organic matter before emission into the atmosphere; f) glacial discharge contributing aerosol-relevant materials to coastal waters before atmospheric emission.

This paper reviews the current state of knowledge regarding the sources and sinks, as well as emission and transformation processes, of primary aerosols in the Arctic and Antarctic (including the Southern Ocean) across the ocean-sea ice-snow-atmosphere interfaces. We discuss how primary aerosol

properties are driven by seawater and sea-ice biogeochemistry and delve into the current state of numerical models representing primary aerosol abundances, sources, and their impacts on polar clouds. Finally, we highlight the most important modeling and observational gaps and provide opportunities for future research. The overarching goal of this paper is to clearly delineate what we know and don't know concerning polar primary aerosols and how future research efforts can reduce uncertainties regarding their impacts on the polar and global climate systems. We place particular emphasis on prospects for future directions in addressing knowledge gaps in polar primary aerosol research through interdisciplinary collaboration.

2. Primary aerosol lifecycle and climate properties in the coupled ocean-sea ice-snow-atmosphere system

2.1. Key categories of primary aerosols in polar marine environments

Primary aerosols in marine environments encompass a diverse array of particle types, including (1) sea salt aerosol, (2) primary biological aerosol particles (PBAPs), (3) primary organic aerosol (POA), and (4) sea salt + POA mixtures (e.g., Blanchard, 1989; Hawkins and Russell, 2010; Gantt and Meskhidze, 2013; Orellana and Leck, 2015; Quinn et al., 2015; Patterson et al., 2016; Schiffer et al., 2018). Table 1 summarizes flux estimates of these primary aerosol types based on a collection of previous work, organized into subtypes if accessible. These estimates are largely derived from global studies, as data specific to polar regions are often unavailable. The reported flux ranges are typically large because existing modelling estimates are limited and/or observations are spatially and temporally sparse. While PBAPs are often considered a subclass of POA, their distinct emissions, physicochemical properties, atmospheric reactivity and transport, and measurement approaches indicate that they represent a fundamentally different aerosol class (e.g., Després et al., 2012; Gantt and Meskhidze, 2013; Freitas et al., 2025). Characterizing them separately, and how they are represented in models, is therefore essential for accurately assessing their roles as CCN and INPs (Section 2.7). Thus, we define them as separate categories here.

PBAPs includes intact cells and cellular fragments of eukarya—such as sea-ice algae and picophytoplankton (0.2–2 μm), nanophytoplankton (2–20 μm), microphytoplankton (20–200 μm)—, fungal spores (5–40 μm), proteins and enzymes (1–10 nm), bacteria (0.2–4 μm), archaea (0.7–4 μm), viruses (20–100 nm), and detritus of various sizes (Lambshead and Schalk, 2001; Després et al., 2012; Fröhlich-Nowoisky et al., 2012; Tesson et al., 2016; Rozema et al., 2017; Moallemi et al., 2021). In Arctic sympagic environments, PBAPs often originate from a combination of long-range transported sources, such as fungal spores, and local contributors like sea ice-associated bacteria (e.g., *Cryolivonia* and marine taxa like *Polaribacter* (Beck et al., 2024; Barry et al., 2025). In the Arctic Ocean, where glacial melt and riverine discharge strongly influence oceanic conditions, additional PBAP contributions may arise from glacial and permafrost-derived soils (Perring et al., 2023; Barry et al., 2023; Wieber et al., 2025; Jensen et al., 2025; Nieto-Caballero et al., 2025), further diversifying the aerosol source composition. Far fewer measurements of PBAPs exist for the Antarctic compared to the Arctic. Unsurprisingly, most observed PBAPs over the Southern Ocean appear to be of marine origin (Uetake et al., 2020) but closer to the Antarctic continent can originate from terrestrial sources (Cao et al., 2021). However, studies have yielded conflicting evidence regarding the influence of meteorological conditions on microbial community composition. Some report clear variability with changing weather patterns in the Southern Ocean along the Antarctic coast (Cao et al., 2021; Malard et al., 2022), while others find little to no correlation when examining the entire latitudinal band from Tasmania to Antarctica (Uetake et al., 2020).

POA includes a diverse array of organic compounds such as carbohydrates, fatty acids, lipids, and extracellular DNA (Gantt and Meskhidze, 2013); POA-only particles are often smaller than 0.2 μm in diameter (Bigg, 2007; Bigg and Leck, 2008). We specifically define POA here as molecular, refractory, or excretory materials from PBAPs. Saccharides are commonly observed in polar primary aerosol (e.g., Hawkins and Russell, 2010; Russell et al., 2010; Gao et al., 2012; Kirpes et al., 2019; Cravigan et al., 2020; Zeppenfeld et al., 2021; Zeppenfeld et al., 2023). Large polysaccharide chains bridged with divalent cations form what are called extracellular polymeric substances (EPS), which are emitted as macromolecular organic gel particles or as coatings on sea salt aerosol (Orellana and Leck, 2015; Kirpes et al., 2019; van Pinxteren et al., 2022; Mirrielees et al., 2024). EPS can further contain other chemical substances, such as sulfates, lipids, fatty acids, proteins, and nucleic acids (Ewert and Deming, 2013; Decho and Gutierrez, 2017). Often, primary aerosols from marine environments are a complex mixture of many of these materials, reflecting the biogeochemical composition of their emission source (Facchini et al., 2008; Prather et al., 2013; Quinn et al., 2015; Twohy et al., 2021).

Table 1. Summary of primary aerosol flux emission estimates. Includes type/subtype, flux estimate range, location, and reference(s). When available, flux estimates include uncertainty. The unit for range is in teragrams per year. Subtypes marked with a question mark, N/A under reference(s), and rows greyed out indicate estimates are not available to date, to our knowledge. Arctic and Antarctic are separated if estimates exist for at least one and/or both. Arctic and Antarctic estimates are highlighted in shades of blue.

Primary aerosol type	Flux estimate range (Tg yr^{-1})	Location	Reference(s)
Sea salt	3,000–70,000	Global	(Jaeglé et al., 2011; Grythe et al., 2014)[1]
Sea salt from open ocean	0.78–6.37	Arctic	(Huang and Jaeglé, 2017; Confer et al., 2023; Leon-Marcos et al., 2025)
Sea salt from open ocean	1	Antarctic	(Huang and Jaeglé, 2017)
Sea salt from blowing snow	0.2–2.24	Arctic	(Huang and Jaeglé, 2017; Confer et al., 2023; Lapere et al., 2024)[2]
Sea salt from blowing snow	2.5	Antarctic	(Huang and Jaeglé, 2017)[2]
Sea salt from leads	0.1–2.24	Arctic	(Confer et al., 2023; Lapere et al., 2024; Emme and Horowitz, 2025)
Sea salt from leads	?	Antarctic	N/A
PBAPs	35	Global	(Fröhlich-Nowoisky et al., 2012)[3]
PBAPs	?	Polar	N/A
Bacteria	0.04–1.8	Global	(Burrows et al., 2009)
Bacteria	?	Polar	N/A
Fungi	17	Global	(Elbert et al., 2007)
Fungi	?	Polar	N/A
POA	95	Global	(Fröhlich-Nowoisky et al., 2012)[3]
POA	?	Polar	N/A
Marine POA	7.9–9.4	Global	(Meskhidze et al., 2011)
Marine POA	?	Polar	N/A
Marine organics from bacteria	3.7	Global	(Gantt and Meskhidze, 2013)
Marine organics from bacteria	?	Polar	N/A
Marine organics from bubbles	10±5	Global	(Gantt and Meskhidze, 2013)
Marine organics from bubbles	?	Polar	N/A
Organics from leads	0.02–0.35	Arctic	(Confer et al., 2023)
Organics from leads	?	Antarctic	N/A
Polysaccharides	0.03±0.01	Tropical oceans	(van Pinxteren et al., 2023)[4]
Polysaccharides	?	Global	N/A

Polysaccharides	0.0004	Arctic	(Leon-Marcos et al., 2025)
Polysaccharides	?	Antarctic	N/A
Amino acids	0.04±0.02	Tropical oceans	(van Pinxteren et al., 2023)[4]
Amino acids	?	Global	N/A
Amino acids	0.002	Arctic	(Leon-Marcos et al., 2025)
Amino acids	?	Antarctic	N/A
Lipids	4.2±2.1	Tropical oceans	(van Pinxteren et al., 2023)[4]
Lipids	?	Global	N/A
Lipids	0.06	Arctic	(Leon-Marcos et al., 2025)
Lipids	?	Antarctic	N/A

[1]Grythe et al., 2014: Dp < 10 μm; [2]Huang and Jaeglé, 2017: Dp < 1 μm; [3]Fröhlich-Nowoisky et al., 2012: 0 < Dp < 2 μm; [4]van Pinxteren et al., 2023: Dp < 1 μm

Primary aerosol emissions in the polar regions are shaped by strong seasonal variability in radiation, surface temperature, snow and ice cover, and biological activity (Figure 1a). Common sources across both the Arctic and Antarctic/Southern Ocean include sea-ice leads (Figure 1c; see Sections 2.2.1 and 2.3.1) and blowing snow (see Section 2.3.2), though important regional distinctions exist (Reiser et al., 2020). Both regions' sympagic systems are increasingly influenced by local terrestrial aerosol sources. Riverine inputs (including from terrestrial, subglacial, and supraglacial rivers) further complicate aerosol composition (Figure 1e), especially in the Arctic, where they transport organic and inorganic material into the ocean (e.g., Irish et al., 2017; Park et al., 2019). Particularly in the Arctic, dust exposed by glacial retreat or runoff (Figure 1f) has become a significant contributor (Bullard et al., 2016; Gassó et al., 2018), mostly in coastal zones (Bhattachan et al., 2015; Simmons et al., 2021; Perring et al., 2023; Meinander et al., 2025). Once deposited into marine waters, terrestrial particles may be chemically and biologically modified and re-emitted as sea spray aerosol (Li et al., 2008; Csank et al., 2019; Cornwell et al., 2020; Weis et al., 2024).

In the Arctic, aerosol populations reflect a mix of natural and anthropogenic influences. Wintertime is dominated by long-range transport of pollution, soot, and mineral and soil dust from lower latitudes (Abbatt et al., 2019; Schmale et al., 2021; Humphries et al., 2023), while summertime sees greater contributions from regional natural sources, aided by shifts in atmospheric circulation and enhanced wet deposition (Stohl, 2006; Schmale et al., 2021; Schmale et al., 2022). The Antarctic, by contrast, remains largely free of direct anthropogenic influences, resulting in a comparatively cleaner atmosphere (Stohl and Sodemann, 2010). However, high-latitude dust sources are emerging in Antarctica, though their impact is less pronounced (Bullard et al., 2016; Bullard, 2017). While a detailed review of geogenic sources is beyond the scope of this manuscript, their emerging significance in both regions warrants further investigation.

Across studies, there is general agreement that sea salt dominates primary marine aerosol mass fluxes, while PBAPs and POA contribute smaller but climatically relevant fractions. PBAP community composition differs widely between the Arctic and Antarctic regions, reflecting both true spatial variability and methodological inconsistencies, but flux estimates are not yet established in the high latitudes. Similarly, POA composition, particularly the abundance and role of polysaccharides and extracellular polymeric substances, shows broad qualitative agreement but limited quantitative consensus. Overall, the synthesis of available work highlights that polar primary aerosol emissions remain highly uncertain, emphasizing the need for more region-specific, process-based observations.

2.2 Physical and biogeochemical influences of ocean and sea ice on primary aerosol composition

In polar regions, the nature of the surface (i.e., open ocean versus sea ice) strongly influences aerosol properties, affecting both their quantity and composition. While both the Arctic and Southern

Oceans share low temperatures and extreme light variability, they differ fundamentally in geography and dynamics, and thereby in sea-ice coverage and characteristics. The Arctic is a semi-enclosed ocean surrounded by land, while the Southern Ocean encircles Antarctica and is openly connected to the global ocean. As a result, the Southern Ocean is a "high-energy" environment, characterized by strong waves that penetrate deep into the ice pack, breaking and rafting the ice. In contrast, the Arctic is relatively "low-energy," with extensive land-fast ice and persistent melt ponds in spring and summer (Figure 1d). Geographically, the Arctic lies at higher latitudes and supports thicker, colder sea ice, whereas the Southern Ocean experiences more snowfall and is more heavily influenced by ice shelves and their melt and calving (Figure 1f). Arctic Ocean circulation and biogeochemistry, on the other hand, are strongly shaped by river inflows (Figure 1e; see Section 2.2.3). These distinct freshwater sources likely host different microbial communities, influencing local aerosol properties. Climate change may be driving convergence in some of these processes, i.e., as Arctic sea ice becomes thinner, more mobile, and less snow-covered, and as Antarctic ice melt and freshwater input increase. However, studies often agree that long-term consequences remain uncertain (e.g., Granskog et al., 2017; Webster et al., 2021).

