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INTRODUCTION

Tara Polaris: Shedding light on microbial and climate feedback processes in the Arctic atmosphere

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The central Arctic is experiencing warming up to four times faster than the global average. This Arctic amplification is accompanied by large deviations in climate projections, making anticipation of high-impact, near-term regional biodiversity and climate change difficult. Several atmospheric processes contribute simultaneously to Arctic amplification and biodiversity change yet remain largely unstudied, not least because of the difficulty to access the central Arctic Ocean and conduct year-round studies. This article introduces the near- to mid-term objectives of the *Tara Polar Station* scoping group on "atmosphere-biosphere interactions," with a focus on identifying and quantifying the origin and genetic composition of local and long-range transported biogenic particles that can impact biodiversity and cloud formation, the role of the stratified boundary layer on vertical fluxes of cloud seeds, bioaerosols and nutrients, and the impact of clouds on atmospheric light transmission. The *Tara Polar Station* is a fortified research vessel built to drift in the Arctic sea ice throughout the next 20 years in ten Tara Polaris expeditions, each lasting one and a half years. The platform allows for year-round interdisciplinary studies targeted at understanding the central Arctic Ocean ecosystem functioning, biodiversity, and climate change at the ocean-ice-atmosphere nexus. This scoping group will deploy novel and automated instruments for in situ, real-time vertical and remote sensing observations of aerosols, clouds, and radiation. The link between the biosphere and atmosphere will be investigated specifically through bio- and chemo-molecular sampling of air, clouds, ice, and water. We expect the early Tara Polaris expeditions to deliver insights that can be implemented into models for improved scenarios of Arctic change, in particular for the next few decades when we expect a regime shift in summer sea-ice presence.

Keywords: Tara Polar Station, Arctic Ocean, Aerosols, Biosphere, Radiation, Clouds

1. Introduction

The Arctic is warming up to four times faster than the rest of our planet (Rantanen et al., 2022), a phenomenon called Arctic amplification (Manabe and Wetherald, 1975; Serreze and Barry, 2011). This warming results in drastic changes in the Arctic marine and terrestrial biosphere: summer sea ice is predicted to vanish completely toward the middle of this century (Guarino et al., 2020),

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there is widespread thawing of permafrost (Wrona et al., 2016), the Arctic is greening (Phoenix and Treharne, 2022), and boreal fires occur further north and more frequently (Jones et al., 2022). What is more, there is hardly any other region on Earth where climate projections deviate as much as in the Arctic (Taylor et al., 2022, and references therein), making the anticipation of high-impact, near-term regional changes difficult. Key quantified drivers of Arctic amplification are the sea-ice and snow albedo feedbacks, as well as temperature feedbacks (Planck and lapse rate feedback) linked to the strongly stratified Arctic boundary layer, among other drivers (e.g., Pithan and Mauritsen, 2014; Taylor et al., 2022). However, other drivers are much less quantified, and large uncertainties remain regarding the effects of changing aerosol populations and clouds in the Arctic (Schmale et al., 2021, and references therein; Wendisch et al., 2023). In the following, we elaborate on the relevance of clouds and aerosols, sources of cloud-forming particles, and specifically their interactions with the biosphere, as well as the role of aerosols as nutrient carriers and their dispersion in a highly stratified atmospheric boundary layer.

Low-level mixed-phase clouds. Cloud radiative effects and their future evolution are particularly uncertain as they depend on a delicate balance between lower atmospheric temperatures and thermodynamics, significantly influenced by surface properties (sea ice, leads, melt ponds, open water, etc.) and the availability of cloud nuclei, that is, cloud condensation nuclei (CCN) and ice-nucleating particles (INP). CCN are responsible for the formation of cloud droplet and INP for ice crystals. Clouds consisting of both the liquid and solid phase are called mixed-phase clouds, and the ratio of liquid droplets to ice crystals determines the cloud radiative effect (Morrison et al., 2012). Low-level mixed-phase clouds are the most dominant cloud type in the Arctic year-round, and typically they warm the Arctic surface (Maillard et al., 2021), except for a short period in summer when they tend to cool it (Shupe and Intrieri, 2004). Specifically, CCN determine the liquid water content of mixed-phase clouds and are the dominant modulator of the warming downward longwave emissions (Morrison et al., 2012), also during winter. Because the concentrations of CCN and INP are relatively low over the central Arctic Ocean, cloud radiative properties are very sensitive to the amount and types of CCN and INP.

Cloud-forming particles in the Arctic. The sources of CCN and INP in the Arctic vary with the seasons: aerosols that form CCN and INP can be sourced locally or transported over long distances, and they can originate from both natural and anthropogenic sources. In the central Arctic, typical CCN are hygroscopic aerosol particles larger than 30 nm, for example, particulate sulfate and sea spray (Karlsson et al., 2022). See **Figure 1** for electron microscopy images. Typical INP are mineral dust particles that induce freezing of supercooled liquid droplets at −20°C, as opposed to homogeneous freezing of water droplets at −38°C, as well as bacteria, cell fragments and similar organic particles that can initiate freezing at temperatures as warm as −8°C (Wex et al., 2019; Creamean et al., 2022).

During winter and early spring, when the Arctic atmosphere is highly stratified and little precipitation occurs (Stohl, 2006), anthropogenic pollution (e.g., particulate sulfate, organics and black carbon) from the mid-latitudes is transported under the Arctic dome, which can extend as far south as 40°N, to high latitudes where it accumulates in the lower atmosphere forming the so-called Arctic haze (Quinn et al., 2007; Schmale et al., 2022). At the same time, large-scale cyclonic systems evoke storms in the central Arctic that generate sea salt aerosol from blowing snow and open leads (Kirpes et al., 2019; Gong et al., 2023; Heutte et al., 2025). During summer, the Arctic dome retracts to the highest latitudes and the atmosphere becomes more dynamic, including more precipitation (Stohl, 2006). This retraction means that the contribution of long-range transport of anthropogenic pollution or of natural aerosols (e.g., particulate organics, methanesulfonic acid, sea spray, black carbon from forest fires, mineral dust from the Sahara or glacial outwash plains) and their precursors (e.g., dimethylsulfide, biogenic volatile organic compounds) is more limited (Kylling et al., 2018; Meinander et al., 2022; Pernov et al., 2022; Schmale et al., 2022; von Salzen et al., 2022). Therefore, in the central Arctic, the contribution of local emissions of particles and precursors becomes more important, especially close to the surface, for example, from open leads, melt ponds, or the marginal ice zone (Leck et al., 2002; Baccarini et al., 2020; Creamean et al., 2022; Yue et al., 2023; Beck et al., 2024). Note that sea spray and methanesulfonic acid can be both locally sourced and long-range transported. The appearance of these local surface sources is, at the same time, an indication that the coupling between the ocean, ice, and atmosphere becomes stronger toward summer. Over the long term, local Arctic emissions are also expected to gain in importance during winter because the anthropogenic influence is declining as a result of stricter air pollution regulations (Schmale et al., 2022; von Salzen et al., 2022).

The biosphere as source of Arctic aerosols and clouds. In this article, we refer to the "biosphere" primarily as the marine (ice and ocean) ecosystems where microbes (e.g., bacteria, archaea, microalgae, other protists, and fungi) and viruses can become aerosolized or where volatile compounds can be released to the atmosphere through physical or biological processes. Terminology used in this manuscript for biogenic aerosol particles is provided in **Table 1**.

