Tara Polaris expeditions: seasonal and long-term contaminant monitoring in the changing central Arctic

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Authors : Jean-François Ghiglione[1,2,*], Lars-Eric Heimbürger-Boavida[3], Marion Fourquez[3], Ian Hough[4], Jeroen E. Sonke[5], Alexandra ter Halle[6], Kathy S. Law[7], Julia Schmale[8], J. Michel Flores[9], Julien Gigault[10], Mathieu Ardyna[10], Stephen G. Kohler[11], Zhiyong Xie[12], Jay T. Cullen[13], Maxime Geoffroy[14,15], Clémentine Moulin[16], Romain Troublé[16], Lee Karp-Boss[17], Chris Bowler[18], Marcel Babin[10], Hélène Angot[4,*]

Affiliations :

1. CNRS, Sorbonne Université, UMR 7621, Laboratoire d'Océanographie Microbienne (LOMIC), Banyuls sur mer, France
2. Research Federation for the study of Global Ocean Systems Ecology and Evolution, FR2022/Tara Oceans-GOSEE, Paris, France
3. Aix Marseille Université, CNRS/INSU, Université de Toulon, IRD, Mediterranean Institute of Oceanography (MIO), Marseille, France
4. Univ. Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, Grenoble, France
5. Géosciences Environnement Toulouse, CNRS/IRD/Université de Toulouse, Toulouse, France.
6. CNRS, Université Toulouse Paul Sabatier, Laboratoire SOFTMAT, UMR 5623, Toulouse, France
7. LATMOS/IPSL, Sorbonne Université, UVSQ, CNRS, Paris, France
8. Extreme Environments Research Laboratory, École Polytechnique Fédérale de Lausanne, Sion, Switzerland
9. Weizmann Institute of Science, Department of Earth and Planetary Sciences, Rehovot, Israel.
10. Takuvik Joint International Laboratory, Laval University (Canada) — CNRS (France), Département de biologie et Québec-Océan, Université Laval, Québec, QC, Canada.
11. Department of Chemistry, Norwegian University of Science and Technology (NTNU), Høgskoleringen 5, NO-7491 Trondheim, Norway.
12. Helmholtz-Zentrum Hereon, Institute of Coastal Environmental Chemistry, Geesthacht 21502, Germany.
13. School of Earth and Ocean Sciences, University of Victoria, Victoria, Canada.
14. Centre for Fisheries Ecosystems Research, Fisheries and Marine Institute of Memorial University, St. John's, Newfoundland and Labrador, Canada

15. Department of Arctic and Marine Biology, UiT The Arctic University of Norway, Tromsø, Norway
16. Tara Ocean Foundation, Paris, France
17. School of Marine Sciences, University of Maine, Orono, 04469, Maine, USA
18. Institut de Biologie de l'École Normale Supérieure, Ecole Normale Supérieure, CNRS, INSERM, Université Paris Sciences et Lettres, 75005 Paris, France

*** Corresponding authors:** Jean-François Ghiglione : ghiglione@obs-banyuls.fr and Hélène Angot : helene.angot@univ-grenoble-alpes.fr

Abstract

The central Arctic atmosphere, cryosphere, hydrosphere and biosphere, is heavily impacted by anthropogenic activities. While some contaminants originate from local activities, the majority are transported over long distances via rivers, ocean currents, and atmospheric pathways. Contaminants can have adverse effects on the environment, ecosystems, and human health, which are expected to intensify with continued emissions and warming climate. This article outlines the objectives for new studies on contaminants in the Arctic Ocean, in particular during the Tara Polaris expedition, with an emphasis on year-round long-term contaminant dynamics and associated ecotoxicological risks. Mercury contamination remains a major concern in the Arctic, especially in the form of methylmercury, which is primarily produced by marine microbes. Methylmercury bioconcentrates, bioaccumulates and biomagnifies to harmful levels in Arctic wildlife and threatens indigenous communities. Anthropogenic lead (Pb), though low in Arctic waters, remains toxic and may be remobilized by climate change. Plastic pollution, from nano- to macro-scales, is widespread across all Arctic compartments, closely interacting with planktonic communities and posing ingestion risks to invertebrates, fish, seabirds and mammals (including humans). Chemicals of Emerging Arctic Concern (CEAC), including newly recognized persistent organic pollutants inherited from past industrial activities (e.g., per- and polyfluoroalkyl substances (PFAS)), are more recalcitrant in the environment than many other synthetic compounds, raising serious questions about their long-term ecological and health effects. In this context, the Tara Polaris expeditions aim to produce high-resolution, year-round observational data in the central Arctic to deepen our understanding of contaminant sources, transport, internal cycling and environmental fate. These data will also support the development and refinement of numerical models for contaminant dynamics in the context of both Arctic and global environmental change.