Biogeochemical models, which are embedded into physical oceanographic models, generally represent the ocean ecosystem in the form of a "NPZD" model (e.g., Deal et al., 2014), including one or more forms of nutrient (N), phytoplankton (P), zooplankton (Z), and detritus (D). Some numerical models also include prognostic representations of ice algae (e.g., Watanabe et al., 2019) and fauna (e.g., Sibert et al., 2010). These components are computed in the near-surface ocean and in the bottom sea-ice layer and are available for parameterizations of primary aerosol precursors. Organic matter transfer directly to the atmosphere requires parameterizations which link the organic material to mechanisms such as bubble bursting or wave breaking (Figure 1b; see Section 2.3). In addition to the NPZD loop, many models include inorganic carbon cycling (dissolved inorganic carbon and alkalinity (e.g., Mortenson et al., 2020), and some models represent the role of the ocean and sea ice in the emission of other trace gasses, such as dimethyl sulfide (DMS) and isoprene (Conte et al., 2020; Hayashida et al., 2020). However, not all of these models include both prognostic representations of ice algae and inorganic carbon cycling, which may lead to different predictions.

2.2.1 Open seawater

In open ocean water, including sea-ice leads and polynyas (Figure 1c), the composition of primary aerosols generated by sea spray (which includes sea salt aerosol, PBAPs, and POA) will be determined by biogeochemical dynamics in the water and ice, as well as the mechanics of spray generation (Section 2.3.1). Arctic sea-ice leads are a known source of primary aerosol from a consensus of studies (Scott and Levin, 1972; Radke et al., 1976; Nilsson et al., 2001; Leck et al., 2002; Held et al., 2011; Quinn et al., 2015; May et al., 2016; Kirpes et al., 2019; Chen et al., 2022), while Antarctic leads have not been studied as extensively. Sea spray aerosol composition reflects that of the seawater, and a particle with the same chloride-to-sodium ratio ($[Cl^-]/[Na^+]$) as seawater indicates nascent, local production (Leck et al., 2002). Depending on factors such as sea-surface salinity and temperature (Liu et al., 2021; Sofieva et al., 2022; Zinke et al., 2022) and primary productivity (Tumminello et al., 2021; Radoman et al., 2022; Santander et al., 2022), studies have shown that sea spray aerosol may be enriched in different materials like surface active substances (Bigg and Leck, 2008), calcium (Salter et al., 2016), transition metals (Guasco et al., 2014), and organic matter (Quinn et al., 2015) relative to the seawater from which they originate.

The composition of sea spray aerosols is impacted by the seasonality of oceanic biological productivity (Orellana and Leck, 2015; Twohy et al., 2021; Dall'Osto et al., 2022; Figure 1a). The

relationships between marine biological processes and sea spray aerosol properties is complex, with much investigation still needed. Biological primary production is generally higher in the Southern Ocean than in the Arctic Ocean due to abundant macronutrients such as nitrate and phosphate (Harrison and Cota, 1991). However, large regions of the Southern Ocean are limited by low iron availability, making sea ice a potentially important reservoir and source of iron for the ecosystem (Martin et al., 1990; Lannuzel et al., 2016). In contrast, the Arctic Ocean is less prone to iron limitation, thanks to inputs from surrounding land and shallow continental shelves (Krisch et al., 2020). During phytoplankton blooms, organic matter has been shown to dominate the submicron mass fraction (aerosols with diameters < 1 μm), while during low biological activity, sea spray aerosol consists almost entirely of salts (e.g., O'Dowd et al., 2004; Facchini et al., 2008). However, other studies have suggested that the aerosol composition is not correlated with local productivity but rather connected to the generally high reservoir of recalcitrant dissolved organic matter in the ocean (Quinn et al., 2014; Kieber et al., 2016). Further, Kirpes et al. (2019) showed higher sea spray aerosol organic content when sea ice was nearby, even in Arctic winter, compared to biologically-productive open water at the same location. Mirrielees et al. (2024) found no clear relationship between microbial composition, chlorophyll-a (an indicator of algae biomass), dissolved organic carbon, dissolved organic nitrogen, particulate organic carbon, or particulate nitrogen with size or concentrations of sea spray aerosol organics during Arctic summer. Yet, Rocchi et al. (2024) showed that seawater glucose content and temperature, rather than chlorophyll-a or bacterial and phytoplankton abundances, best explained observed sea spray aerosol production and size distributions.

Sea spray aerosol produced near sea ice is often particularly enriched in organic matter (up to 50% by volume), rivaling aerosols associated with mid-latitude water blooms (Eom et al., 2016; Kirpes et al., 2019; Cravigan et al., 2020). Ice melt stratifies surface waters, triggering large phytoplankton blooms in the MIZ during spring and early summer (Barber et al., 2015). These blooms may coincide with peak biological aerosol emissions (Yan et al., 2020), though recent Arctic observations suggest rising fall bloom frequency and storm activity could extend the PBAP production season into autumn (Ardyna et al., 2014). Conversely, stratification can also reduce primary production by limiting nutrient supply from subsurface waters (e.g., Tremblay et al., 2015; Ardyna et al., 2020), thereby reducing marine primary aerosol production in some cases. PBAPs in marine environments reflect different community compositions observed between seawater and aerosols, implying preferential emission of certain species (Fahlgren et al., 2010; Freitas et al., 2022). Hence, the connection between oceanic productivity, seawater community composition, and aerosol emission rates and composition is not straightforward (Mirrielees et al., 2024) and is likely changing along with the climate.

Direct transfer of materials between the water and atmosphere passes through the sea-surface microlayer (SML; Figure 1b), which concentrates organic material in a thin layer (10s to 100s of μm) at the surface (e.g., Hardy, 1982; Cunliffe et al., 2013; Engel et al., 2017). Many compound classes that are commonly enriched in the SML have also been detected in aerosols (Cochran, et al., 2017). For example, mid-latitude mesocosm experiments have shown individual saccharides to be enriched by up to 16 times that of the SML, with greater enrichment in sea spray aerosol (3 to 1,314 times) compared to bulk seawater (Jayarathne et al., 2016). In the Arctic, Zeppenfeld et al. (2023) found marine carbohydrates to be enriched in the SML compared to the bulk seawater and much further enriched in aerosol particles. Enrichment in the SML is generally expressed as the ratio of the compound concentration in the SML to that in bulk seawater, whereas aerosol enrichment is commonly expressed relative to sodium as a conservative sea salt tracer, yielding a dimensionless enrichment factor (e.g., Quinn et al., 2015, and references therein). While the SML is not explicitly represented in most biogeochemical models (Burrows et al., 2022), at least one

parameterization for SML exchange processes has been developed (Pound et al., 2024). However, there have been few opportunities for model-measurement comparisons of SML and sea spray aerosol composition for detailed evaluation.

Overall, while Arctic leads and the MIZ are recognized as key sources of sea spray aerosols, Antarctic contributions are less studied, and the relationship between seawater composition and aerosol organics remains inconsistent across studies. Limited observations and strong spatiotemporal variability make it difficult to quantify organic content, highlighting a major knowledge gap.

2.2.2 The sea-ice environment

Sea ice, with its surface brine skim and snow, as well as melt ponds, plays a key role in polar aerosol production, contributing organic and inorganic primary aerosols distinct from traditional "sea spray aerosol". Its unique microbial habitat including viruses, bacteria, microalgae, and small organisms (Bluhm et al., 2017) generates EPS and dimethylsulfoniopropionate (DMSP), a precursor to DMS, and methanethiol, a major source of secondary aerosol (Krembs and Engel, 2001; Bayer-Giraldi et al., 2011). Studies have indicated that the concentration of bacteria in sea-ice brines can exceed that observed in seawater (Krembs and Engel, 2001; Riedel et al., 2007; Collins et al., 2008; Collins and Deming, 2011). To survive in the ice, microorganisms produce a number of organic substances as intra- or extracellular antifreeze and ice-binding proteins (e.g., Bayer-Giraldi et al., 2011; Winder et al., 2023). These organics accumulate in sea-ice brine channels and then are released into the underlying seawater, enriching the SML and contributing to organic coatings on sea spray aerosol released from sea-ice leads (Section 2.2.1).

While bacteria and viruses persist year-round throughout sea ice at both poles, algal biomass distributions differ between poles: in the Arctic, algae generally concentrate near the ice bottom due to the predominance of stable, thicker, and landfast ice (e.g., Arrigo et al., 2012; Meiners et al., 2012; Leu et al., 2015; Meiners et al., 2018), whereas in the Antarctic/Southern Ocean, thinner, more dynamic pack ice promotes algal growth throughout the column, including surface layers, due to flooding and rafting (Kattner et al., 2004; Weeks, 2010; Arrigo, 2017). Rafting and flooding supplies nutrients to the upper parts of the sea ice, in gap layers and in snow. This structural contrast between Arctic and Antarctic sea ice likely affects aerosol composition and emission potential, although as yet, there is little direct evidence to quantify that comparison. Arctic multi-year ice typically hosts shade-adapted algal communities, whereas first-year ice supports algae better suited to high, variable light; the transition toward younger ice could shift community composition and aerosol output (Campbell and Lorenz, 2022). Multi-year ice has always been rare in the Southern Ocean. Light transmission supporting under-ice phytoplankton growth is limited by snow on sea ice and the sea ice itself. In the Arctic, melt ponds are a dominating feature in spring, allowing enhanced light transmission (e.g., Light et al., 2008; Webster et al., 2015) and ice algal growth (Leu et al., 2015), while thinner, more mobile ice enables frequent and extensive blooms in both polar regions (Ardyna et al., 2020; Horvat et al., 2022; Figure 1a).

Sublimating blowing snow over sea ice contributes to aerosol concentrations (Figure 1c), especially during polar winters as described in more detail in Section 2.3. High concentrations of EPS and bacteria have also been observed at the surface of the ice, including in snow and frost flowers (Ewert et al., 2013; Barber et al., 2014), with potential to be transferred to the atmosphere with blowing snow. Similarly, particulate inorganic salts can be released into the atmosphere from shallow snowpacks due to the migration of brine up to the snow-atmosphere interface or from precipitated solid salts within the bottom layers of the snow as the sea-ice surface cools and brine channels and pockets contract (Assur, 1960; Wagenbach et al., 1998; Dieckmann et al., 2008; Whitehead et al., 2012; Hara et al., 2017; Petrich and Eicken, 2017). The

sequential precipitation of different salts from sea-ice brines, as the temperature decreases, imparts a clear ionic fractionation to the salt aerosols associated with blowing snow that is distinct from sea spray aerosol (Wagenbach et al., 1998; Frey et al., 2020). In addition, sea salt aerosol deposited at the snowpack surface (Domine et al., 2004) may be re-lofted. Changes in snowpack depth on sea ice (Webster et al., 2018) will impact whether brine reaches the snow-atmosphere interface (Domine et al., 2004). The role of frost flowers as a source of primary aerosols remains debated. Observational and modelling studies have suggested that frost flowers might (Rankin et al., 2000; Xu et al., 2016; Hara et al., 2017) or might not (Roscoe et al., 2011; Yang et al., 2017) contribute to sea salt aerosol production.

Recent work suggests that fresh meltwater reservoirs, like melt ponds (Figure 1d), are a potential source of primary aerosol (Leck and Bigg, 2005; Yan et al., 2020; Creamean et al., 2022; Smith et al., 2023; Mirrielees et al., 2024; Mavis et al., 2025), with notable variations and highest aerosol precursor concentrations in the MIZ and near aged melt ponds (Zeppenfeld et al., 2023). As the microbial community of meltwater often differs from seawater (Xu et al., 2020; Smith et al., 2023), this might impact the generated aerosols (Hardge et al., 2017; Rapp et al., 2018). Mirrielees et al. (2024) generated aerosols using melt pond water, finding the resulting aerosol organic composition to be enriched in long-chain fatty acids and siliceous material compared to seawater-generated aerosols that were dominated by carbohydrates. However, the prevalence, magnitude, and mechanisms of aerosol emissions from melt ponds are unknown and unquantified. Melt pond parameterizations in models usually only include their impact on albedo and light transmission and do not explicitly include any biogeochemical processes, much less aerosol emissions. Under future climate scenarios, the marine environments at both poles undergo distinct changes, potentially altering the availability of primary aerosol sources and their emission processes. The Arctic sea ice has been steadily diminishing over the past few decades (Cai et al., 2021) and so far, is responding more rapidly to climate change than the Antarctic (Shokr and Ye, 2023). Projections indicate the Arctic could become ice-free in September by 2050 (e.g., Kim et al., 2023). Whereas Antarctic sea ice has exhibited a slow increase over past decades, recent trends indicate a rapid decline (Eayrs et al., 2021), which, intriguingly, may contribute to future warming all the way in the Arctic (England et al., 2020).