Primary biological aerosol particles (PBAP) can be deposited onto local surfaces and reemitted. They can also be emitted from distant terrestrial or marine ecosystems and transported to the Arctic. Generally, they are efficient INP. In addition to PBAP, gaseous biogenic volatile organic compounds (BVOCs) also originate from the biosphere. Examples for marine microbial origin include dimethylsulfide (DMS), isoprenes, organohalogens, C2-C3 hydrocarbons, and monoterpenes. There are also gaseous emissions from the terrestrial Arctic, sub-arctic, and boreal regions, for example, vegetation or boreal fires (Ardyna et al., 2022). BVOCs can facilitate the formation of new particles and augment particle

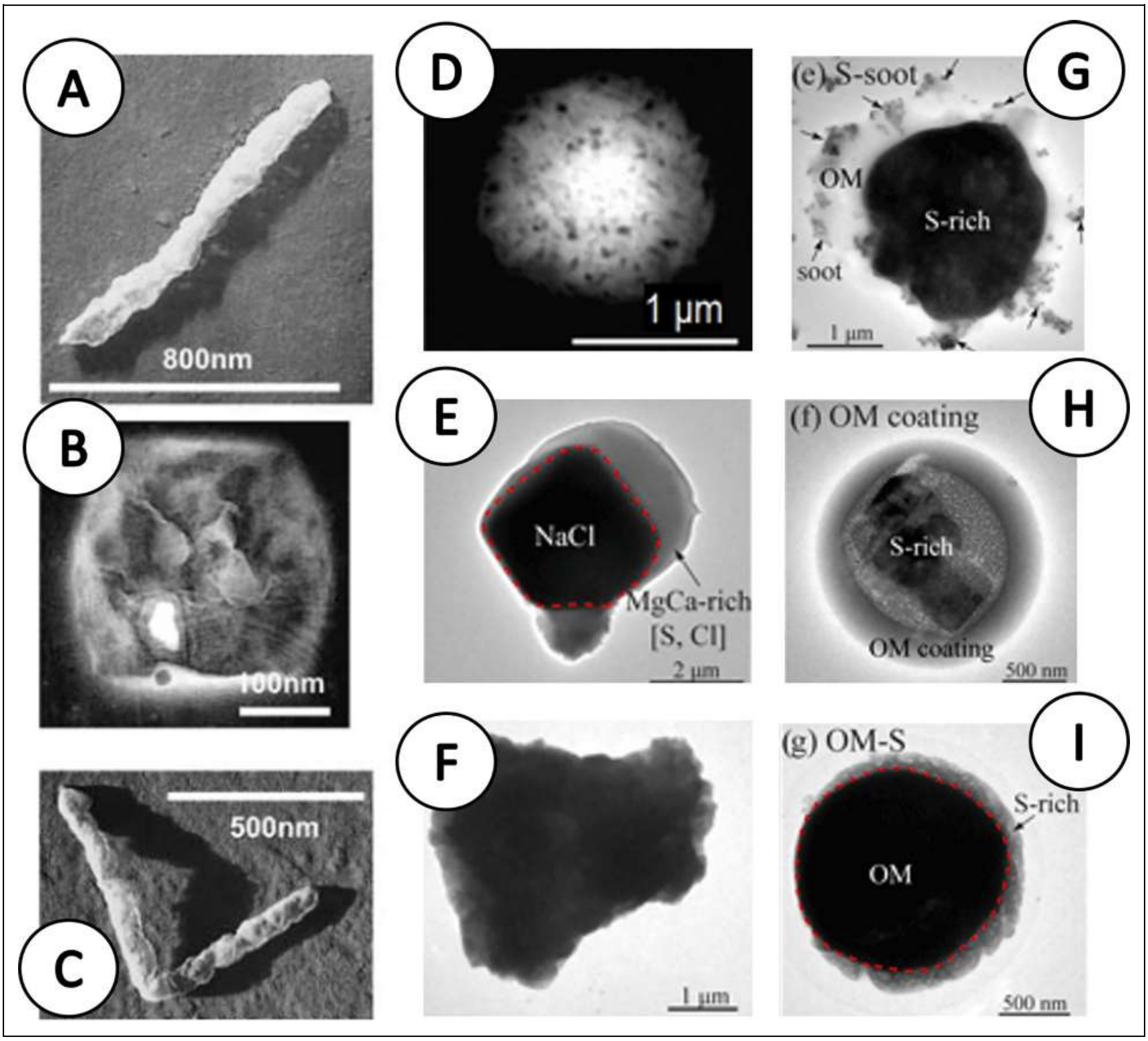

Figure 1. Electron microscopy images of airborne aerosol particles. (A) Bacterium, (B) virus-like particle, (C) fragment of a diatom, (D) partially aged sea spray, (E) fresh sea salt, (F) mineral dust, (G) soot particles mixed with sulfate (S), (H) secondary organic matter (OM) coating on sulfate, and (I) primary organic matter particle mixed with sulfate. Images in A–C are from Leck and Bigg (2005); in D, from Kirpes et al. (2018); and in E–I, from Xu et al. (2021). All images are reproduced under CC BY 4.0 International and were assembled specifically for this work.

Table 1. Explanation of terminology regarding biogenic aerosol particles

Term	Explanation
Biogenic particles	Overarching term referring to both primary and secondary aerosols from biological sources in the terrestrial or marine biosphere
Primary biogenic particles	Called primary biological aerosol particles (PBAP; Figure 1) and include microorganisms (e.g., bacteria, microalgae), fragments of microorganisms and cells, and exudates such as transparent exopolymer particles (Orellana et al., 2011; Després et al., 2012, and references therein). PBAP generally contain DNA and may or may not contain viable microorganisms
Secondary biogenic particles	Formed by oxidation of emitted gases from marine microorganisms (e.g., dimethylsulfide), terrestrial vegetation (e.g., isoprenoids such as alpha-pinene), or animals (e.g., ammonia from bird colonies)

growth into CCN size ranges, impacting aerosol size distributions and altering cloud microphysics (Rosati et al., 2022).

The connections between the atmosphere and biosphere span large spatial and temporal scales for different seasons (**Figure 2**). However, the quantity, diversity,

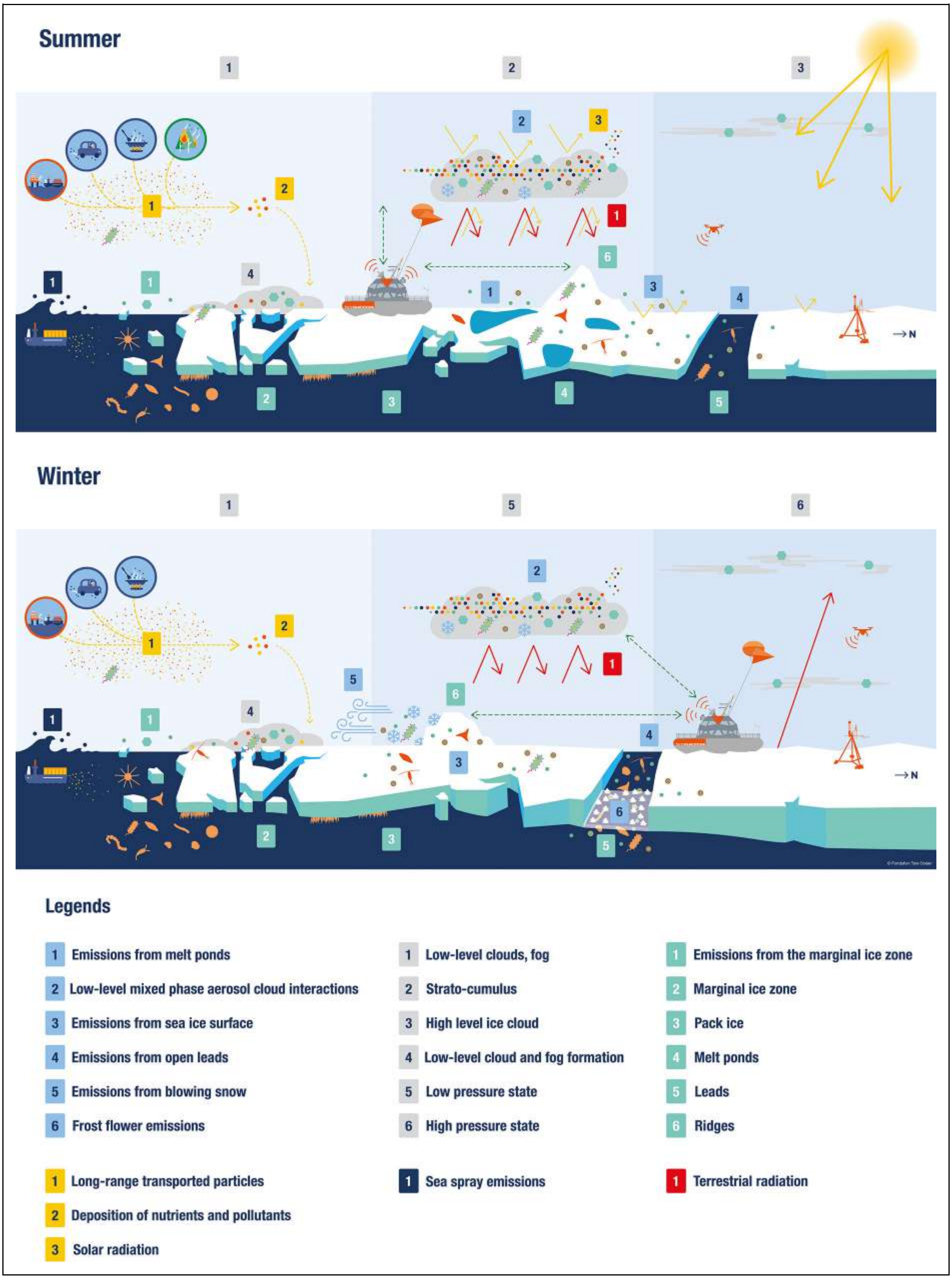

Figure 2. Key processes of biosphere-atmosphere interactions in the Arctic. The top panel shows summer; the bottom panel, winter. The images show a hypothetical transect from the open ocean to the dense pack ice. Hexagons represent ice-nucleating particles, while colored dots and round markers represent different types of aerosols. Bioaerosols are illustrated as green rounded-rectangles with red whiskers.