Keywords

Arctic Ocean, contaminants, climate change, pollutant dynamics

1- Introduction

The Arctic region, once regarded as a remote and pristine wilderness, is increasingly confronted by complex environmental challenges driven by the rapidly warming climate and the presence of both legacy and emerging contaminants (Hung *et al.*, 2022). By contaminants, we refer broadly to substances resulting from human activities into Arctic environments where they would not naturally occur or where they are found at unusually high levels. When such substances cause harmful effects on ecosystems or human health, they are considered pollutants. Complementing the atmospheric science program presented by Schmale et al. (2025), which focuses on aerosols and trace gases from both natural and anthropogenic sources and their impact on clouds and radiative forcing, our study addresses legacy and emerging contaminants that are widespread across Arctic ecosystems, and represent substantial threats to Arctic ecosystems and human health (Reiersen, Guardans et Sydnes, 2020).

In the central Arctic Ocean, low temperatures extend the half-lives of many chemicals, in some cases by decades, and the phenomenon of "cold trapping" further enhances their persistence in the Arctic environment (e.g., Wania, 2003). Moreover, climate change is reshaping the transport pathways and environmental fate of contaminants, with the potential to remobilize substances that were sequestered in glaciers, sea ice, snow, permafrost, and sediments. Legacy contaminants, such as mercury (Hg) and persistent organic pollutants (POPs), remain a major concern for Arctic biota despite international regulatory efforts such as the Minamata and Stockholm Conventions aimed at curbing their environmental release. These legacy substances are defined by their environmental persistence and their capacity to bioaccumulate through food webs, and have been documented at elevated trophic levels in Arctic biota including fish, polar bears, killer whales, seals, and seabirds (McKinney *et al.*, 2022). Prolonged exposure to these contaminants increases the risk of immune dysfunction, reproductive impairment, and carcinogenic outcomes in affected wildlife (Dietz *et al.*, 2022). Additionally, Indigenous Arctic communities, whose traditional diets depend heavily on local wildlife, face heightened health risks (including neurological, developmental, and immune system disorders) linked to the consumption of contaminated food sources (Basu *et al.*, 2022).

In recent years, the range of environmental contaminants identified in Arctic ecosystems has broadened to include Chemicals of Emerging Arctic Concern (CEAC). These emerging

contaminants such as microplastics, novel brominated and chlorinated flame retardants or per- and polyfluoroalkyl substances (PFAS), intensify ecological risks by introducing novel stressors that may disrupt species interactions and undermine ecosystem resilience (Obbard *et al.*, 2014; Xie *et al.*, 2022). Often originating from industrial, mining, municipal, or infrastructure-related sources, these substances are increasingly being detected in Arctic biota, while the paucity of data on their biological effects hampers comprehensive risk assessments for Arctic biota (Sonne *et al.*, 2021).

Contaminants reach the Arctic through multiple pathways, primarily via atmospheric circulation, ocean currents, and riverine inputs (Dastoor, Angot, *et al.*, 2022; Hung *et al.*, 2022). Long-range atmospheric transport plays a particularly critical role in Arctic contamination. Transport from mid-latitudes is most effective during the winter months, when lower-level air masses from Eurasia dominate inflows to the Arctic. Although long-range transport is dominant in this season, local sources such as wood combustion and fossil-fuel-based power generation also contribute significantly to pollutant levels (Schmale *et al.*, 2018). In contrast, during the summer, the northward retreat of the Arctic front restricts the influx of mid-latitude air masses, making regional emission sources more influential (Dastoor, Wilson, *et al.*, 2022). A notable example is the consistent summertime peak in atmospheric Hg concentrations (Angot *et al.*, 2016), which has been linked to regional cryospheric sources. These include re-emissions from the snowpack and oceanic evasion processes occurring in the marginal ice zone (Araujo *et al.*, 2022; Yue *et al.*, 2023; Huang *et al.*, 2025).

Climate change is altering the transport dynamics and environmental fate of contaminants in the Arctic (Hung *et al.*, 2022). Rising temperatures, declining sea ice, and shifting precipitation patterns are transforming the physical characteristics of the region, thereby influencing the distribution and behavior of pollutants across Arctic ecosystems. These changes can lead to the remobilization of legacy contaminants sequestered in northern soils, vegetation, and glaciers, potentially increasing their bioavailability to marine organisms (Chételat *et al.*, 2022). Transformation processes within the Arctic Ocean further complicate the environmental fate and behavior of contaminants. For example, Hg is subject to unique atmospheric and marine transformations, including atmospheric Hg depletion events and *in situ* methylation processes (Lehnherr *et al.*, 2011; Lehnherr, 2014; Jonsson *et al.*, 2022). These transformations can increase the toxicity and bioavailability of Hg, thereby amplifying its ecological impact across Arctic marine food webs. Borealization also modifies the contaminant levels in the Arctic due to the northward range expansion of boreal species having different contaminant concentrations than their Arctic counterparts (Jacobsen et al. in press).