Overall, observations consistently show that blowing snow contributes to aerosol concentrations, whereas the role of frost flowers remains debated, with some studies indicating they are a source of sea salt aerosols and others suggesting minimal contribution. Melt ponds are acknowledged as potential aerosol sources, but the prevalence, magnitude, and mechanisms of their emissions remain uncertain and appear to vary by location and season.

2.2.3 Freshwater inputs

Freshwater inputs (through river discharge, glacial runoff, and coastal permafrost thaw) could influence primary aerosol precursor materials in several ways. Freshwater inputs into polar oceans represent significant sources of nutrients such as nitrate, phosphate, and iron (e.g., Minghui Zhang et al., 2021; Samui et al., 2024; Figure 1e). These inputs can alter coastal ocean biogeochemistry, yet their role in driving primary aerosol emissions at the air–sea interface remains poorly understood. They can also introduce terrestrial biological and lithogenic materials that may become airborne as sea spray aerosol (Dall'Osto et al., 2022; Cornwell et al., 2020; Mirrielees et al., 2024). Changes in water salinity also impact primary aerosol production (May et al., 2016; Zinke et al., 2022; Rocchi et al., 2024). Moreover, freshwater-induced stratification from rivers alters vertical nutrient and phytoplankton distributions, both of which affect the timing and magnitude of biological activity in sea ice and surface waters (Vancoppenolle et al., 2013; Lannuzel et al., 2020; Gibson et al., 2022). The freshwater content of the surface water also impacts the

structure and consistency of sea ice (Petrich and Eicken, 2017), with implications for brine expulsion, gas exchange, and microbial activity in the ice, snow, and upper ocean, processes that could indirectly shape the composition and flux of primary aerosols. The freshwater content of the seawater can be identified using salinity, oxygen isotope analysis, turbidity, and colored dissolved organic matter (Cooper et al., 2022; Kim and Timmermann, 2024).

In the Arctic, freshwater contributions are substantial and year-round, originating from rivers, streams, and thawing permafrost (Carmack et al., 2016; Ahmed et al., 2020; Brown et al., 2020; Shiklomanov et al., 2021), as well as glacial outflows from Greenland (Csank et al., 2019; Perner et al., 2019). In the Antarctic, similar inputs from glacial melt and outflow (e.g., Gilbert and Kittel, 2021; Goldberg et al., 2023; Davison et al., 2024) may become increasingly important. While the Southern Ocean is currently freshening more slowly than the Arctic, this balance may shift (Silvano et al., 2025). Antarctic glacier melt, the dominant source of Southern Ocean freshening (Pan et al., 2022), coupled with recent declines in Antarctic sea ice, may lead to more rapid freshening and stratification in the future. Freshwater dynamics may differentially influence biotic and abiotic primary aerosol sources (see Sections 2.4.1, 2.4.2), especially in coastal environments leading to primary sea spray aerosol production (Park et al., 2019; 2022). Even so, observational constraints on how these processes translate to aerosol production and properties remain limited, and thus yield a poorly understood aspect of polar aerosol-climate interactions.

2.3 Emission processes

2.3.1 Sea spray aerosol emission mechanisms

Direct emissions from leads have been observed to contribute to the variability in particle concentrations and composition in the atmospheric boundary layer adjacent to the leads (Scott and Levin, 1972; Radke et al., 1976; Nilsson et al., 2001; Leck et al., 2002; Held et al., 2011; May et al., 2016; Chen et al., 2022). Mechanistically, sea spray aerosols are mainly produced through wind-driven bubble bursting processes at the surface of open seawater (Figure 1b; Quinn et al., 2015; Deike et al., 2022; Jiang et al., 2022). Smaller film drops produced during bubble bursting and with a greater SML influence are enriched in organics, while larger jet drops primarily contain inorganic salts, more reflective of the bulk seawater (Leck et al., 2002; Bigg and Leck, 2008; Gantt and Meskhidze, 2013; Quinn et al., 2014). This enrichment occurs during droplet production when the bubble film collapses at the air-water interface, primarily scavenging surface-active organics in the SML in the form of small and numerous drops (Wang et al., 2017). The resulting sea spray aerosol population is then a mixture of aerosols, with varying organic enrichments, produced from both film and jet drops (Wang et al., 2017). Nilsson et al. (2001) also found emissions from leads to be dominated by supermicron aerosols (diameters > 1 μm) by number, as compared to submicron aerosols from open water, suggesting differences in chemical composition due to differences in seawater bubble size distributions when sea ice is present (Norris et al., 2011). The chemical nature of the organic matter in seawater, particularly the surfactant activity and solubility, plays a key role in the bubble mediated transfer of molecules from the sea-air interface to the atmosphere (Cochran et al., 2017).

The flux of sea spray aerosol produced from open water bubble bursting increases with wind speed (Quinn et al., 2015), including from sea-ice leads (Nilsson et al., 2001; Leck et al., 2002), yet has lower organic content as demonstrated by mid-latitude sea spray aerosol laboratory studies (Madawala et al., 2024). Sea spray aerosol generation from leads, compared to the open ocean, is inhibited by the presence of sea ice (Nilsson et al., 2001), which reduces fetch (the distance wind blows over open water) and thereby wave action (Smith and Thomson, 2016). As a result, sea spray aerosol emission rates are expected to

increase with lead size, which can range up to several kilometers in width and up to hundreds of kilometers in length (Li et al., 2020) and be greatest for polynyas, particularly coastal polynyas that are maintained by high winds, such as the katabatic winds descending off the Antarctic continent (Yan et al., 2020). Even without wave action, leads in the pack ice have been observed to be "bubbly" (Norris et al., 2011), with aerosol production (Held et al., 2011). Norris et al. (2011) suggested that the substantial numbers of bubbles they observed under conditions of low wind speed, short open water fetch, and cooling surface waters were due to complex lead dynamics and/or sea-ice formation. Additional likely sources of bubbles from narrow leads include sloshing of water against ice, gas released from melting sea ice (Nilsson et al., 2001), and gas emitted during microbial cellular respiration (Johnson and Wangersky, 1987).

Sea spray aerosol emissions in most atmospheric models are represented as pure sodium chloride from the open ocean only (see Section 3.2), however recent studies have started to include more detail on sea salt (e.g., Prank et al., 2022). Common parameterizations of sea salt aerosol emissions are a nonlinear function of 10-m wind speed that varies by particle size (Monahan et al., 1986; Gong, Barrie, and Blanchet, 1997; Gong et al., 1997; Gong, 2003). The emissions of smaller (< 1.4 to 2.5 μm) sea salt aerosols in many atmospheric chemical transport and coupled earth system models (ESMs) additionally vary as a function of sea-surface temperature, following Mårtensson et al. (2003), while the Monahan et al. (1986) wind speed-only parameterization is used for larger particles (e.g., Soares et al., 2016; Paulot et al., 2020; Zhao et al., 2021). Some aerosol models simply extrapolate source functions valid for larger particles to the smaller sizes (Grythe et al., 2014), whereas others use a parameterization that comprises a broad size spectrum (Long et al., 2011) and includes observationally-constrained dependence on sea-surface temperature for all sizes (Jaeglé et al., 2011; Sofiev et al., 2011; Ovadnevaite et al., 2014; Gantt et al., 2015; Barthel et al., 2019; Ioannidis et al., 2023). A few models have begun to incorporate a separate marine organic aerosol component emitted as sea spray (e.g., Meskhidze et al., 2011; Gantt et al., 2015; WTK Huang et al., 2018; Burrows et al., 2022; Ioannidis et al., 2023). These include a physically-based scheme dependent on ocean biogeochemistry (in ESMs; McCluskey et al., 2019; Burrows et al., 2022; Zhao et al., 2021), and an empirical function based on observed seawater chlorophyll-a concentrations (in atmospheric chemical transport models; Gantt et al., 2012; Gantt, Johnson, et al., 2015; Vergara-Temprado et al., 2017), despite the fact that observations show there is a poor correlation between sea spray aerosol organic content and chlorophyll-a (Collins et al., 2016; Rocchi et al., 2024). However, due to limited availability of proxies from models or remote sensing that represent microbial activity within the surface ocean, chlorophyll-a remains in use due to lack of an alternative that is more reasonable. The latest climate models from IPCC still significantly underestimate sunlight reaching the Southern Ocean surface compared to satellite data (e.g., Mallet et al., 2023). This highlights major gaps in our understanding and modeling of cloud formation in the region, which is likely linked to major uncertainties in natural aerosol sources including primary emissions from the Southern Ocean. McCluskey et al., (2023) studied Southern Ocean aerosol and INPs in the Community Earth System Model version 2 and major uncertainties in simulated aerosols in this region, which cascading impacts on predicted clouds, and is a longstanding issue (Murphy et al., 1998).

Limited atmospheric chemical transport model studies have included sea salt aerosol emissions from open sea-ice leads, and in the Arctic only, either parameterized using the same functions as open ocean emissions (Ioannidis et al., 2023; Emme and Horowitz, 2025) or based on the flux measurements from Nilsson et al. (2001) (Lapere et al., 2024). For the spatial extent of leads, these studies have used sea-ice concentration from reanalysis meteorology, or lead fraction from sea-ice reanalysis, sea-ice models, or satellite products. Existing satellite-based estimates of lead fractions in the Arctic disagree substantially in magnitude and variability, depending on the sensor and algorithm used (von Albedyll et al., 2023). Certain

products (e.g., from MODIS; Reiser et al., 2020) are unable to distinguish between thin-ice covered and open leads, leading to overestimates of sea ice lead emissions (Lapere et al., 2024), while some are unable to resolve leads smaller than 1-3 km (e.g., Röhrs and Kaleschke, 2012; von Albedyll et al., 2023), which may lead to underestimates.

Climate-change associated decreases in Arctic and Antarctic sea-ice concentrations and increases in wind speeds are expected to amplify wave energy and heights (Casas-Prat and Wang, 2020), thereby increasing polar sea spray aerosol emissions. In the Arctic, the summer period of open water is lengthening with earlier melt and delayed freeze-up (Johnson and Eicken, 2016; Årthun et al., 2021), thereby expanding the time frame and spatial extent for open water sea spray aerosol emissions. Thinning Arctic sea ice (e.g., Lindsay and Schweiger, 2015; Sumata et al., 2023) increases the prevalence of ice fracturing (Rheinlænder et al., 2024), even in the cold season, which results in greater lead coverage, and greater sea spray aerosol emissions, year-round (May et al., 2016).

Collectively, observations agree that sea-ice leads contribute to aerosol variability, with bubble-mediated sea spray producing both organic-rich film drops and mainly inorganic jet drops. Emissions increase with lead size and wind speed but are reduced by ice cover, though smaller leads can still produce aerosols via melting ice and microbial activity. Models show large uncertainty (few include lead-specific emissions, satellite-based lead fractions disagree, and organic content is often underestimated) so the overall importance of lead emissions remains unclear. Climate-driven ice loss and stronger winds are expected to amplify lead coverage and sea spray emissions, especially in the Arctic.

2.3.2 Aerosols from blowing snow

Snow on sea ice containing salt has recently been observed to be a source of sea salt aerosol in the polar atmosphere upon snow particle lofting and sublimation (Figure 1c; Giordano et al., 2017; Frey et al., 2020; Gong et al., 2023; Bergner et al., 2025; Heutte et al., 2025). Three main processes can explain the presence of sea salt within polar snow: (1) upward brine migration from sea ice, (2) incorporation of frost flowers buried by snowfall, and (3) dry or wet deposition of advected sea salt aerosol or wind blown frost flowers (e.g., Domine et al., 2004). Brine is found at the top of sea ice as a result of ion exclusion during seawater freezing or of flooding, due to negative freeboard caused by a thick snow cover (Kattner et al., 2004; Ackley et al., 2020). Capillary action drives migration of sea-ice brines from the sea-ice surface into the overlying snowpack by up to a few tens of centimeters in both the Arctic and Antarctic (Massom et al., 2001; Domine et al., 2004). Thus the surface salinity of shallow snowpacks is higher than of deeper snowpacks (Peterson et al., 2019; Frey et al., 2020; Ranjithkumar et al., 2025). Multiphase and photochemical reactions occur on the snow surface, resulting in changes in surface snow chemical composition and the release of reactive halogen gasses (Pratt et al., 2013; Custard et al., 2017; Raso et al., 2017) that may in turn impact blowing snow aerosol composition. For deep snowpacks, the surface snow salinity is dictated most by snow redistribution (Domine et al., 2004) and deposition of sea salt aerosol originating from local sources, including blowing snow and open water (Peterson et al., 2019; Frey et al., 2020; Confer et al., 2023). Salinities of surface and blowing snow over sea ice are generally much lower (<0.5 ‰) compared to the ocean (35 ‰), yet still 1-2 orders of magnitude larger than in surface snow on the terrestrial ice sheets (e.g., Frey et al., 2006).