and origin (local vs. remote sources of PBAP and BVOCs), relative to other aerosols, in the central Arctic are largely unknown. A complicating factor for source identification is that climate change is changing atmospheric transport patterns across the Arctic (Heslin-Rees et al., 2020; Pernov et al., 2022) such that source regions and their importance, including central Arctic sea ice, are likely to change rapidly in the future. A major outstanding question is, where do INP originate?Recent observations from the Multidisciplinary drifting Observatory for the Study of Arctic Climate expedition (MOSAiC; e.g., Shupe et al., 2022) that drifted with central Arctic sea ice in 2019 and 2020 indicate that PBAP, likely bacteria, constitute a significant fraction of total aerosols and are related to INP close to the central Arctic Ocean surface (Creamean et al., 2022; Beck et al., 2024). Another study conducted over the central Arctic Ocean (Porter et al., 2022) showed that highly active INP stemmed from the Siberian Arctic Ocean sector where riverine outflow might be the source of active ice-nucleating PBAP. On Svalbard, highly active INP were associated with terrestrial PBAP (Pereira Freitas et al., 2023). However, the contribution of remote versus local PBAP to the central Arctic INP budget remains unquantified, as does the contribution of other remote sources, such as mineral dust, which may be increasing due to Arctic land ice retreat (Tobo et al., 2019; Meinander et al., 2022). In light of the changing central Arctic ecosystem, notably an increasing area of ice-free ocean with longer open water conditions, the local emissions of PBAP from leads, melt ponds, and ice-free water might also change drastically, which could have implications for mixed-phase clouds (Beck et al., 2024).

Typically, INP form ice crystals via the process of immersion freezing (Kanji et al., 2017), in which a droplet first forms and subsequently freezes. This process means that PBAP emitted from phytoplankton blooms, terrestrial vegetation, thawing permafrost, and forest fires can also function as CCN. In turn, CCN types, concentration, and size distribution are important in determining cloud extent, lifetime, phase partitioning, water content, precipitation properties, and overall effect on the energy budget (Quaas and Gryspeerdt, 2022). Increased CCN from biogenic emissions could have the potential to change cloud radiative effects critically in the future, specifically when other sources of CCN are scarce in summer and fall (Lange et al., 2019). Typical sources of CCN in the high Arctic are sea spray, blowing snow, and secondary particles containing particulate sulfate and organics (Karlsson et al., 2022; Bergner et al., 2025; Heutte et al., 2025). The role of PBAP as CCN is not yet quantified, however.

The above demonstrates that emissions from the biosphere influence clouds as primary (Orellana et al., 2011; Porter et al., 2022; Pereira Freitas et al., 2023) and secondary particles (Leaitch et al., 2013; Burkart et al., 2017). Conversely, clouds can also influence the biosphere. Clouds have a strong influence on the availability of photosynthetically active radiation (PAR) that reaches the sea ice and open ocean surfaces and is necessary for photosynthetic microorganisms to thrive (Laliberté et al., 2016). Generally, clouds reduce direct solar radiation but enhance diffusive PAR availability through additional scattering, and are hence an important local feedback factor. In addition, clouds modulate the surface temperature (Maillard et al., 2021) and thereby impact the local biosphere.

Biogeochemical cycles and nutrients. Atmospheric aerosols also contain major elements (such as nitrogen, iron or phosphorus) and organic matter, making them an important external source of nutrients to the upper ocean when deposited, potentially influencing marine microorganisms and biogeochemical cycles depending on the biogeochemistry of the receiving surface-ocean ecosystem, as suggested by models (Moore et al., 2013; Altieri et al., 2021). Net primary production in the central Arctic Ocean is limited by nutrient availability, particularly nitrate (Tremblay et al., 2015). Atmospheric nitrogen deposition originates from anthropogenic emissions, such as shipping (Raut et al., 2022), and also natural sources such as boreal fires that have been linked to phytoplankton blooms (Ardyna et al., 2022). The ocean cannot be considered a one-way recipient of atmospheric nitrogen deposition, however. Some of the deposited nitrogen originates from the ocean and cycles through the atmosphere before being redeposited. Overall, how much of the aerosol-nitrogen deposited to the ocean is truly external in origin and how much of this external input is anthropogenic is not clear (Jickells et al., 2017; Altieri et al., 2021).

PBAP account for a significant portion of organic nitrogen in marine aerosols and may be able to sustain microbial activity, including nitrogen processing in the atmosphere (Dall'Osto et al., 2012). In addition, atmospheric dust is a source of nutrients such as iron, shown to be a secondary limitation of primary production in Fram Strait (Krisch et al., 2020). The extent to which nutrient deposition influences the development of microorganisms in snow and ice and central Arctic emissions of PBAP into the atmosphere is little explored (Okin et al., 2011; Clark et al., 2020).

Knowledge gaps and research questions. Advances in understanding of marine biosphere-atmosphere interactions have been made recently, for example, through the Surface Ocean Lower Atmosphere Study (SOLAS) initiative (Willis et al., 2023, and references therein; Sellegri et al., 2024, and references therein), and other international field experiments (Landwehr et al., 2021; Moallemi et al., 2021; Gallo et al., 2023). However, knowledge of biosphere-atmosphere interactions and their impacts specifically on central Arctic climate change and ecosystem functioning remains limited.

Historically, most attention has been focused on the direct radiative impact of anthropogenic aerosols, which were found to contribute nearly 0.3°C of Arctic warming per decade, an amount similar to the effect of CO_2 (von Salzen et al., 2022). Among the knowledge gaps, and remaining highly uncertain, are the effects of naturally sourced particles and their precursors on clouds, as well as their interactions with clouds (Schmale et al., 2021). In particular, aerosol-mediated interactions between the atmosphere and biosphere in the sea ice and ocean play critical roles in climate feedback processes in the central Arctic, the importance of which have been recognized only recently (Cuthbertson et al., 2017; Šantl-Temkiv et al., 2019; Creamean et al., 2022).

In addition, the available knowledge about biogenic aerosols and gases in the central Arctic stems from

Table 2. Definition of main research questions and associated research themes (Section 3)

No.	Research Question	Plain Language Question	Associated Research Theme
1	What are the origin and taxonomic composition of biogenic particles and sources of gases in the central Arctic Ocean?	What is there and where do they come from?	Identifying the airborne microbiome, toward data integration and improved modeling
2	How are airborne biogenic particles and gases dispersed vertically and horizontally?	Where do they go?	Vertical profile measurements, toward data integration and improved modeling
3	What are the impacts of airborne biogenic particles and gases on cloud formation, atmospheric light transmission, and biogeochemistry?	What is their impact?	Remote sensing and radiation measurements, toward data integration and improved modeling

measurements made near the surface ocean (Cuthbertson et al., 2017; Šantl-Temkiv et al., 2019; Creamean et al., 2022). However, because of frequent strong surface-based temperature inversions (as low as a few tens of meters) in the Arctic boundary layer (Jozef et al., 2023), surface observations are not necessarily representative of atmospheric composition at cloud level, where PBAP can unfold their climatic effects. Moreover, particles transported into the central Arctic Ocean atmosphere are often located above surface inversions in the boundary layer and do not necessarily mix down to the surface (Ansmann et al., 2023). Hence, surface and vertically resolved observations in the atmosphere are key to our understanding.

As a result of the rapid Arctic warming (Rantanen et al., 2022) and the dynamically changing anthropogenic and natural aerosol sources (e.g., Schmale et al., 2021; von Salzen et al., 2022), we anticipate critical impacts of the marine-ice-snow biosphere on the atmosphere and vice versa that need to be quantified year-round and specifically throughout the Arctic's transition toward an ice-free summer ocean. We therefore identify three leading research questions for the initial Tara Polaris expeditions that are shown in **Table 2**.

The *Tara Polar Station* platform. Specifically focused on the Arctic, the *Tara Polar Station* is a unique platform that will facilitate the study of processes influencing critical climate-ecosystem linkages involving interactions between the atmosphere, the Arctic snow and sea ice, and the ocean biosphere. The platform is intended to observe the central Arctic Ocean over two decades (2026–2046) through ten drifts of 18 months covering all seasons. The specificity of *Tara Polar Station* with respect to other polar research vessels is described in detail in (Babin et al., n.d.). Briefly, *Tara Polar Station* will be operated by a crew of four sailors (captain, chief mate, chief engineer, and cook), along with a journalist and a medical doctor. Throughout the winter, six highly trained science-engineers will be on board with an additional six scientists during the summer. This approach makes the overall logistical effort lean and sustainable for many years. It is fundamentally different from traditional expeditions, for example, MOSAiC (Shupe et al., 2022), SHEBA (Persson et al., 2002), or N-ICE (Granskog et al., 2016), hosting up to 60 scientists for a maximum of 1 year. A specific advantage of *Tara Polar Station* is the opportunity to carry out regular measurements in the central Arctic Ocean over multiple years. The *Tara Polar Station* will essentially be the first quasi-permanent, in situ observatory in the central Arctic Ocean, where so far only temporally limited expeditions have taken place, and therefore large data gaps exist. Building on this unique opportunity, the key objectives of Tara Polaris expeditions are to understand the seasonal dynamics, connectivity, adaptive mechanisms, and potential feedbacks on climate of the central Arctic Ocean microbiome, distinguishing it from previous Arctic Ocean expeditions. In particular, measurements will also be made during winter and will include vertical profiles of the atmosphere. *Tara Polar Station* can also operate exclusively on batteries for multiple hours per day, thereby limiting the influence of exhaust gas on measurements of atmospheric composition. In addition, the deployment of the multidisciplinary platform will enable researchers to link genomic data contextually, matching surface seawater and ice samples to the atmospheric samples in order to study possible microbial emission and connectivity. Linking these data requires curated records of in-situ measured environmental parameters, which are planned to be coordinated with biological sampling. Interdisciplinary formulation of research questions and design of related sampling strategies are anchored in and led by five scoping groups within the *Tara Polar Station* scientific coordination team, where the groups focus on atmosphere-biosphere interactions (this article), small-scale biology and physics in sea ice (Vancoppenolle et al., n.d.), epi- and meso-pelagic life in an ice-covered ocean (Geoffroy et al., n.d.), long-term observations (Ardyna et al., n.d.), and pollution (Ghiglione et al., n.d.).

In the following, we outline three process-level research themes that can tackle our specific research questions over the first several drift seasons and describe the envisioned methodological approach as well as concrete links to the other *Tara Polar Station* scoping groups. We close by highlighting the expected outcomes and giving a longer-term outlook.

2. Research themes

2.1. The airborne microbiome

The emission, dispersal, diversity, and viability of airborne microorganisms (e.g., bacteria, archaea, algae, other protists, and fungi) and viruses (**Figure 1**) at the ice-ocean-atmosphere interfaces are critical to ecosystem functioning and the consequences of climate perturbations in the central Arctic, the latter mainly through impacts on clouds. While there is some evidence that the terrestrial and marine atmospheric boundary layers in polar regions support a highly diverse and nonrandomly assembled microbiota (Orellana et al., 2011; Leck et al., 2013; Archer et al., 2020; Šantl-Temkiv et al., 2020), the diversity of microbes within PBAP and the airborne microbiome is largely unexplored over the Arctic (Harding et al., 2011; Cuthbertson et al., 2017). Moreover, existing diversity estimates are strongly influenced by methodological biases (Šantl-Temkiv et al., 2020; Mescioglu et al., 2021). The type, amount, and efficiency of particle emissions from the ocean, ice, and snow together with their atmospheric deposition, and possible reemission, hold large uncertainties. These uncertainties include whether they are emitted "alone" or as "passengers" on other particles. For example, marine organic aerosols associated with fresh sea spray aerosol have been observed in Arctic winter (Kirpes et al., 2019). Emission and deposition fluxes, which are needed to improve process treatments in models simulating climate and ecosystem impacts, have not yet been derived. Although microbial emissions have been assumed to be negligible in the Arctic (Burrows et al., 2013; Spracklen and Heald, 2014), recent evidence points to them as being key contributors to the INP population close to the surface (Pereira Freitas et al., 2023; Beck et al., 2024).

Drifting with ice floes over multiple seasons will facilitate elucidation of critical processes related to selective microbial emissions (Lang-Yona et al., 2022) and pinpoint local central Arctic sources and emission and loss mechanisms. PBAP introduced above are related to "warm INPs." During the MOSAiC expedition, PBAP were observed in the presence of melt ponds, where the wind speed was too low to entrain air into the water with subsequent bubble bursting, which suggests that microbially mediated bubble formation and bursting might play a role (e.g., Flores et al., 2021), rather than a wind-induced mechanism (Beck et al., 2024). However, other studies have not found evidence for bubbles in melt ponds (Geilfus et al., 2023), nor sufficient bubble production in open leads, as studied during the Swedish expedition Arctic Ocean 2018 (M Salter, personal communication, March 28, 2019). Additional results from summer INP studies during MOSAiC suggest that the sea ice and snowpack hold significant amounts of biological INPs likely emitted via melt ponds (Mavis et al., n.d.). During the MOSAiC winter, "bursts" of PBAP were detected, lasting several hours, but whether they were local or remote in origin remains to be clarified (Beck et al., 2024). Probing the near-surface atmosphere, together with the surface ocean, sea ice, ridges, snow, melt ponds, and leads, for microbial diversity over the course of multiple seasons can be expected to reveal the specific sources of airborne microorganisms. The probing approach could be based on amplicon sequencing of the small subunit (16S/18S) rRNA gene and metagenomic analyses of the microbial communities. As such a field experiment is labor intensive, it will be carried out most thoroughly during summer, when twelve scientists will reside on board and sampling all matrices with a frequency of 2–3 days will be possible. During winter, the sampling frequency will be reduced to once every 1–2 weeks.

Airborne microorganisms have been shown to remain viable and to initiate cloud formation through ice nucleation (Deguillaume et al., 2008; Delort et al., 2010). Some microorganisms have been implicated in processing atmospheric nitrogen (Hill et al., 2007), degrading selected organic carbon compounds (Ariya et al., 2002), and possibly performing photosynthesis (Després et al., 2012). Viable infectious (algicidal) bacteria and viruses are known to be transmitted in marine aerosols (Sharoni et al., 2015; Lang-Yona et al., 2024). Specifically for the Arctic, the viability of long-range transported microbes and their potential local impacts are critical unknowns.

Within this research theme, we aim to answer the following specific questions:

- What is the diversity of airborne microbial communities, and what are the ecological drivers of their taxonomic and genomic compositions?
- What are the processes governing aerosolization, viability, and deposition of airborne biological particles?
- What are the origins of airborne microbes in the central Arctic Ocean, and how do they exchange between land, ice, snow, the ocean, and the atmosphere?

2.2. Atmospheric dispersion and interactions with clouds

Knowledge about aerosol properties in the central Arctic Ocean, and the distribution of aerosol types, CCN and INP, is based mainly on collection of data in the free troposphere by limited aircraft campaigns which took place primarily in spring and summer (e.g., Brock et al., 2011; Schmale et al., 2011; Law et al., 2014, and references therein; Abbatt et al., 2019, and references therein; Wendisch et al., 2019, and references therein). Sampling of the lower atmosphere over pack ice has been limited, and the contribution of PBAP, as well as other aerosols, at various heights in the Arctic boundary layer is largely unknown. Our basic knowledge of airborne microorganisms near the surface stems from summer icebreaker campaigns between 1991 and 2020 (Leck et al., 1996; Leck et al., 2001; Tjernström et al., 2004; Tjernström et al., 2014; Shupe et al., 2022), where primarily microscopy-based techniques showed that biological particles are present in the surface atmosphere layer as well as in clouds. However, to assess the direct and indirect radiative impact of biosphere-sourced aerosols, knowing their vertical distribution is vital, for example, biosphere-sourced CCN and INP will only unfold their climate-relevant potential if they reach cloud level.