Under wind action, salty snow particles can be lifted several tens of meters into the atmosphere, and upon sublimation generate dry sea salt aerosol (e.g., Yang et al., 2008; Yang et al., 2019), which carries the distinct chemical fractionation of sea-ice brines. Blowing snow has been found to be a major contributor to the winter and spring sea salt aerosol budget in sea-ice covered regions (Giordano et al., 2017; J Huang

et al., 2018; Frey et al., 2020; Gong et al., 2023; Bergner et al., 2025; Heutte et al., 2025), likely contributing to observed increases in cold season pan-Arctic sea salt aerosol over the last three decades, as first-year sea ice has become predominant over multi-year ice (Confer et al., 2023). For example, in the Antarctic, the number densities of particles with diameters < 2 μm consisting mostly of sea salt increased during individual storms above sea ice by up to 2-3 orders of magnitude above background concentrations of 0.01-0.1 cm^{-3} (Frey et al., 2020). Simulations with global models match observations during winter and spring reasonably well when a blowing snow source is included (e.g., Huang and Jaeglé, 2017; Yang et al., 2019) and allow to assess the impact on the sea salt aerosol budget at regional scales. They show increases in polar wintertime sea salt aerosol number concentrations as high as 70 cm^{-3} in the Antarctic and 50 cm^{-3} in the Arctic when compared to open ocean-only simulations (Ranjithkumar et al., 2025). Another model estimate shows that from November 2019 to April 2020 north of 70 °N, sea salt aerosol produced from blowing snow accounts for about 27.6% of the total particle number (Gong et al., 2023). Even low-salinity snow on top of sea ice holds enough salt to account for observed sea salt aerosol concentration spikes in surface-near air during and after storms (Frey et al., 2020), leading to significant production of sub-micron sea salt aerosol, which can act as efficient CCN and impact regional clouds (see Section 2.7) and the surface radiative energy balance (see Section 2.6).

Sea salt aerosol emissions associated with blowing snow have so far only been included in atmospheric chemical transport models, based largely on the Yang et al. (2008) parameterization (e.g., Huang and Jaeglé, 2017; Rhodes et al., 2017; Frey et al., 2020; Marelle et al., 2021; Gong et al., 2023). The main model parameters driving sea salt aerosol production from blowing snow are snow particle size distribution, snow salinity and age, and meteorology (temperature, wind speed, relative humidity) (Ranjithkumar et al., 2025), yet there are limited measurements for evaluation of these terms. Recent model updates take into account spatial and temporal variability in key model parameters. The snow particle size distribution has been parameterized as a function of wind speed (Ranjithkumar et al., 2025). Snow salinity has been parameterized as a function of snow depth (Confer et al., 2023; Ranjithkumar et al., 2025), whereas Huang et al. (2018) iteratively inferred the seasonal variation in surface snow salinity from computed sea salt aerosol and satellite-derived aerosol extinction. The parameterization of blowing snow itself needs further refinement as it has been shown to significantly over- or underestimate the occurrence of these events likely due to the role of temperature dependent snow metamorphism (Chen et al., 2022; Ranjithkumar et al., 2025), which thereby leads to inaccuracies in modeling aerosol production from blowing snow. Overall, based on existing observational and modelling studies, the relative importance of blowing-snow emissions to primary polar aerosol production remains uncertain, especially in the Antarctic, where observations of these processes are scarce.

2.4 Atmospheric transformation processes after emission

2.4.1 Abiotic processing

Atmospheric processing (aging) includes all the physical, chemical, and biogeochemical processes (see Section 2.4.2) that modify aerosol properties, including number concentration, size distribution, chemical composition, and cloud-forming capabilities. Primary aerosols age through multiphase reactions, condensational growth, and/or coagulation with other particles. Aerosols transported to the polar regions from lower latitudes, undergo substantial atmospheric aging along the way during this transport (Willis et al., 2018), but aging is expected to be slower within the polar atmospheres, due to lower abundances of particles and reactive gasses (Fierce et al., 2015). Increased atmospheric residence times (Freud et al., 2017)

and increased pollution levels during the winter-spring Arctic haze season promote aerosol aging (Barrie et al., 1994). In the Arctic, wintertime secondary sulfate formation is nearly all anthropogenic, with a substantial biogenic component in the summer (Norman et al., 1999; Udisti et al., 2016; Manousakas et al., 2020). Sulfate concentrations in the Arctic cold season have been decreasing since the 1980s because of decreasing emissions in the midlatitudes, but summertime concentrations have been increasing in most regions (AMAP, 2021). It is not clear if recent summertime increases are due to increased natural sulfate from DMS, or to increases in local anthropogenic emissions such as Arctic shipping.

Multiphase reactions during sea salt aerosol transport can lead to enrichment in sulfate and nitrate, with simultaneous chloride depletion through the release of chlorine-containing gasses (including HCl, Cl_2, and $ClNO_2$) that can alter the atmosphere's oxidation capacity (Hara et al., 1999; Kerminen et al., 2000; Hara et al., 2002; Kirpes et al., 2018; Kirpes et al., 2020; Gonçalves et al., 2021; Xue et al., 2024). Reactions which involve ultraviolet light and those that occur during surface ozone depletion and bromine explosion events (Kawamura et al., 2005; Gonçalves et al., 2021; Rosati et al., 2021) are unique to polar day (spring). Additionally, ultraviolet light and acidification reactions can degrade EPS emitted as part of sea spray aerosol (Quinn et al., 2015; Orellana et al., 2021). Primary aerosols can also coagulate with other aerosols, such as secondary aerosols formed by new particle formation, as observed in over the Southern Ocean near the Antarctic coastline (Wang et al., 2023) and in the Arctic (e.g., Korhonen et al., 2008; Struthers et al., 2011).

Oxidized organics also condense onto primary aerosols, further growing particles and changing their composition to include a larger organic fraction than originally emitted (e.g., Willis et al., 2018; Abbatt et al., 2019). Ammonia emissions from polar seabird colonies have also been shown to contribute to the growth of aerosol particles to CCN-relevant sizes (i.e., larger than 80 nm) via partitioning to form particulate ammonium (Croft et al., 2016; Boyer et al., 2025). Secondary non-sea-salt sulfate, such as methanesulfonate resulting from the oxidation of ocean-derived DMS, can also form on aerosols as they age (Kirpes et al., 2018; Kirpes et al., 2020; Moffett et al., 2020; Miming Zhang et al., 2021). Recently in the Arctic, Kirpes et al. (2022) observed solid particles, for which the morphology and composition were consistent with the collision of a newly-formed sulfate particle with a larger organic-coated ammonium sulfate particle leading to contact efflorescence. Since solid particles inhibit the uptake of water and other trace gases, the observed particle phase is expected to impact aerosol reactivity and multiphase reactions.

Within clouds, particles are processed both chemically, i.e., aqueous-phase reactions involving gases dissolved into cloud and fog droplets (Ervens et al., 2011), and physically through coalescence among cloud droplets and aerosols. Upon evaporation of a cloud or fog droplet, the resulting aged aerosol particles are often larger than their original sizes prior to cloud processing (Zhang et al., 2023). From fall to spring, surface air masses in the Arctic spend more time in-cloud (Freud et al., 2017), enabling increased aerosol cloud processing, forming species including sulfate (Lata et al., 2023) and organic acids (Kawamura et al., 2012). The composition of the resulting cloud processed aerosol with sulfate can be seasonal, while oxygenated organics can be observed year-round (e.g., Gramlich et al., 2023). Modeling using GEOS-Chem-TOMAS (a global 3D chemical transport model) suggests that coagulation scavenging of aerosols by clouds, facilitated by aerosols already activated in cloud droplets, can limit the number of particles with diameters below 200 nm throughout the year (Croft et al., 2016). Limited observations in both the Southern Ocean, indicating cloud processing of sea spray aerosol by biogenic sulfate, with potential has been observed (Twohy et al., 2021; Zhang et al., 2023), but relatively few studies report on such processes for primary aerosols in the southern polar region.

Collectively, these studies illustrate that atmospheric processing profoundly transforms the composition, size, and reactivity of both primary and transported aerosols in the polar regions. While aging mechanisms such as multiphase reactions, condensation, and cloud processing are well documented in the Arctic, corresponding evidence from the Antarctic remains limited, leaving key uncertainties in how these processes influence aerosol-cloud interactions and regional climate.

2.4.2 Biotic processing

Besides chemical reactions, biotic processing within the atmosphere may also be relevant for the production or degradation of organic matter in primary aerosols. Bacteria can be metabolically active in the aqueous phase of clouds and on the surface of or in particles (Ervens and Amato, 2020, and references therein). The best estimated formation rates of organic matter in aerosols due to bacterial processing to date is 3.7 Tg yr^{-1}, which is on the same order of magnitude as marine organic emissions due to bubble bursting (10±5 Tg yr^{-1}; Gantt and Meskhidze, 2013; Table 1). Current atmospheric models consider bacteria as inert variables and neglect cell growth and multiplication (Ervens and Amato, 2020). However, there is strong evidence for in-situ biogenic production of organic matter in atmospheric marine particles and cloud water. Malfatti et al. (2019) observed higher microbial enzymatic activity on aerosol particles than in seawater and hypothesized that after ejection from the ocean, active enzymes can dynamically enhance the organic matter concentration of marine aerosol particles. Based on carbohydrate measurements in seawater and aerosol particles in the vicinity of the western Antarctic peninsula, Zeppenfeld et al. (2021) concluded that bacteria selectively consume and release specific organic compounds within primary aerosols. Such biotic processes might explain observed changes in aerosol composition and are likely not restricted to polar regimes, as they seem to occur over both the Southern Ocean (Zeppenfeld et al., 2021) and the tropical Atlantic Ocean (van Pinxteren et al., 2022; 2023).

However, distinguishing between atmospheric processing due to biotic and abiotic effects remains challenging. Jaber et al. (2021) and Renard et al. (2022) evaluated the atmospheric aging of marine POA constituents and considered both biotic and abiotic (mainly oxidation) processing. Their calculations revealed different atmospheric lifetimes for the individual organic species relative to oxidation and biological processes. Yet, they could not quantify the biotic and abiotic transformation rates under realistic atmospheric conditions due to complex and partly de-correlated mechanisms. Ervens and Amato (2020) suggested a framework to estimate the production of secondary biological aerosol mass in clouds by microbial cell growth and multiplication. “Aerobiology”, the study of living organisms on atmospheric particles, is still a discipline in its infancy (Alsante et al., 2021), and more investigation is required into the atmospheric viability and lifetimes of microorganisms within marine particles in the atmosphere to determine their functionality and overall importance.

2.5 Removal via wet and dry deposition

Aerosols are removed from the atmosphere by wet deposition, after their uptake in clouds and precipitation, or by dry deposition, when they are brought into contact with the surface by turbulence or gravitational settling (Emerson et al., 2020; Farmer et al., 2021). Both dry and wet deposition are usually slower in polar regions, especially during winter; dry deposition is slower in the stable atmospheric conditions that are frequent in cold regions and over frozen surfaces, while wet removal is slower because of less precipitation in winter and less efficient removal by ice clouds. However, there are few observational studies of aerosol deposition, either via dry or wet deposition routes, and especially over the Antarctic sea

ice. The lack of observations results in major modeling uncertainties (Lee et al., 2013; Farmer et al., 2021), and the relative importance of dry and wet deposition for aerosol removal in the polar regions remains an unresolved question (Willis et al., 2018).

Measurements seem to show that dry deposition velocities over relatively smooth sea-ice and snow covered areas are generally smaller than over the rougher open ocean or rocky ground (Nilsson and Rannik, 2001; Grönlund et al., 2002). Sea spray from the open ocean and leads can deposit onto snow on sea-ice surfaces in both polar regions (Section 2.3.1). After blowing snow events, the primary sea salt aerosol can then re-deposit onto the snow surface somewhere downwind (Confer et al., 2023). Chen et al. (2022) pointed to the chemical complexity of the snowpack, due to deposition of various trace gases and aerosols, and how this could potentially impact blowing snow aerosol composition. To our knowledge, there are no studies that evaluate dry deposition of marine POA or PBAPs onto open polar waters nor onto snowpack on sea ice. Presumably, these primary aerosol types are deposited with snowfall after serving as CCN and/or INPs in precipitating clouds (see Section 2.7). In models, dry deposition is typically represented as the sum of a gravitational settling velocity, calculated explicitly, plus another deposition velocity parameterized by a resistance approach, representing how particles are brought from the atmosphere to the near surface by turbulence and removed (Slinn, 1982; Zhang et al., 2001). The near surface deposition velocity is a function of 2 main parameters, an "aerodynamic resistance" which mostly depends on atmospheric stability, and an empirical "surface resistance", which depends on surface and aerosol properties.

Scavenging of aerosols by clouds and precipitation is a significantly more efficient removal mechanism than dry deposition (Willis et al., 2018, and references therein). For instance, wet deposition effectively removes natural aerosols, including sea salt, soil dust, and sulfate particles, whether locally produced or transported over long distances (Shaw, 1979; De Angelis et al., 1997; Budhavant et al., 2014). Fog can also act as an efficient scavenger of aerosols, particularly sea salt, in polar marine environments (Zhao et al., 2022). The prevalence of smaller aerosols (up to approximately 70 nm in diameter) in summer has been linked to the efficient removal of larger particles, whereas less effective wet removal in spring and winter contributes to the relative abundance of larger aerosols during that time (Freud et al., 2017; Macdonald et al., 2017; Willis et al., 2018). In atmospheric models, wet deposition is typically divided into two processes: "washout," referring to the impaction of aerosols by falling hydrometeors, and "rainout," which involves the uptake of aerosols into clouds followed by their removal when cloud droplets or ice crystals precipitate (e.g., Carnelos et al., 2024). Both washout and rainout can be parameterized using simple functions of cloud water content and precipitation fluxes (e.g., Luo et al., 2019), with separate treatments for liquid and ice phases. Alternatively, rainout can be represented using more detailed, process-based models that explicitly simulate aerosol-cloud interactions and the subsequent conversion of cloud water or ice to precipitation (e.g., Sui et al., 2020). However, this mechanistic approach is not inherently more accurate, as the underlying cloud processes are themselves highly uncertain. In contrast, the simpler empirical approach is often calibrated to best match observed deposition rates. The complex feedbacks between increasing open water and young ice, increasing sea spray aerosol and DMS emissions, increasing atmospheric humidity, and potential aerosol wet scavenging (e.g., Browse et al., 2014) accentuate the importance of improving understanding wet deposition in the changing climate.

Even after deposition, aerosols can still indirectly affect atmospheric composition through snowpack processes (Section 2.3.2). In addition, deposition of both nutrient and pollutant compounds onto the sea ice and the surface ocean (e.g., Barrie et al., 1992; de Jong et al., 2013; Clark et al., 2020) may generate biogeochemical feedbacks, impacting biogenic gas and aerosol production (both positively and negatively), compared to brown and black carbon deposition on sea ice can reduce light available for

photosynthesis (Marks et al., 2017) and enhance melt and accompanying complex sea-ice feedbacks (Section 2.2.2).

Overall, studies generally agree that both wet and dry deposition proceed more slowly in the polar regions due to stable atmospheric conditions, frozen surfaces, and limited precipitation. While wet deposition appears to dominate aerosol removal, its relative importance and efficiency, particularly in the Antarctic, remain uncertain because of sparse observations and differing model treatments.

2.6 Direct radiative impacts

Sea spray and blowing snow aerosols interact directly with solar and thermal radiation, affecting the atmosphere's energy balance. Sea salt aerosols efficiently scatter incoming shortwave solar radiation, with almost no absorption of solar radiation (e.g., Takemura et al., 2002), but because of their large sizes, they also absorb some longwave radiation emitted from the Earth (e.g., Satheesh and Lubin, 2003). In contrast, there is conflicting evidence regarding whether PBAPs scatter or absorb radiation, although their impact in polar regions is likely limited due to their relatively low concentrations compared to sea salt aerosols (Minghui Zhang et al., 2021, and references therein). In polar regions, the direct radiative effect of primary aerosols is most significant during summer, when incoming solar radiation is high and concentrations of sea salt, POA, and PBAPs peak, yet they can still have a significant impact on direct radiative forcing during polar night in winter, when only their longwave radiative effects persist (Ji et al., 2025). In addition, the direct effect of scattering aerosols is less important over extensive snow and ice in winter, because the reflection of solar radiation back to space from aerosols is much smaller than the reflection from high albedo surfaces (e.g., Thorsen et al., 2020). When inorganic sea salt is coated with organic constituents, its hygroscopicity decreases, which in turn lowers their scattering ability (e.g., Forestieri et al., 2016). As such, knowledge of the aerosol particle's hygroscopicity and the ambient relative humidity is important to determine the aerosol light scattering properties (Zieger et al., 2010). At high latitudes, emissions from open leads can contribute a large fraction of sea spray aerosols and contain a large organic fraction compared to blowing snow sources (Kirpes et al., 2019), which therefore decreases their ability to scatter light. Similar to sea spray, the hygroscopicity of PBAPs inherently determines their size and thus their direct radiative properties (Minghui Zhang et al., 2021).

Currently, the hygroscopicity of sea salt aerosol is diversely represented in models (Burgos et al., 2020), which results in large uncertainties in their optical depth and aerosol-radiation interactions (Zieger et al., 2017). The current estimates of annual mean sea salt aerosol optical depth (uniteless) in AEROCOM (Aerosol Comparisons between Observations and Models) and CMIP6 (Coupled Model Intercomparison Project Phase 6) ensembles have a wide range of values for both the Arctic and Antarctic, ranging from between 0.001 and 0.09 (Sand et al., 2017; Lapere et al., 2023). The AEROCOM ensemble suggests that the direct radiative effect of all aerosols has a net cooling effect in the Arctic (-0.30 to 0.09 W/m^2), with the largest negative (positive) contribution coming from non-sea-salt sulfate (anthropogenic black carbon) and a weak warming effect in the Antarctic (0.0 to 0.1 W/m^2), where the forcing is dominated by anthropogenic black carbon and biomass burning aerosols (Sand et al., 2017).

Ultimately, while studies generally agree on the strong scattering role of sea salt, evidence for PBAP radiative impacts is mixed. Variability in organic content and hygroscopicity introduces major uncertainty, reflected in the wide range of modeled sea salt optical depths and radiative forcings across the polar regions.

2.7 Impacts on cloud formation and properties

Aerosols that act as CCN and INPs strongly influence cloud microphysical and radiative properties, particularly in polar regions where clouds critically modulate the surface energy budget over high-albedo ice surfaces, because of the relatively pristine atmospheric conditions compared to lower latitudes (Mauritsen et al., 2011; Stevens et al., 2018; Gjelsvik et al., 2024; Sotiropoulou et al., 2024). Even modest increases in aerosol concentrations can substantially affect cloud cover, radiative properties, lifetime, and precipitation processes. Distinct microbial communities in Arctic and Antarctic sympagic environments (van Leeuwe et al., 2018), along with differences in the timing, intensity, and distribution of algal blooms, likely contribute to the observed inter-polar contrasts in primary CCN and INP emissions. CMIP models show stronger shortwave cloud scattering over Antarctica and the Southern Ocean than over the Arctic (Zelinka et al., 2020), implying more reflective clouds in the southern high latitude. However, model divergence and biases in aerosol distributions reflect the lack of information available about the role and importance of biogenic primary aerosols and resulting substantial uncertainty in polar cloud forcing (Lapere et al., 2023).

CCN activation under supersaturated conditions initiates liquid cloud droplet formation and is typically modeled using Köhler theory or its simplified κ-Köhler parameterization (Köhler, 1936; Petters and Kreidenweis, 2007; Petters and Kreidenweis, 2013). Primary aerosols such as sea salt, POA, and PBAPs can serve as CCN depending on their hygroscopicity (Després et al., 2012; Orellana and Leck, 2015; Kleinheins et al., 2025). Climate-driven changes in sea ice and associated pelagic and sympagic ecosystems can alter both the amount and composition of CCN, especially in the Southern Ocean, where CCN concentrations are typically lower than in the Arctic (Humphries et al., 2021; Kim et al., 2017; Lubin et al., 2020; McFarquhar et al., 2021; Tatzelt et al., 2022). Seasonal contrasts in CCN abundance in the Arctic and Antarctic reflect differing proximities to continental sources, including terrestrial dust (Hamilton et al., 2014) and springtime Arctic haze (Jung et al., 2018; Ahn et al., 2021). Both regions also receive contributions to CCN from marine biological activity, sea spray aerosol (especially salts) and blowing snow (Leck et al., 2002; Schmale et al., 2018; Orellana et al., 2021; Gong et al., 2023).

In polar regions, INPs primarily originate from POA and PBAPs and are exceptionally scarce, especially over the Southern Ocean (Bigg, 1973; Belosi et al., 2014; McCluskey et al., 2018; Twohy et al., 2021; Tatzelt et al., 2022; Moore et al., 2024). Certain PBAPs that contain ice-binding proteins that function to adhere to sea ice may also act as critical surfaces for atmospheric ice crystal formation (e.g., Bar Dolev et al., 2016). INP concentrations peak in summer, driven by increased biological activity in open ocean and meltwater environments (Bigg and Leck, 2001; Mason et al., 2016; Creamean et al., 2018; Creamean et al., 2019; Irish et al., 2019; Šantl-Temkiv et al., 2019; Wex et al., 2019; Hartmann et al., 2021; Creamean et al., 2022; Pereira Freitas et al., 2023; Sze et al., 2023). Most models rely on temperature-dependent INP parameterizations which often underperform in remote environments (Fletcher, 1962; Cooper, 1986; Meyers et al., 1992). More sophisticated approaches estimate INPs from aerosol physicochemical properties (Phillips et al., 2008; Koop and Zobrist, 2009; Hoose et al., 2010; Niemand et al., 2012; Tobo et al., 2013; DeMott et al., 2015; Ullrich et al., 2017; McCluskey, Ovadnevaite, et al., 2018; Li et al., 2022; Wieder et al., 2022; Frostenberg et al., 2023), though substantial uncertainties remain, particularly regarding stochastic (time-dependent) versus deterministic (time-independent) nucleation theories (e.g., Knopf et al., 2020). INPs play a pivotal role in mixed-phase cloud evolution and precipitation via processes such as the Wegener–Bergeron–Findeisen mechanism (e.g., Fan et al., 2011). This is particularly relevant in the Arctic, where long-lived mixed-phase clouds are common (Morrison et al., 2012). In contrast, the Southern Ocean

is dominated by supercooled liquid clouds, likely reflecting the extreme scarcity of INPs in the region (C. S. McCluskey et al., 2018; Lasher-Trapp et al., 2021; McCluskey et al., 2023; Sokol and Storelvmo, 2024). Nevertheless, mixed-phase clouds can still form in deeper layers and under very cold conditions approaching homogeneous freezing (Zhang et al., 2019; Mace et al., 2021).

While measurements provide aerosol source apportionment and quantitative metrics of aerosol-cloud interactions, simulation experiments that incorporate CCN and INP effects of primary aerosols remain indispensable for estimating their climate impact. This is particularly relevant in pristine regions with limited observations, where natural aerosols prevail. Further advances in aerosol-cloud microphysical processes, as well as the inclusion of POA and PBAPs ice-activation potential in ESMs will be critical for reducing uncertainties and improving the representation of aerosol-cloud-climate interaction.

3. Key gaps in current understanding of polar primary aerosols

3.1. Observational limitations in polar primary aerosol research

Despite growing interest, our understanding of primary aerosol generation and emission processes in polar environments remains limited, particularly in regards to full aerosol size distributions, biological characteristics, chemical composition, and fluxes from diverse marine sources that exhibit strong spatial and temporal variability. Observational efforts face both logistical and analytical challenges, especially given the harsh conditions, low aerosol concentrations, and relatively limited infrastructure in the polar regions. Most measurements have been confined to coastal ground stations or during summer, leaving substantial gaps across seasons, vertical profiles, and remote regions. The gaps discussed here are summarized in Table 2.

Table 2. Key observational challenges in polar primary aerosol research, along with recommended strategies to address these knowledge gaps. Each challenge is defined by a more general category regarding observations, parameterization, instrumentation, processes, spatiotemporal properties, and interdisciplinarity.