The lack of vertical profile measurements, in particular during the polar night, is a critical shortcoming, as the Arctic atmosphere is highly stratified (Persson et al., 2002; Graversen et al., 2008; Jozef et al., 2023), and distinct layers are often decoupled from each other, strongly inhibiting vertical exchange. Such stratification, especially in the presence of surface-based temperature inversions, leads to layering of aerosols, where ground-based measurements are often not representative of cloud-level concentrations (Creamean et al., 2021; Lonardi et al., 2024). During winter and early spring, the Arctic Ocean is influenced by Arctic haze: aerosols transported mainly at low levels from Eurasia that generally can be measured at the surface, but their properties differ in the various stratified layers in the lower atmosphere (Law et al., 2014; Thomas et al., 2019; Engelmann et al., 2021). In addition, natural sources such as sea spray aerosol, blowing snow (Gong et al., 2023), or emissions from melt ponds could inject microorganisms into the Arctic boundary layer close to the surface. How much these emissions influence cloud formation or are deposited back onto the surface is unclear, because the surface atmosphere is often decoupled from layers aloft. Hence, vertical in situ measurements that can be used to determine microbial diversity, viability, CCN, and INP properties are needed to gain insight into vertical fluxes (emissions and deposition) of surface-emitted aerosols. Such measurements can be performed using tethered balloons and drones with additional measurements of aerosol fluxes on a fixed mast on the sea ice.

There are limitations for collecting in situ vertical profile observations. In the central Arctic storms are more prevalent in winter (Rinke et al., 2021). Deployment of surface-based remote sensing instrumentation, as planned on the *Tara Polar Station*, becomes indispensable to measuring the vertical exchange between surface-sourced particles and those residing in decoupled layers aloft. Emerging aerosol sources, driven by climate change, such as intensifying boreal fire emissions or high latitude dust, may be transported to the central Arctic Ocean predominantly in the free troposphere above the reach of drones and tethered balloons (Engelmann et al., 2021; Ansmann et al., 2023); their effects on cloud formation and phase can best be observed by lidars and radars throughout the seasons. These observations are necessary to quantify the contributions of various particle source types, including from the biosphere, to the CCN and INP populations and thereby their effects on cloud properties.

Heterogeneity of atmospheric compounds does not only apply to the vertical but also to the horizontal dimension. Aerosol concentrations as well as water vapor, a key ingredient to cloud formation, can change widely across central Arctic surfaces, such as over pack ice, leads, and melt ponds. In particular, lead openings in winter can induce vertical mixing in the lower atmosphere through release of heat from the ocean (Cox et al., 2023); if scaled across the many leads of the Arctic, these features can influence cloud formation. Vertical mixing of air masses also affects dry deposition of aerosols to the surface (Spackman et al., 2010), and may play a role in the deposition of nutrients to sea-ice ecosystems.

As the Arctic changes, both the local sources of aerosols and microorganisms will change, as well as the long-range transported natural and anthropogenic particles (Schmale et al., 2021, and references therein). At the same time, warming temperatures, reduced sea ice, and evolving cloud properties will change Arctic boundary layer thermodynamics, with effects on vertical mixing and feedbacks on cloud formation and properties, including light transmission. This research theme will address the following fundamental open questions:

- What are the vertical distributions, quantities, and properties of PBAP and biogenic gases emitted jointly or separately from the central Arctic Ocean?
- Are low-level clouds fed by aerosols, and specifically biosphere-sourced particles, from local surface sources or from long-range transported aerosols?
- What is the contribution and impact of biosphere-sourced particles to the general aerosol population that forms clouds?

2.3. Biological activity and solar radiation; impacts on energy budget

Biological and photochemical activity in sea ice, snow, and the Arctic Ocean are limited or affected by several factors, including the availability of sunlight at ultraviolet (UV) and visible wavelengths. UV radiation arriving at the surface can be harmful to microorganisms, whereas photosynthetically active radiation (PAR, 400–700 nm) is used by photosynthetic microorganisms and fuels primary production. The amount of PAR available to organisms in the ice, snow, and water depends on many factors. Notably, it depends significantly on multiple scattering events between highly reflective snow and ice surfaces and the atmosphere, including the presence of clouds (Laliberté et al., 2016, and references therein), as well as transmission through snow, sea ice, and water. Laliberté et al. (2021) found that the transfer of PAR through the atmosphere decreased at a rate of 2.3% per decade due to the increase in Arctic cloudiness and the weaker radiative interaction between the atmosphere and the surface. They also found that irradiance at the surface and under sea ice is underestimated if scattering between sea ice and clouds is not taken into account in the radiative transfer calculations. However, large uncertainties exist regarding the propagation of PAR through the atmosphere and the role of clouds and aerosol layers. In addition, aerosols deposited at the surface reduce surface albedo (e.g., black carbon from fires or mineral dust; von Salzen et al., 2022). In particular, the propagation of certain wavelengths and their conducive or detrimental effects on microbial life are not well understood. Improving the quantification of atmospheric PAR dependence on cloud properties, such as phase (liquid, ice, or mixed), extent, thickness, and the type of aerosol layers, is important. Aerosols originating from local emissions (e.g., sea spray aerosol, PBAP, sublimated blowing snow) or remote long-range transport sources (e.g., boreal fires, Arctic haze) can influence clouds (Ansmann et al., 2023; Gong et al., 2023). Because the multiple scatterings between the surface, cloud, and aerosol layers strongly influence PAR at the surface, where it becomes most relevant for Arctic ecosystems, the evolving effects of surface reflectivity (albedo) and transmissivity due to changes in sea ice, melt ponds, snow cover, and leads on PAR must be understood (Webster et al., 2022).

Cloud coverage and properties (phase, thickness and height) are changing over the central Arctic (Wang et al., 2021). Because clouds, and particularly low-level mixed-phase clouds, have a strong longwave radiation and often warming effect, the entire surface energy budget in the central Arctic is anticipated to change drastically (Wendisch et al., 2023), thereby constituting an important climate feedback process. There are many critical challenges related to cloud observations in the central Arctic, including a satellite blind spot at roughly >82°N (Engelmann et al., 2021), high surface albedo, and the difficulty inherent to remotely sensing cloud phase, in particular ice crystals which tend to concentrate at the bottom of clouds (Creamean et al., 2021, and references therein). These ice crystals might have nucleated on biological INP. The *Tara Polar Station* therefore provides a unique opportunity to deploy surface-based remote sensing technology to thoroughly investigate clouds, cloud-forming aerosols, radiative transfer, and the surface energy budget.

Within this research theme we aim to answer the following specific questions:

- What is the effect of cloud phase, height, cover, and thickness on the transmission of PAR?
- Do aerosols, from local or remote sources, significantly impact atmospheric transmission of PAR directly or indirectly through cloud formation?
- What is the sensitivity of the central Arctic Ocean surface energy budget to the presence of clouds and aerosol layers and their properties?
- What is the effect of clouds over the seasonal cycle on the surface energy budget?

3. Approach

Studying atmosphere-biosphere interactions that occur over a large range of temporal and spatial scales requires a combination of different observational approaches (**Figure 2**). To obtain information on airborne microorganisms and aerosol chemical composition and origins, particles will be collected onto filters from sites on and away from *Tara Polar Station* (details below). General information on aerosols, for example, their number, composition and size distributions, and trace gas concentrations (e.g., CO_2, CH_4, CO, O_3, DMS, isoprene) will be obtained in real time from instrumentation installed permanently on *Tara Polar Station* (**Table 3**). These real-time observations are not discussed further as they use established methods previously described and deployed on other research vessels (Baccarini et al., 2020; Karlsson et al., 2022; Angot et al., 2022; Heutte et al., 2023).

To cover the vertical dimension, we have two approaches. First, we plan to operate remote sensing instruments for detecting aerosols, cloud, and radiation flux from *Tara Polar Station* and on the ice. Second, a small tethered balloon will be deployed along with drones to collect vertical and horizontal in situ information, respectively. To answer our more detailed questions about processes governing surface fluxes (emission, deposition) and microorganism-cloud interactions, dedicated field efforts with more comprehensive measurements are envisioned, for example, deployment of a large tethered balloon or measurements on a sea-ice-based mast (e.g., for deposition fluxes).