Category	Challenge	Recommendation
Aerosol properties	Limited data on coarse mode aerosol number concentrations, chemical composition, and biological characteristics	Measurements of full aerosol size distributions, single-particle and size-resolved chemical composition, and a combination of metagenomic and fluorescent bioaerosol properties
INPs	Difficulty drawing conclusions on seasonal cycles of INP abundance and sources in low concentration regimes in polar regions	Network of long-term simultaneous measurements of INPs with high time resolution for better source retrieval.
Contamination	Ship stack and local infrastructure pollution complicates background measurements	Aerosol and trace gas measurements to apply a universal data filtering algorithm and/or improved sector sampling; autonomous cross-disciplinary platforms
Freshwater inputs	Uncertain effects of freshwater sources (e.g., melt, runoff) on aerosol emissions	Measurements of aerosols downwind of these environments and linking to the same measured properties in the water; bubble tank experiments using various water sources
Emission processes	Poorly constrained aerosol emissions from diverse marine and cryospheric sources, such as blowing snow and melt ponds, and their links to biogeochemistry	Improved aerosol number flux and vertical measurements above these surface sources combined with biogeochemical variables and bubble

		measurements; laboratory chamber experiments
Deposition	Poorly understood deposition processes, particularly for POA and PBAPs	Improved level of detail of characterization of particles in the surface snowpack; aerosol flux measurements
Seasonal & spatial coverage	Observations largely limited to summer and coastal sites; major gaps across seasons, vertical profiles, and remote regions	More measurements during non-summer seasons by making use of overwintering sites, annual cycle measurements, improved autonomous aerial platforms and aerosol instrumentation; application of new remote sensing products
Aerosol instrumentation	Limited high-resolution measurements in low-concentration regimes; many instruments measure aerosol mass, not number	Expanded, quantitative single-particle techniques to resolve complex aerosol mixtures and source variability; chemically-resolved aerosol flux measurements; detailed marine organic composition measurements
Remote sensing	Satellite sensors limited by polar night, cloud cover, bright surfaces, and infrequent overpasses; challenges distinguishing thin ice, melt ponds, and leads	Combined data from multiple sensors to better resolve connections between atmospheric and surface processes; engagement with planning of future missions and using tools like drones, etc.
Cloud measurements	Large uncertainties in satellite and ground-based cloud measurements	Validation of remote sensing with in situ cloud measurements; improved in situ cloud probes for use beyond traditional crewed aircraft; improved measurements of secondary ice production
Interdisciplinary integration	Temporal and spatial mismatches among atmospheric, oceanic, and cryospheric datasets hinder integrated studies	More coordination among interdisciplinary teams to integrate such measurements; targeted field measurements, including use of distributed networks on multiple platforms, to evaluate cross-disciplinary processes
Parameterization development	Insufficient observational basis for developing robust source-specific aerosol parameterizations	Testing and adapting known parameterizations specifically to polar primary aerosol measurements in different environmental regimes

Temporal and spatial mismatches among atmospheric, oceanic, and cryospheric datasets further hinder interdisciplinary studies. Traditional methods for biological characterization of aerosols, while effective, are often labor-intensive and limited in spatiotemporal resolution. Remote sensing offers a solution for increasing spatial coverage, yet these sensors are often limited by their inability to detect biological particles, polar night, cloud cover, low aerosol loadings, challenges over bright surfaces, and/or and the polar holes in satellite coverage. Additionally, satellite overpasses are too infrequent to resolve rapid sea-ice changes, and some remote sensing methods struggle to distinguish between open water, thin ice, and melt ponds, or to resolve the surface from overlying clouds. Lead detection products (e.g., Röhrs and Kaleschke, 2012; Murashkin et al., 2018; Reiser et al., 2020; Müller et al., 2023; von Albedyll et al., 2023), while advancing, are limited in resolution, seasonality, and temporal coverage and can disagree greatly (von Albedyll et al., 2023). Aerosol-cloud interactions are also difficult to constrain, as satellite and ground-based cloud observations suffer from substantial uncertainties, especially under background polar

aerosol conditions. As a result, while progress has been made, linking primary aerosols to their changing sources, Earth system feedbacks, and impacts on cloud microphysics and radiative forcing (Sections 2.6, 2.7) remain major research challenges.

The polar environment also pushes the limits of observations due to logistical challenges and detection limits of current instrumentation, particularly for high spatiotemporal resolution measurements in low-concentration regimes. Limited data on particle fluxes hinder accurate quantification of emissions under varying conditions, and such measurements are notoriously difficult to obtain. Deposition processes (Section 2.5), especially for POA and PBAPs in the Antarctic, remain understudied, contributing to substantial model uncertainties. Background measurements are further complicated by pollution from nearby infrastructure such as ship stacks, requiring meticulous field planning to ensure data quality. Most techniques measure aerosol mass, though climate feedbacks (e.g., cloud formation) are driven by aerosol number. While instrumentation continues to advance, expanded single-particle measurements are needed to quantify number distributions and variations among aerosol sources such as nascent sea spray, POA, PBAPs, aged aerosols, mineral dust, and transported pollutants, to disentangle natural from anthropogenic sources and develop useful parameterizations.

Connecting primary aerosol properties to cryospheric biogeochemistry is particularly complex, as sea-ice loss and biological activity vary regionally (Section 2.2), influencing aerosol emission mechanisms, magnitude, and composition (Section 2.3). Sea spray aerosol production in the polar regions is modulated by salinity, temperature, microbial activity, marine organics in the SML and the bulk water, and sea-ice dynamics, suggesting strong seasonal and regional variability that remains under-characterized. Sea-ice features (including Antarctic leads, Arctic melt ponds, and blowing snow) are emerging as potentially significant sources of PBAPs, POA, CCN, and INPs, yet their individual contributions are inadequately constrained, particularly given overlapping influences on mixed aerosol types that include sea salt. Blowing snow aerosol processes are especially uncertain. Additionally, the influence of freshwater inputs such as sea-ice melt, river discharge, iceberg calving and melting, land-fast ice melting, and glacial runoff (Section 2.2.3) on aerosol emissions remains uncertain.

3.2. Modeling challenges in representing polar primary aerosols

Atmospheric models, both global and regional, continue to struggle with reproducing observed aerosol composition and abundance in the polar regions. While models help bridge spatial gaps, their accuracy hinges on constraints from accurate, intercomparable observations over time and space. Current uncertainties in aerosol sources, properties, and emission processes hinder reliable predictions of aerosol-cloud interactions and their climate impacts, critical feedbacks in these rapidly changing environments. Many models also struggle to accurately represent cloud microphysics, partly due to observational uncertainties in aerosols and clouds (Section 3.1), inherent measurement limitations, and incomplete understanding of processes such as secondary ice production (i.e., ice multiplication) (Korolev and Leisner, 2020; Zhao and Liu, 2021; Zhao and Liu, 2022), especially in polar clouds (Sotiropoulou et al., 2020; Järvinen et al., 2022; Pasquier et al., 2022).

The current state of modeling of polar primary aerosol sources and emission processes are summarized in Figure 2. A major challenge is the poor representation of local primary aerosol sources at high latitudes. The oversimplification of representing sea spray aerosol as pure sodium chloride fails to capture the complexity of polar primary aerosol populations (Section 2.3.1). Furthermore, current global climate models and ESMs often struggle to model sea ice and snow, typically are unable to resolve leads,

and generally exclude key polar-specific aerosol emission processes such as blowing snow sublimation or sea spray aerosol emissions from sea-ice leads and polynyas.

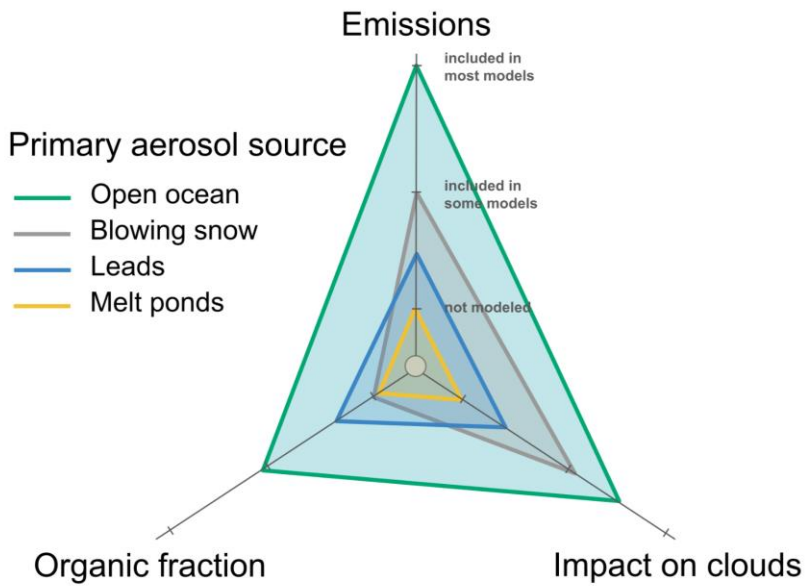

Figure 2. Integration of polar primary aerosol sources in current atmospheric models. The three axes represent the degree of inclusion of polar-specific primary aerosol sources in models: open ocean sea spray (green), blowing snow (gray), leads (blue), and melt ponds (yellow). The vertical axis shows the integration of the source itself, the left axis shows how much the organic fraction of each source is parameterized, and the right axis shows whether models can provide estimates of the impact on clouds of these sources.

The absence or inadequate parameterization of blowing snow processes leads to biases in both mean aerosol concentrations and their seasonal variability. Blowing snow aerosol production remains highly uncertain, especially with respect to particle size distributions, fluxes, and chemical composition. Few models accurately simulate the threshold wind speeds for snow lofting, which are influenced by snow age and morphology. Furthermore, the number of aerosol particles produced per sublimating snow particle is unknown, complicating model parameterization. Simultaneous blowing snow and lead-driven aerosol emissions, both wind-dependent, are also difficult to disentangle observationally and in models.

Similarly, sea spray aerosol fluxes from leads are not explicitly modeled, partly due to the difficulty of making size-resolved flux measurements and the limited availability of high-resolution satellite lead data. Some regional and global atmospheric chemistry models include these sources and tend to perform better, though uncertainties remain. In many models, sea spray aerosol emissions are simply scaled by sea-ice fraction, a method that cannot resolve emissions from narrow leads due to coarse model and satellite resolutions, as well as the absence of lead-specific emissions (Section 2.3.1). Satellite products offer potential for enhancing the spatial coverage of leads for models for fall, winter and spring, but higher spatial resolution is needed to improve lead-related aerosol representation. Nonetheless, recent studies (e.g., Lapere et al., 2024) have made progress in explicitly modeling lead emissions.

Biogenic aerosol emissions are likewise underrepresented in models. Marine organic emissions from open water are rarely incorporated into models (e.g., Burrows et al., 2022), and when included, the modeled organic aerosols are subject to significant uncertainties in sea spray aerosol mass fluxes and

underlying biogeochemical drivers, especially when sea ice is present. Differences in sea-ice structure and history influence the concentration and release of biogenic material (Section 2.2.2), yet most models treat sea ice uniformly. Sea-ice models typically lack structural or textural differentiation, limiting their utility in representing biologically relevant processes such as algal entrainment and organic aerosol production. Biogeochemical models are further limited by gaps in understanding of light and nutrient availability, species-specific productivity, and stressor impacts (Section 2.2). While progress has been made (e.g., Willis et al., 2023), sub-grid heterogeneity in processes like algal blooms, ice dynamics, and snow-ice formation remains difficult to parameterize. These gaps lead to poor representation of the pathways through which biogenic material enters the atmosphere.

Model limitations extend to aerosol processing (Section 2.4) and fate. Hygroscopicity of marine aerosols is often oversimplified, despite its importance for cloud nucleation (Section 2.7) and radiative properties (Section 2.6). Wet and dry removal processes are also challenging to simulate accurately and significantly affect aerosol burdens (Section 2.5). These modeling gaps contribute to large uncertainties in simulated aerosol concentrations, including in the latest-generation climate models. For instance, as shown in Figure 3, Arctic sea salt aerosol optical depth (AOD) shows strong seasonality that is consistent between models, although significant wintertime spread persists. In the Antarctic, models fail to reproduce the seasonality altogether (e.g., Lapere et al., 2023). Spatial resolution limitations also mean that summer sea-ice-related aerosol sources in the Antarctic are entirely missed.

Most climate models do not distinguish between the Arctic and Southern Ocean, applying the same parameterizations despite regional differences in sea-ice structure, snowpack, and dynamics. For example, flooding of sea ice and associated snow-to-ice conversion is typically included and varies between regions, but differences in ice texture and growth mechanisms (e.g., columnar vs. granular ice, platelet ice formation; Petrich and Eicken, 2017) are not. These factors influence the concentration and retention of biogenic material, and thus the potential for aerosol generation, yet are largely absent from model formulations.

Advances in sea-ice modeling (e.g., Shen et al., 2021; Wongpan et al., 2021) have introduced more realistic representations of specific ice types and their dynamics. However, these improvements have yet to be translated into biogeochemical or aerosol modules. The extent to which models can accurately simulate aerosol emissions from the Arctic and Southern Oceans will depend on incorporating these complex ice formation processes and their links to biogeochemical cycling. Finally, emerging research is beginning to explore the biogeochemical impacts of ice-shelf interactions, including tabular iceberg calving, river and glacial discharge, and land-fast ice on shallow Arctic shelves. However, these processes are not yet integrated into most climate models, and their contributions to aerosol sources remain an open question.

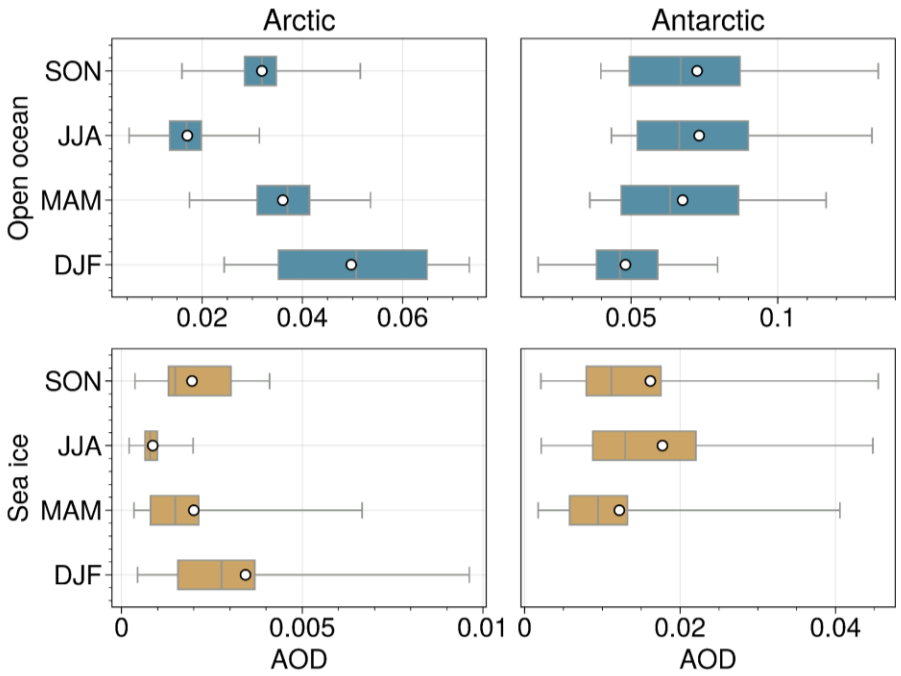

Figure 3. Seasonal distributions of sea salt aerosol optical depth (AOD) at 550 nm averaged in the oceanic polar regions. Seasonal distributions are shown in 3-month increments averaged in the Arctic (60°N–90°N, left) and Antarctic (60°S–90°S, right) over open ocean areas (top) and sea-ice regions (bottom). The Antarctic continent is excluded here. Data from 10 CMIP6 (Coupled Model Intercomparison Project Phase 6) models for the period 2000–2014, for the historical scenario. SON, JJA, MAM, and DJF represent calendar months (Sep, Oct, Nov; Jun, Jul, Aug; Mar, Apr, May; and Dec, Jan, Feb). Open ocean is defined as the grid cells where sea ice concentration is below 10%, and sea-ice regions are where sea-ice concentration is above 50%. This mask changes each month to reflect the evolution of sea ice. Data were obtained through the Earth System Grid Federation platform (http://esgf-node.ipsl.upmc.fr, last accessed 01/12/2024).

4. Pathways forward: Interdisciplinary approaches to polar primary aerosol research

Despite growing interest and recent advancements, our understanding of primary aerosols in the polar environment remains limited. Field observations and laboratory/modelling experiments are critically needed to constrain and parameterize aerosol size distributions, chemical composition, and fluxes from diverse marine sources, which exhibit strong spatial and temporal variability. Over the past decade, numerous interdisciplinary campaigns have advanced our knowledge of polar primary aerosols (e.g., Creamean et al., 2019; Schmale et al., 2019; Park et al., 2020; Yan et al., 2020; Hartmann et al., 2021; Inoue et al., 2021; McFarquhar et al., 2021; Creamean et al., 2022; Porter et al., 2022; Mallet et al., 2023; Kawana et al., 2024; Moore et al., 2024; Barry et al., 2025). These efforts reflect a growing maturity in collaboration between atmospheric, sea-ice, and oceanic scientists, who are rapidly expanding our ability to study aerosol-climate interactions in polar systems. Two particularly impactful recent initiatives are the NETCARE (NETwork on Climate and Aerosols: addressing key uncertainties in Remove Canadian Environments) and MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate) projects. The 5-year NETCARE program achieved meaningful advances in linking surface ocean and atmospheric boundary layer observations, as well as integrating measurements with modeling (Abbatt et al., 2019), but challenges arose in interpreting datasets influenced by differing transport and process timescales in the ocean and atmosphere. The 13-month MOSAiC expedition fostered collaboration across atmospheric, sea-ice,

oceanographic, biogeochemical, and ecosystem disciplines, and spurred new research into links between ocean and sea-ice biogeochemistry, primary aerosol formation, and cloud processes (Nicolaus et al., 2022; Rabe et al., 2022; Shupe et al., 2022; Fong et al., 2024), all while underscoring limitations in measuring interface processes (e.g., bubble-mediated aerosol fluxes from melt ponds). These ambitious efforts have illuminated key aspects of primary aerosol sources, emission mechanisms, biogeochemical links, atmospheric transformation, and climate relevance. At the same time, they have raised new questions and emphasized the need for continued targeted observations to fill remaining knowledge gaps and refine our understanding of polar aerosol-climate interactions.

4.1. Advancing polar primary aerosol field observations

Advancing our understanding of aerosol-cloud interactions in polar regions requires not only higher spatial and temporal resolution in observations, but also enhanced capacity for detailed process-level measurements of air-ice-ocean exchanges. Traditional field methods (ships, camps, and aircraft) often disturb surface conditions, produce their own emissions, and can interfere with natural exchange processes. Therefore, autonomous technologies capable of monitoring the system without human presence are essential. For example, ice buoys equipped with a suite of sensors (microsensors embedded in sea ice and snow, meteorological and aerosol instrumentation in the boundary layer, and chemical, biological, and physical sensors in surface waters) could enable continuous, minimally invasive observations of aerosol production across evolving conditions. These systems could be adapted from existing buoy, mobile aerosol, and energy flux station designs (e.g., Nicolaus et al., 2022; Shupe et al., 2022; Rabe et al., 2024; Mavis et al., 2025), and even brief deployments via helicopter could be invaluable. Short-term measurements in and near (downwind and upwind of) features, such as blowing snow zones, leads, melt ponds, freshwater layers, and areas affected by glacial or riverine input, can capture ephemeral processes that are otherwise missed..

In-situ aerosol flux measurements (e.g., Donateo et al., 2023) are needed across the full range of polar marine surfaces, from open ocean and the MIZ to first- and multi-year sea ice with variable snowpacks, melt ponds, and open leads. For example, measurements of sea spray aerosol emission fluxes are particularly needed in polynyas and leads, spanning seasons, wind speeds, and a range of open water sizes. Flux measurements in tandem with snow sampling is also needed to quantify aerosol deposition. Additionally, the biogeochemical composition of open leads and brine channels, including EPS and other bio-organic matter, particularly in winter, is needed to define its potential role in aerosol formation. In leads and polynyas, and especially environments affected by freshwater, concurrent biological and EPS observations, physical process measurements such as bubble size distributions and fluxes, and chemical measurements such as water isotopes, could significantly improve our understanding of seasonal variability in PBAP and POA aerosol sources.

Fluxes should be complemented by vertical profiles of aerosol concentrations, CCN, and INPs, to assess their impacts on cloud formation and properties. Given the low concentrations and shallow near-surface gradients in polar environments, these measurements are challenging. However, advances in tethered balloon systems and drones now enable vertically resolved aerosol property measurements, including INPs, providing crucial context between surface and airborne data (e.g., Creamean et al., 2018; Porter et al., 2020; Zinke et al., 2021; Pilz et al., 2024; Pohorsky et al., 2025; Creamean et al., 2025). Quantitative in situ surface fluxes and vertical aerosol profiles are critical to constraining the strength and variability of surface sources, validating model parameterizations, and improving estimates of aerosol impacts on lower atmospheric composition, cloud formation, and climate feedbacks.

A major analytical challenge remains the characterization of the material that contributes to CCN and INP populations (whether sea salt, PBAPs, detrital minerals, or organics) and determining its origin from bulk seawater, the SML, sea ice, and/or overlying snow. Mapping the properties of and the relationships between these source materials and primary aerosols is not straightforward. Moreover, aerosol chemical composition and associated radiative and nucleating properties are highly size-dependent, requiring size-segregated and, ideally, single-particle measurements to distinguish aerosol population heterogeneity and identify source signatures and atmospheric processing (Riemer et al., 2019). Traditional approaches that rely on bulk ion ratios as chemical fingerprints should be augmented by more advanced techniques, such as stable sulfur isotope analysis, which can distinguish between anthropogenic and marine sulfate sources (Seguin et al., 2011; 2014). The detailed molecular characterization of biological organic matter remains particularly difficult and typically requires collection and offline ultrahigh-resolution mass spectrometry analysis. While autonomous detection of organic aerosol molecular composition is not yet feasible, more routine ship-based measurements using mass spectrometry or (meta)genomic and proteomic analyses (Mock et al., 2022) could significantly advance our understanding of source variability and impacts on INP and CCN populations. Particularly for INPs, networks of routine measurements of INPs and supporting aerosol biological and physicochemical information is needed for better source assessment. Long-term observatories are essential for maintaining comprehensive records to study aerosol-cloud interactions on climate-relevant timescales. Recent satellite-based assessments of dust INP impacts on Arctic clouds under comparable meteorological regimes (Zamora and Kahn, 2024) offer a valuable framework that could be expanded and adapted to study the roles of sea salt and biological particles across both polar regions.

Integrating fluorescent techniques, optical microscopy, proteomic, and metagenomic analyses holds strong potential for expanding observational coverage and enabling more comprehensive characterization of biological aerosols. When paired with concurrent biological community assessments across environmental compartments including ice, snow, seawater, and air, these approaches are essential for identifying and quantifying key aerosol sources and their variability. Complementary measurements of full aerosol size distributions and single-particle chemical composition can further enhance source attribution, particularly when combined with air mass trajectory analysis. Moreover, implementing sector-based sampling strategies coupled with aerosol and trace gas observations, and filtered through a universal data-screening algorithm, would allow researchers to isolate natural aerosol signals while minimizing contamination from local anthropogenic sources such as ship emissions or coastal villages.

Equally important as aerosol chemical and biological characterization is the direct sampling of cloud particles and subsequent analysis of cloud residuals, which include the particles that acted as CCN or INPs or were scavenged by falling cloud droplets and ice crystals. This provides a direct link between atmospheric aerosols and cloud-active constituents. Recent studies in Ny-Ålesund during NASCENT (Ny-Ålesund Aerosol Cloud Experiment; Pasquier et al., 2022) and on the Swedish icebreaker Oden during the MOCCHA (Microbiology-Ocean-Cloud-Coupling in the High Arctic; Leck et al., 2021) and ARTofMELT (Atmospheric rivers and the onset of Arctic melt; Tjernström and Zieger, 2025) campaigns successfully separated cloud particles from aerosols and characterized the resulting residuals, enabling comparison with interstitial aerosols, those that did not activate or were not scavenged into cloud droplets. The use of counterflow virtual impactors (CVIs) upstream of aerosol sampling instruments (Twohy et al., 1997; Shingler et al., 2012) provides an effective method for separating cloud particles from interstitial aerosols (Karlsson et al., 2021; Karlsson et al., 2022; Gramlich et al., 2023; Duplessis et al., 2024; Pereira Freitas et al., 2024). While some studies have taken this a step further by attempting to separate cloud droplets and

ice crystals (Boulter et al., 2006; Kupiszewski et al., 2015; Hiranuma et al., 2016), additional methodological development is needed to enhance the robustness and accessibility of this technique for broader application. Improvements in cloud measurements (e.g., in situ probes) and data products (e.g., radar and lidar retrievals) are necessary to assess interactions between primary aerosols and clouds. During blowing snow events, critical gaps remain not only in the characterization of CCN and INPs associated with lofted snow particles, but also in their representation across the broader suite of aerosol production mechanisms. Addressing these gaps requires coordinated measurements of snow and sea ice physical, biological, and chemical properties—including snow sublimation budgets, snowpack microstructure, meteorological conditions, aerosol and snow size distributions, and aerosol composition—to better constrain source processes and air-surface exchange dynamics during these events.

Together, these measurement innovations and analytical strategies are crucial for constraining the production, processing, and impacts of polar primary aerosols. Without them, efforts to improve model parameterizations under different environmental regimes and understand climate feedbacks in polar systems will remain fundamentally limited.