A difficulty inherent to performing atmospheric molecular and chemical analyses from platforms that emit exhaust gases themselves (e.g., from fuel combustion, cooking and the ventilation systems) is that samples can easily become contaminated. This challenge a manageable for real-time data because contaminated periods can be removed using established methods (Beck et al., 2022). However, as some variables (e.g., organic compounds) collected on filters are highly sensitive to combustion exhaust and even short periods of contamination can influence the measurements, ideal collections can only occur when *Tara Polar Station* operates on batteries for a few hours each day. Because the sampling time is limited during battery operation, the mass collected may not be sufficient. In addition, other types of exhaust (e.g., sanitary facilities, laboratories) can also contaminate the samples. Therefore, in the first test mission, two additional options will be tested: a small container for filter-sampling will be placed on the foredeck at maximum distance from exhaust vents and controlled by a wind direction sensor that only allows sampling when air comes from the clean sector; and a sledge, equipped with a new type of long-lasting and cold-resistant batteries, will be placed on the sea ice away from the platform for filter-sampling. Moreover, the *Tara Polar Station* microbiome might influence the sampled microbiome; hence, meticulous tests before the first deployment will be conducted to identify appropriate sampling locations on the platform, while blank filters will be taken regularly during drift experiments. At the same time, *Tara Polar Station* exhaust emissions will be characterized under relevant Arctic conditions (e.g., cold and dark).

Deploying a drifting platform in the Arctic also entails challenges that will impact data availability and representativeness (Babin et al., n.d.). For example, taking samples that require regular excursions onto the sea ice is only possible during favorable conditions (e.g., good visibility, stable sea ice), and may be limited substantially during adverse conditions. The chosen instruments are deemed to be suitable for long-term observations under harsh conditions, but failure cannot be excluded. While the team of science-engineers operating the instrumentation is highly trained and communication with principal investigators is possible, not all failures might be reparable on site, leading to data gaps. Care will be taken to establish sufficient redundancy and limit risks. From a more general perspective, the sea-ice drifts are expected to follow similar trajectories in each expedition, which means that the spatial data coverage will be constrained, while the use of satellite data and modeling will contribute to placing Tara Polaris expedition data into the wider geographical context.

In the following, more insights are provided about observations needed to address our main research questions throughout four research themes (**Table 2**). **Tables 3–5** deliver an overview of planned instrumentation, their deployment and derived variables. **Table 5**

Table 3. Filter samplers and real-time instrumentation, with list of instrumentation, deployment location, variables, and sampling frequency

Instrument	Location	Variables[a]	Sampling Frequency[b]
		Filter samplers	
MOUDI[c] impactor	*Tara Polar Station*	DNA, INP, biogenic particles	24 hours, each day
High volume samplers	*Tara Polar Station*	DNA, INP, biogenic particles, major ions, isotopes, trace elements, elemental, and organic carbon	24–72 hours, each day; weekly for isotopes
BioSpot-GEM	*Tara Polar Station*	Collection of particles from 10 nm to 10 µm, for capture of viable microorganisms	24–72 hours, each day
Custom-made samplers	*Tara Polar Station*	INP, DNA, single particle morphology, chemical composition	24 hours, each day
SASS[d] 3100	*Tara Polar Station* mast	DNA	24–72 hours, each day
Custom-made samplers	On ice near leads	INP, DNA, single particle morphology, chemical composition	24 hours, once per week
SASS[d] 3100	On ice near leads	DNA	24 hours, once per week
		Real-time composition measurements	
Scanning mobility particle sizer (SMPS)	*Tara Polar Station*	Fine mode aerosol size distribution and estimation of CCN, particle number concentration, pollution detection	Minutes
Wideband integrated bioaerosol spectrometer (WIBS)	*Tara Polar Station*	coarse mode aerosol size distribution, fluorescence (derivates: proxy for PBAP)	Seconds
Optical particle counter	*Tara Polar Station*	Coarse mode aerosol size distribution	Seconds
Ozone monitor	*Tara Polar Station*	Air mass identification	Seconds
CO_2 monitor	*Tara Polar Station*	Air mass identification	Seconds
Cloud condensation nuclei counter (CCNC)	*Tara Polar Station*	CCN number concentration	Seconds
Aethalometer	*Tara Polar Station*	Aerosol absorption (derivate: black carbon)	Seconds

[a]Ice-nucleating particles (INP), cloud condensation nuclei (CCN).

[b]The indicated frequency is an approximation and will be refined after first tests.

[c]Micro-orifice uniform deposit impactor (MOUDI), a multistage filter sampler that allows sampling particles in various size ranges.

[d]SASS® 3100 Dry air samplers.

mainly refers to intensive summer observation periods. We refer the reader to the companion manuscripts in this special feature (Ardyna et al., n.d.; Geoffroy et al., n.d.; Vancoppenolle et al., n.d.) for sampling and analysis protocols for ocean and ice samples.

3.1. Identifying the airborne microbiome

The abundance and diversity of aerosol microbes need to be analyzed to identify biogenic exchanges between the surface and atmosphere. Specifically, our primary strategy will be to collect airborne microbial biomass on filters for genomic sequencing with devices operating at collection rates of 100–300 L min^{-1} for timescales of hours to days. The airborne microbiome can experience shifts in community composition and abundance with altitude. As a result, the vertical distribution of microbes will be examined via the deployment of collectors on flight platforms (e.g., tethered balloons or drones). Moreover, net fluxes of particles in the atmosphere will be studied by positioning samplers downwind of open leads, melt ponds, or on ridges. At the same time, the microbial community associated with snow, ice, and ocean, lead, and melt-pond waters will be sampled and analyzed together with the other scoping groups based on synchronized sampling plans. Comparing microbial communities in these reservoirs with the adjacent aerosol microbiomes will provide new insights into potential emission sources and net fluxes of diverse airborne microbes. Drawing upon data from biodiversity databases will shed light on potential remote source types and regions, which will be linked to *Tara Polar Station* and flight platform-based filters.

The airborne microbial community will be characterized using previously described DNA extraction methods for ocean and aerosol microbiomes (Logares et al., 2014;

Table 4. Remote sensing, vertical profiling, and meteorology, with list of instrumentation, deployment location, variables, and sampling frequency

Instrument	Location	Variables[a]	Sampling Frequency[b]
		Remote sensing/radiometers	
SLIM532/808 micro-lidar	*Tara Polar Station*	Horizontal and vertical profiles of aerosol optical properties (backscatter, extinction), fine/coarse mode aerosol contributions (color ratio), shape discrimination	Minutes
Mini SAOZ	*Tara Polar Station*	Spectrally resolved UV-VIS radiation measurements	Minutes
BASTA Mini Radar	*Tara Polar Station*	Reflectivity, cloud mask, phase partitioning (liquid/ice), ice water content, ice crystal effective radius	Minutes
Radiometers	Over the ice	Shortwave, PAR, longwave radiation, up, and downwelling	Minutes
		Routine deployment: small helikite, 3 kg payload; drone, 1 kg payload	
Custom-made samplers	Small helikite and drone	INP, DNA, single particle morphology, chemical composition	8 hours, once per week; virtual tower
SASS 3100	Small helikite and drone	DNA	8 hours, once per week; virtual tower
Optical particle counter	Small helikite and drone	Coarse mode aerosol size distribution	Seconds, once per week; virtual tower
Weather sonde	Small helikite and drone	Temperature, relative humidity, wind direction and speed	Seconds, once per week; virtual tower
Particle counter	Small helikite and drone	Particle number concentration	Seconds, once per week; virtual tower
Thermal desorption tube	Large helikite	Biogenic volatile organic compounds	Minutes
		Meteorological measurements	
Basic weather station	*Tara Polar Station*	Temperature, relative humidity, pressure, wind direction and speed, global radiation	Seconds
Weather station	Mast on sea ice	Temperature, relative humidity, pressure, wind direction and speed, precipitation, longwave and shortwave down and upwelling radiation	Seconds

[a]Photosynthetically active radiation (PAR), ice-nucleating particles (INP).

[b]The indicated frequency is an approximation and will be refined after first tests.

Sunagawa et al., 2015; Lang-Yona et al., 2022; Lang-Yona et al., 2024). Specifically, prokaryotic community composition will be analyzed primarily via amplicon sequencing targeting the 16S rRNA gene. This commonly used approach will facilitate comparison to other large-scale bioaerosol sampling efforts (Lang-Yona et al., 2022) and has been shown to provide concurrent coverage of bacterial and archaeal microbial communities in Arctic waters and sediments (e.g., Fadeev et al., 2021). A second primer pair (e.g., Comeau et al., 2011) will be used to target 18S rRNA genes in microbial eukaryotes. Analysis of population genomics will be performed on selected samples via whole genome shotgun sequencing using short-read (Illumina) protocols and, if feasible, long-read protocols such as PacBio for ultra-low input library construction.

Complementary to the genetic analysis of aerosol microbiomes, isotopic analyses of atmospheric aerosols will be carried out to gain further insights into their origins. The multi-isotopic (oxygen, nitrogen, and sulphur) composition of aerosols collected on filters over several days or weeks will be measured. The results will provide powerful constraints in source apportionment studies, in particular in distinguishing between the multiple possible emission sources, formation pathways, and biological and atmospheric cycling (e.g., Thiemens, 2006; Altieri et al., 2021). Nitrates originating from different emission sources and formation pathways generally have

Table 5. Campaign deployments, with list of instrumentation, deployment location, variables, and sampling frequency

Instrument	Location	Variables[a]	Sampling Frequency[b]
Campaign deployment: large helikite, 30 kg payload, multiple times per week			
Custom-made samplers	Large helikite	INP, DNA, single particle morphology, chemical composition	8 hours
SASS 3100	Large helikite	DNA	8 hours
Optical particle counter	Large helikite	Coarse mode aerosol size distribution	Seconds
Weather sonde	Large helikite	Temperature, relative humidity, wind direction and speed	Seconds
Particle counter	Large helikite	Particle number concentration	Seconds
MOUDI impactor	Large helikite	DNA, INP, biogenic particles	8 hours
Absorption photometer	Large helikite	Aerosol absorption (derivate: black carbon)	Seconds
MiniSMPS	Large helikite	Fine mode aerosol size distribution, particle number concentration, pollution detection (derivates: CCN)	Minutes
Cloud droplet analyzer	Large helikite	Cloud droplet number concentration and size distribution	Minutes
Nephelometer	Large helikite	Aerosol scattering	Seconds
Thermal desorption tube	Large helikite	Biogenic volatile organic compounds	Minutes
Campaign deployment: flux tower			
3D sonic anemometer	Flux tower	Vertical wind velocity, small-scale turbulence	Several Hz
Particle counter	Flux tower	Particle size distribution and number concentration (for dry deposition)	1 Hz
Snow particle counter	Flux tower	Snow particle number concentration and size distribution	Seconds

[a]Ice-nucleating particles (INP), cloud condensation nuclei (CCN).

[b]A sampling time of 8 hours might not be sufficient for DNA analysis, in which case samplers would be deployed over multiple flights and sealed in-between to prevent contamination.

a distinctive nitrogen or/and oxygen isotopic signature (ratio of the heavy to light stable isotope). Particulate nitrate is formed from NO_x emissions that result from combustion processes, whereby the isotopes vary between, for example, fossil and biogenic fuels. As a result, stable isotope analysis of aerosol nitrate is commonly used to identify the different sources and estimate their contributions (Savarino et al., 2007; Morin et al., 2008; Shi et al., 2021; Albertin et al., 2024). Analysis of atmospheric aerosols will be complemented by isotopic analysis of snow samples (Frey et al., 2009; Clark et al., 2020; Hattori et al., 2023). We will also continuously measure meteorological and relevant environmental variables (e.g., wind speed, lead fraction, boundary layer height) to help elucidate the physical conditions that determine fluxes (deposition, emission) of atmospheric microbes.

3.2. Vertical profile measurements

For regular vertical in situ measurements, a practical approach is to deploy a small tethered balloon with a light-weight payload up to 1–2 km altitude to collect data on atmospheric PBAP and other aerosols and trace gases, together with meteorological variables, across seasons. This approach can fill the winter observational gap, for which tethered balloons are particularly suitable except during storms (Pohorsky et al., 2024). Icing of the balloon or the heated inlet and payload is typically not a key challenge during the very cold and dry winter conditions, as shown by deployments in continental Alaska (Pohorsky et al., 2025) with meteorological conditions comparable to the central Arctic Ocean. Riming of the platform might occur during the warmer and more humid months, requiring more maintenance and potentially more frequent, shorter flights. Recent technological development of miniaturized, high data quality aerosol instrumentation (see **Tables 4** and **5**) will enable us to answer our fundamental research questions on biological particles and their influence on cloud properties. In particular, several hour-long balloon flights, deployed on a weekly basis, will permit real-time observations of vertical and lateral exchange processes and to sample within cloud decks as they evolve. These flights will also provide sampling times long enough to collect sufficient biomass on filters for airborne microbiome analysis, and link surface observations from the ocean, leads, melt ponds, snow, and sea ice quantitatively to cloud level. Comparative genomics can unravel differences in microbial populations between the boundary layer and lower free troposphere, as well as influences from remote sources. Regular vertical profiling over an entire drift season (>1 year) will amass an unprecedented amount of vertical in situ data, in addition to thermodynamic information of the lower atmosphere, very much needed for numerical weather prediction improvement. In addition, during periods of calm weather, the tethered balloon can be operated as a virtual tower, hovering for multiple days with instrumentation placed along the tether, allowing detailed study of microbial and aerosol vertical fluxes, hitherto virtually unknown. Sampling over larger horizontal distances in atmospheric layers aloft can be achieved with a drone system payload complementary to the small tethered balloon. Note that a "traditional" radiosounding program with weather balloons is not feasible on *Tara Polar Station* because of the need to store large amounts of helium.

A large tethered balloon with a lifting capacity of >20 kg, which can carry a more comprehensive payload, is also envisioned for specific Tara Polaris expeditions (Pohorsky et al., 2024) to collect more detailed data on the microbiome versus other aerosol impacts on clouds, origin, and transport pathways. Analysis of vertical aerosol composition measurements, combined with measurements in the sea ice, can provide some insights into aerosol deposition (Spackman et al., 2010) and could be complemented by additional regular measurements using wet and dry deposition samplers. Dedicated campaigns using sea-ice-based flux tower measurements can determine, for example, aerosol emission and dry deposition fluxes (Donateo et al., 2023) and link to studies of nutrients and microorganisms in the ice and ocean.

3.3. Remote sensing and radiation measurements

Our approach combines continuous, autonomous, cloud radar, and aerosol lidar observations (Delanoë et al., 2013) deployed on board *Tara Polar Station* to provide information complementary to the in situ observations. Obtained variables include aerosol layers (such as height and particle size) and aerosol optical depth observed by the lidar, as well as cloud presence, phase (liquid and ice), and water content (synergy between lidar and radar). The instruments will also provide information about the boundary layer extent. Vertical profiles with tethered balloons will provide unique in situ information about aerosol and cloud properties for remote sensing validation (Pohorsky et al., 2024). Also planned are deployments of remote sensing instrumentation scanning vertically across various zenith angles or scanning horizontally. These measurements will provide highly resolved temporal and spatial/vertical information about aerosol distributions over Arctic sea ice and with respect to cloud presence. Such observations are both unprecedented and indispensable due to variations in boundary layer thermodynamics across leads, ice, and melt ponds, which will occur under the horizontal lidar scanning path. Space-borne remote sensing north of 82°N generally cannot detect aerosols and clouds (Engelmann et al., 2021), but such data products can complement the observations from the Tara Polaris expeditions further south for large-scale and long-term changes (see also Ardyna et al., n.d.). The new EarthCare satellite in near-polar orbit with its active sensing instruments can detect aerosols and clouds over Tara Polaris expedition locations (Wehr et al., 2023), and validation experiments are planned.

Spectrally resolved UV-VIS measurements of atmospheric radiation will be carried out using a mini-SAOZ UV-visible spectrometer that can be used to calculate wavelength dependence of radiation arriving at the snow, ice, or ocean surfaces and retrieve ozone and nitrogen dioxide atmospheric columns (Kreher et al., 2020). This specifically developed instrument has already been deployed to make routine autonomous measurements in harsh polar conditions (Bognar et al., 2019; Pazmiño et al., 2023, and references therein) and routinely on the research vessel Marion Dufresne (Tulet et al., 2024). It will be deployed together with standard in situ measurements of upward and downward shortwave and longwave radiation, which will be obtained from a 10 m mast located over the sea ice. In addition, meteorological variables, notably surface and air temperatures at various heights, as well as winds, constitute critical observations for all scoping groups, and will be obtained on the *Tara Polar Station* and the sea ice.