4.2. Laboratory studies in advancing understanding of polar primary aerosol

Many critical processes influencing polar primary aerosol emissions are too complex to fully disentangle in the field, often requiring simultaneous measurements that are logistically challenging or incompatible. For example, determining the relative contributions of the SML versus bulk surface waters to aerosol composition requires coincident measurements of aerosol fluxes and detailed water and aerosol chemistry under a range of wind and temperature conditions at challenging sub-zero temperatures and dynamic sea ice conditions. Similarly, distinguishing between aerosol contributions from brine skim, and overlying snow on sea ice during dynamic freeze-thaw and wind events presents significant observational challenges. Studies have shown that even investigating the role of sea surface temperature on sea spray aerosol fluxes and size distributions is not simplistic, given the complexity of these emissions and the numerous controlling factors, including those that may not even be known yet.

For such questions, interdisciplinary laboratory and ‘lab-in-the-field’ experiments may offer effective paths forward, both to add controllable parameters to the system and to improve comparison to field observations. These should span multiple scales and include bubble chamber experiments with different water sources, wind tunnel studies simulating blowing snow, and sea-ice chamber experiments under controlled temperature variations, including freeze-up and melt conditions (Fassnacht et al., 2024). Field-deployable systems and laboratories in low-latitude institutional labs can both support these studies. Facilities like the Roland von Glasow Air-Sea-Ice Chamber at the University of East Anglia (Thomas et al., 2021) and the Scripps Ocean-Atmosphere Research Simulator (SOARS; Moore et al., 2025) are especially valuable, as they enable aerosol emissions to be studied in tandem with evolving sea-ice and ocean conditions. Importantly, smaller-scale benchtop experiments can also yield valuable insights. For instance, because ice tank facilities are difficult to inoculate with realistic microbial communities, targeted laboratory studies in sea spray chambers (e.g., Prather et al., 2013; Stokes et al., 2013; McCluskey et al., 2018), but with sea ice, snow, melt water, and seawater combinations (e.g., Mirrielees et al., 2024; Freitas et al., 2025), both at home and in the field, can help illuminate the relationships between biological composition in sea ice or surface waters and aerosols. Translating results from simplified laboratory settings to the complexity of the natural environment and modelling must be done cautiously. However, these more controlled studies are critical for identifying the key processes and can motivate future field-based measurements to evaluate whether similar results are obtained under real-world conditions. In fact, these

comparisons between laboratory and field results can highlight processes for which we do not understand the most important driving forces, thereby motivating future laboratory experiments.

4.3. Bridging scales and improving parameterizations of polar marine aerosols in models

Bridging spatial and temporal scales remains a fundamental challenge in numerical modeling of polar aerosol and cloud processes. Process models, which are often one-dimensional and computationally efficient, enable detailed comparisons with targeted field or laboratory observations and can resolve fine-scale processes not feasible in regional or global frameworks. However, such models do not necessarily outperform large-scale models when evaluated against observations, especially when metrics are integrated over space and time. This paradox underscores the need for rigorous procedures to evaluate, scale, and translate process-based parameterizations across model hierarchies.

Crucially, parameterizations derived from small-scale observations or laboratory experiments should not be directly implemented into global models without accounting for sub-grid processes and interactions at larger scales. These adjustments should not be made directly within global models, for instance, by tuning the emission source to match large-scale observations such as AOD, since multiple interacting processes (e.g., emission strength, aerosol size distribution, wet and dry deposition, optical properties, transport, meteorology, and water uptake) can produce similar AOD values, potentially masking underlying inaccuracies. To ensure fidelity for the right reasons, collaboration is needed among observing scientists and process, regional, and global modelers to evaluate parameterizations under a range of conditions and across scales and evaluate if the process understanding is maintained across parameterisations. This includes coordinated efforts to recommend how local processes such as bubble-mediated emissions or blowing snow events should be represented within the coarser resolutions of climate models. Such models cannot represent each individual underlying process such as bubble bursting but need an observation-informed high-level representation of their net effect on aerosol emissions.

Model intercomparisons play a critical role in identifying uncertainties not only in parameterizations (e.g., aerosol deposition or source functions) but also in the physical drivers that modulate those processes, such as precipitation or surface temperature. Improved diagnostics can help dissect these uncertainties and clarify model differences. For instance, compartmentalizing the drivers of emission variability (e.g., sea-ice algae versus phytoplankton blooms) can explain why some models predict regional increases while others show decreases under similar conditions (e.g., Vancoppenolle et al., 2013). Haddon et al. (2024) demonstrated this by developing diagnostics of sympagic bloom phenology, identifying key dates for bloom onset and peak based on light and nutrient availability. Such diagnostics not only aid inter-model comparison but also advance understanding of environmental controls and their response to climate forcing.

Moving forward, the modeling community would benefit from shared guidance on appropriate parameterizations for key polar aerosol processes, including sea spray, blowing snow, open leads, and sources of CCN and INPs. While further discussion among modeling experts is needed to refine these recommendations, a minimum standard setup could be proposed to promote consistency and discourage the continued use of outdated or inappropriate schemes.

4.4. Opportunities for field-laboratory-modeling efforts

Modelers and observationalists in Earth system science have made significant strides in working collaboratively (Steiner et al., 2016). Increasingly, early-career researchers are emerging who defy

traditional disciplinary boundaries, integrating both numerical modeling and field-based methods in their work. It is becoming standard practice for modelers to participate in the early planning phases of field campaigns, and ongoing dialogue between those collecting and analyzing physical samples and those developing models has greatly enhanced the realism, relevance, and accuracy of simulations (e.g., Hayashida et al., 2017; Mortenson et al., 2017; Mortenson et al., 2018). Simply adding atmospheric measurements to an oceanographic cruise (or vice versa) is insufficient due to the logistical challenges of the required measurements. Additionally, it is crucial for modelers to clearly communicate exactly which parameters they need from their observational collaborators for their modeling experiments. Workshops and even informal conversations across disciplines outside the context of any specific campaign can inspire innovative ideas and experimental designs, whether conducted in situ, in vitro, or in silico.

As models grow more sophisticated, the challenge is to maintain expert-level dialogue across disciplines, refining the representation of complex processes while developing the observational tools to capture the high-resolution data required for model initialization and validation. For models that resolve smaller scale processes than can be represented in Earth system models (e.g. regional scale, column models, large eddy simulation models), key observational needs include aerosol size distributions, biological and chemical composition, and CCN and INP activity, as well as meteorological and near sea-surface parameters such as temperature, wind speed, atmospheric stability, sea-ice thickness, lead fraction, snow properties, and seawater composition. The typical time resolution of these models being one hour or less, observations with a 1-min to 1-hour time frequency are the most informative.

Global models, in contrast, benefit from multi-year, spatially extensive datasets. Meeting this need requires stronger collaboration with engineers to design autonomous, cold-adapted instrumentation capable of withstanding harsh polar conditions, thereby increasing the temporal and spatial density of both atmospheric and oceanic observations. While there are already well-established partnerships with the remote sensing community, greater interaction is needed between field scientists studying fine-scale air-ice-ocean exchange processes and those developing satellite algorithms designing future sensors. This interaction is mutually beneficial in that remote sensing scientists benefit from in situ observations for satellite validation.

Emerging tools from machine learning (ML) and artificial intelligence (AI) offer promising pathways for interpreting sparse datasets across complex systems. For example, Chamberlain et al. (2025) recently used ML models with paired observations of community structure, metabolic activity, and oceanographic data to assess spatial and seasonal patterns between microbial communities and oxygen utilization in the Arctic Ocean. Similarly, Wang et al. (2019) applied ML to estimate the production of bromine-containing short-lived substances in lower-latitude oceans. While these approaches show promise, more engagement is needed to bring data scientists into the fold to validate and apply these techniques to polar aerosol research.

Opportunities to exercise these practices include the Tara Polar Station (https://fondationtaraocean.org/en/schooner/tara-polar-station/), the Antarctic InSync initiative (https://www.antarctica-insync.org/), and collaborative networks such as CATCH (the Cryosphere and ATmospheric CHemistry; Thomas et al., 2019) and PICCAASO (Partnerships for Investigations of Clouds and the biogeoChemistry of the Atmosphere in Antarctica and the Southern Ocean; Mallet et al., 2023). The upcoming Fifth International Polar Year in 2032–2033 (https://www.ipy5.info/) offers a timely and strategic platform for coordinated efforts across atmospheric, oceanic, and cryospheric science communities to tackle outstanding questions related to polar primary aerosols (e.g. https://indico.psi.ch/event/15591/). In addition, new and improved satellite observations, such as PACE (Plankton, Aerosol, Cloud, Ocean

Ecosystem; https://pace.oceansciences.org/) and EarthCARE (https://earth.esa.int/eogateway/missions/earthcare) from NASA (National Aeronautics and Space Administration), now provide online data that will likely be valuable for interdisciplinary polar studies on primary aerosols from sea-ice environments.

5. Summary

This paper presents a comprehensive overview of primary aerosols in polar sympagic regions, exploring their connections to ocean and sea ice biogeochemistry, transformation pathways, removal processes, and impacts on cloud formation and the surface energy budget. We highlight key knowledge gaps in the characterization and processes governing these aerosols and explore directions for future interdisciplinary research aimed at addressing these uncertainties. Future opportunities include the Tara Polar Station, Antarctica InSync, the 5th IPY, and collaborative networks such as CATCH and PICCAASO, and new satellite data from PACE and EarthCARE.

As climate projections indicate a shift toward a rainier Arctic (Bintanja and Andry, 2017; Boisvert et al., 2023) with implications for cloudiness and phase (Huang et al., 2021; Carlsen and David, 2022; England and Feldl, 2024), a fresher and windier Southern Ocean (Roach et al., 2023), more precipitation in Antarctica (Tewari et al., 2022), and reduced sea and land ice across both poles (Eayrs et al., 2021; Heuzé and Jahn, 2024), alongside changes in primary productivity and ecosystem dynamics (Gamberg, 2020; Lannuzel et al., 2020; Cavanagh et al., 2021; Johnston et al., 2022), it is essential to build a robust understanding of current primary aerosol populations. Doing so will improve our ability to anticipate and interpret their future evolution and climate feedbacks in a changing polar environment.

6. Acronym appendix

AEROCOM – Aerosol Comparisons between Observations and Models
AOD – aerosol optical depth
AMAP – Arctic Monitoring and Assessment Programme
ARTofMELT – Atmospheric rivers and the onset of Arctic melt
CATCH – the Cryosphere and ATmostpheric CHemistry
CCN – cloud condensation nuclei
CMIP – Coupled Model Intercomparison
CMIP6 – Coupled Model Intercomparison Project Phase 6
CVI – counterflow virtual impactor
DMS – dimethyl sulfide
DMSP – dimethylsulfoniopropionate
EPS – extracellular polymeric substances
ESM – Earth System Model
GEOS-Chem-TOMAS – Goddard Earth Observing System Chemistry coupled with the TwO-Moment Aerosol Sectional
INP(s) – ice nucleating particle(s)
IPCC – Intergovernmental Panel on Climate Change
MIZ – marginal ice zone
MOCCHA – Microbiology-Ocean-Cloud-Coupling in the High Arctic
MODIS – Moderate Resolution Imaging Spectroradiometer

MOSAiC – Multidisciplinary drifting Observatory for the Study of Arctic Climate
ML/AI – machine learning/artificial intelligence
NASA – National Aeronautics and Space Administration
NASCENT – Ny-Ålesund Aerosol Cloud Experiment
NETCARE – NETwork on Climate and Aerosols: addressing key uncertainties in Remote Canadian Environments
NPZD – nutrient, phytoplankton, zooplankton, detritus
PACE – Plankton, Aerosol, Cloud, Ocean Ecosystem
PBAP(s) – primary biological aerosol particle(s)
PICCAASO – Partnerships for Investigations of Clouds and the biogeoChemistry of the Atmosphere in Antarctica and the Southern Ocean
POA – primary organic aerosol
SML – surface microlayer
SOARS – Scripps Ocean-Atmosphere Research Simulator
SOLAS – Surface Ocean-Lower Atmosphere Study

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Competing interests

The authors have declared that no competing interests exist.

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ChatGPT was used to assist in editing and improving the wording of this manuscript.

Supplemental material

None

Data accessibility statement

All data are reproduced from other sources. Data from the CMIP6 models used in Figure 3 can be downloaded from the Earth System Grid Federation platform (https://esgf-node.ipsl.upmc.fr/search/cmip6-ipsl/). Models include BCC-ESM (Beijing Climate Center Earth System Model), CESM (Community Earth System Model), CNRM-ESM (Centre National de Recherches Météorologiques Earth System Model), CanESM (Canadian Earth System Model), EC-Earth (European Community Earth System Model), IPSL-CM6 (Institut Pierre-Simon Laplace Climate Model version 6), MIROC-ES2L (Model for Interdisciplinary Research on Climate, Earth System version 2 for Long-term simulations), MPI-ESM (Max Planck Institute for Meteorology Earth System Model), MRI-ESM (Meteorological Research Institute Earth System Model), and NorESM (Norwegian Earth System Model).

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