3.4. Toward data synthesis and improved modelling of key processes

Integrating the results obtained from the measurements described in Sections 3.1–3.3 will allow us to answer our main research questions on the origin of airborne microorganisms, their atmospheric behavior and climatic impact. For example, the long-term and colocated observations of PBAP (as obtained from fluorescence measurements) and INP can be used to determine the relevance of PBAP for warm (e.g., −9°C) INP, as has been done for the MOSAiC expedition through covariance analysis (Beck et al., 2024). The genomic analyses on filters obtained in parallel to the INP filters (both on the ground and aloft) can constrain the type of microorganisms and their provenance, that is, local versus long-range transported. This information can then be paired with observations of local conditions and genomic analysis of samples from, for example, occurrence of melt ponds, open leads, drifting into the marginal ice zone, and general atmospheric circulation of air masses through back trajectory simulations (e.g., Asplund et al., 2024). Over multiple years these data will allow us to estimate the surface source strength of warm INP as a function of local conditions and season, relative to other sources. Paired with the thermodynamic observations of the boundary layer, cloud formation and cloud phase, the objective is to derive a parameterization of local biological INP contribution to central Arctic cloud formation.

The novel data collected during Tara Polaris expeditions will be used to constrain and underpin science required for improved numerical model treatments of critical processes influencing emissions and recycling of the airborne microbiome and its role in low-level Arctic cloud formation and general aerosol-cloud interactions. The ultimate aim is to develop a coupled ice-ocean-atmosphere biophysico-chemical model leading to improved predictions of the coupled Arctic climate-biological system. Data will be used by members of the *Tara Polar Station* community to improve simulations of the Arctic Ocean boundary layer including dynamics, mixed-phase clouds, and the surface energy budget (atmosphere-ice interactions), using, for example, high-resolution simulations of the Weather Ranging and Forecasting (WRF) model (e.g., Sterk et al., 2013; Arteaga et al., 2024) or Large Eddy Simulations. Significant uncertainties exist in modeling the Arctic surface energy budget (Solomon et al., 2023), particularly in the winter season for which few data exist.

Simulations using the FLEXPART dispersion model, coupled to WRF dynamics (e.g., Raut et al., 2017), will be used to investigate INP sources, and regional chemical-aerosol models, such as the WRF-Chem model (e.g., Ioannidis et al., 2023; Lapere et al., 2024), will be used to examine and improve treatments of Arctic Ocean aerosol-cloud interactions. Current models run over the Arctic include rather simplified treatments of, for example, sea spray aerosol (Ioannidis et al., 2023; Lapere et al., 2023) or aerosols acting as INPs and associated aerosol-cloud interactions (e.g., Kawai et al., 2023). While model treatments of the airborne microbiome (bioaerosols) and their impacts on clouds, including ice nucleation, have been developed, further improvements are needed (Patade et al., 2022; Cornwell et al., 2023); treatments specific to the Arctic are very simplified (Gjelsvik et al., 2025) and very much in their infancy. With regard to PAR transmission, previous studies have focused on estimating PAR transmission under sea ice and its influence on algal growth (e.g., Clement Kinney et al., 2023) or on changes in atmospheric PAR transmission based on analysis of satellite data (Laliberté et al., 2021). Here, Tara Polaris expedition data will be used to evaluate model simulations (e.g., WRF-Chem), including detailed schemes for atmospheric PAR (UV, near-IR) fluxes as a function of wavelength, cloud properties, and aerosols, to investigate impacts on surface PAR.

4. Connection to other *Tara Polaris expedition* themes

Successful characterization of atmosphere-biosphere interactions is strongly connected to research questions and activities of the Tara Polaris expedition priorities focused on small-scale biology and physics in sea ice (Vancoppenolle et al., n.d.), as well as epi- and mesopelagic life in an ice-covered ocean (Geoffroy et al., n.d.). Specific links include the accurate determination of surface albedo, especially for heterogeneously dispersed melt ponds and leads, to quantify the availability of PAR to the central Arctic. Multiple reflections of PAR strongly depend on surface albedo patterns influenced by physical processes, such as melt pond and ridge development, and by the presence of sediments and deposited dust or black carbon on sea ice, as well as cloud properties. Albedo also impacts under-ice irradiance and light-mediated processes in the pelagic realm (i.e., under-ice productivity, ocean vertical migration, ecosystem dynamics, and carbon export).

To link the airborne microbiome to microbial life in the surface ocean, sea ice, brine, snow, leads, and melt ponds (scoping groups on sea ice and ocean), and to unravel mechanisms of emission to the atmosphere, two links are decisive. First, regular samples from these media are needed, where the same variables (e.g., DNA sequences) are determined in all samples to link surface sources to airborne observations as well as deposition of atmospheric constituents, including nutrients, to snow and ice across all seasons. This need notably includes quantification of nutrients in all surface types and airborne transportation of elements such as nitrogen, carbon, and iron. While quantification of airborne elements will be conducted routinely and year-round by the atmosphere scoping group, other sea-ice surfaces (e.g., melt ponds) will be probed on the basis of projects that will likely cover the summer and potentially other seasons during a specific drift. Second, small-scale process observations, such as microbial ejection with brine formation at the sea-ice surface and migration into snow or directly to the atmosphere, are critical because microorganisms in snow or in leads can be aerosolized, for example, during high wind conditions. Such intensive observations are planned for the summer of the first drift starting in 2026 (Polaris I; Babin et al., n.d.). Similarly, observations of bubble production in leads and melt ponds from microbial activity or physical processes can shed light on PBAP emissions under calm wind conditions. As these observations are complex and time-intensive, they will only be possible starting from the second drift in 2028 (Polaris II) as part of a specific summer project. These connections will answer questions on airborne microbiome sources and emission mechanisms. Direct links also exist for atmospheric gas exchanges to and from the ocean (e.g., CO_2 and DMS). Complementary to the detailed mechanistic studies are long-term observations, another focus of Tara Polaris expeditions (Ardyna et al., n.d.), which are required to understand the climate-driven changes of the central Arctic system and how they impact the airborne microbiome. At the same time, the research described here constitutes critical input to the scoping group on long-term observations by defining sentinel variables and providing key parameters of the surface energy budget and meteorology.

5. Foreseen outcomes

We are far from understanding the importance of atmosphere-biosphere interactions on climate change and ecosystem health in the central Arctic, but there is clear evidence that these interactions will affect cloud formation, PAR, the surface energy budget, and nutrient availability. Because the central Arctic Ocean is so difficult to access, a platform like *Tara Polar Station* is required, first to identify and second to quantify, relevant processes that are not yet understood or even known. Previous central Arctic missions with comparable objectives to those of Tara Polaris expeditions, such as MOSAiC, the Swedish Arctic Ocean expeditions or $(AC)^3$ (Wiedensohler et al., 1996; Tjernström et al., 2012; Shupe et al., 2022; Wendisch et al., 2023) have provided critical insights into atmosphere-biosphere interactions. What sets the Tara Polaris expeditions apart is the continuous effort over the next 20 years. Tara Polaris expeditions will generate knowledge during a period when the Arctic is changing rapidly. Over its first few years of operation, we foresee the following outcomes:

- improved understanding about the type, sources, and emission mechanisms of biological aerosols over the central Arctic Ocean;
- understanding of the relevance of local and remote particles, including biological origin, on cloud formation;
- quantification of the sensitivity of atmospheric PAR transmission to clouds and aerosols; and
- improved model treatments of atmosphere-biosphere processes.

We also anticipate identifying aerosol processes and molecular compositions that are currently unknown and that can then be investigated more thoroughly during future Tara Polaris expeditions. Such aspects will likely be linked to the expected drastic transformation of the central Arctic Ocean as it moves toward ice-free summers in the coming decades. The current state-of-the-art measurements proposed here cannot yet explore this new state of the Arctic ecosystem and its far-flung implications, but improved model predictions can contribute to exploring possible future changes.

Data accessibility statement

Data obtained from Tara Polaris expeditions will be made publicly available in repositories that are common to the specific disciplines. For example, atmospheric observations are planned to be provided on PANGAEA in universal formats for climate and biogeochemistry data, while raw "omics" data will be deposited to the European Nucleotide Archive at EMBL-EBI.

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Competing interests

The authors have declared that no competing interests exist.

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