Microorganisms comprising bacteria, archaea, and microeukaryotes play a pivotal role in mediating many of these transformation processes (Villar, Cabrol et Heimbürger-Boavida, 2020). Microbial communities dominate the Arctic Ocean in terms of biomass and are fundamental to the health and stability of marine ecosystems (Brandt, Wassmann et Piepenburg, 2023). As primary producers, photosynthetic microalgae (i.e., phytoplankton and sea-ice algae) form the base of the Arctic food web, sustaining higher trophic levels such as zooplankton, small fish, and crustaceans (Gosselin *et al.*, 1997). The ongoing loss of multi-year sea ice has been linked to long-term taxonomic shifts in microbial community composition and diversity (Edwards *et al.*, 2020). In particular, microbial community changes from older sea ice (lower MeHg) to younger sea ice (higher MeHg) resulted in a 40 % increase in MeHg (per square meter of sea ice) since 1979 despite a 45 % decline in the total sea-ice volume (Schartup, Soerensen and Heimbürger-Boavida, 2020). Simultaneously, warming and borealization processes have driven substantial shifts in microbial community composition and productivity throughout the water column, with cascading effects on ecosystem functioning and food web dynamics (Ardyna et Arrigo, 2020; Lewis, van Dijken et Arrigo, 2020). These microorganisms are increasingly exposed to environmental contaminants, which can undermine their resilience to additional stressors (Bölter et Müller, 2016; Arrigo *et al.*, 2020). Microplastics add another layer of complexity by providing novel surfaces for microbial colonization –the so-called "plastisphere" –which can facilitate the transport of harmful pollutants and invasive microbes throughout the Arctic marine environment (Kettner *et al.*, 2019). Together, these pressures threaten microbial communities and higher trophic levels, potentially disrupting key ecosystem functions such as nutrient cycling, carbon sequestration, and energy flow (Grannas *et al.*, 2013).

Despite substantial progress in Arctic environmental monitoring, challenges persist in achieving year-round, comprehensive observational coverage. While the Arctic is among the most extensively monitored oceanic regions, current efforts are heavily skewed toward the summer season (Schmale, Zieger et Ekman, 2021; Kohler *et al.*, 2024). This pronounced seasonal sampling bias despite some evidence for strong seasonal cycling limits our ability to fully understand the sources, transport, and biogeochemical cycling of contaminants. Without consistent, high-resolution, multi-seasonal data, it remains difficult to develop accurate models or to assess the full ecological and health implications of contaminant exposure in this rapidly changing region. Monitoring efforts in the Arctic face unique challenges due to the region's vast, remote geography, harsh climatic conditions, and the complex interactions between contaminants and ecological processes. Current monitoring approaches rely on a combination

of *in situ* sampling, remote sensing, and modeling to trace pollution sources, transport pathways, and ecological effects (Krapivin *et al.*, 2021). However, substantial knowledge gaps remain, particularly in the spatial and temporal coverage of data on contaminants, such as Hg and plastics together with associated contaminants (Obbard *et al.*, 2014; Kohler, Heimbürger-Boavida, *et al.*, 2022). Addressing these deficiencies will require enhanced international collaboration and the development of standardized methods to ensure data comparability and support long-term environmental assessments (Evangeliou *et al.*, 2020). Effective monitoring strategies and policy implementation are critical for mitigating the impacts of pollution and ensuring the long-term sustainability of the Arctic environment (Kirdyanov *et al.*, 2020).

Governance frameworks such as the Arctic Monitoring and Assessment Programme (AMAP), the Arctic Council, the United Nations Convention on the Law of the Sea (UNCLOS), and multilateral agreements like the Stockholm Convention on persistent organic pollutants (POPs) provide essential mechanisms for addressing Arctic pollution. In its most recent report, AMAP issued an urgent recommendation for baseline mapping, trend monitoring, and the monitoring of Hg, litter and microplastics (Reiersen, Guardans and Sydnes, 2020). Building on the momentum of the 3rd Arctic Science Ministerial and the ongoing work of the Arctic Council, the European Union's latest policy for a peaceful, sustainable, and prosperous Arctic has explicitly prioritized the issue of litter and emerging contaminants on its environmental agenda.

Here, we review the presence, sources, internal cycling, sinks and mass balance of contaminants in the central Arctic Ocean and provide research themes for future surveys. Among those surveys, the Tara Polaris expeditions will comprise year-round, long-term observations from the Tara Polar Station (*TPS*) to capture the seasonal variability of contaminant dynamics in this rapidly changing region (Babin *et al.*, submitted; Nicolaus *et al.*, submitted). This observatory approach will be embedded within a broader understanding of the coupled sea-ice (Vancoppenolle *et al.*, in prep), ocean (Geoffroy *et al.*, submitted) and atmosphere (Schmale *et al.*, 2025) systems, ensuring consistency with the physical context of contaminant pathways and transformations. A central aim of this initiative is to develop a sustainable strategy for contaminant surveillance, focusing on the optimization of sampling methodologies, sample frequency, and logistical feasibility in remote polar conditions. This research also underlines the critical need to link contaminant presence, particularly Hg, Pb, plastics and other CEACs, to their ecological effects. Emphasis will be given on integrative frameworks such as the exposome and microbial ecotoxicology to advance our understanding

of how these contaminants influence Arctic ecosystem function at both the molecular and community levels.

2. Research themes

The main research themes of this initiative are summarized in Fig. 1, which highlights the focal areas of contaminant monitoring, sources, transformations, and ecological impacts in the central Arctic.

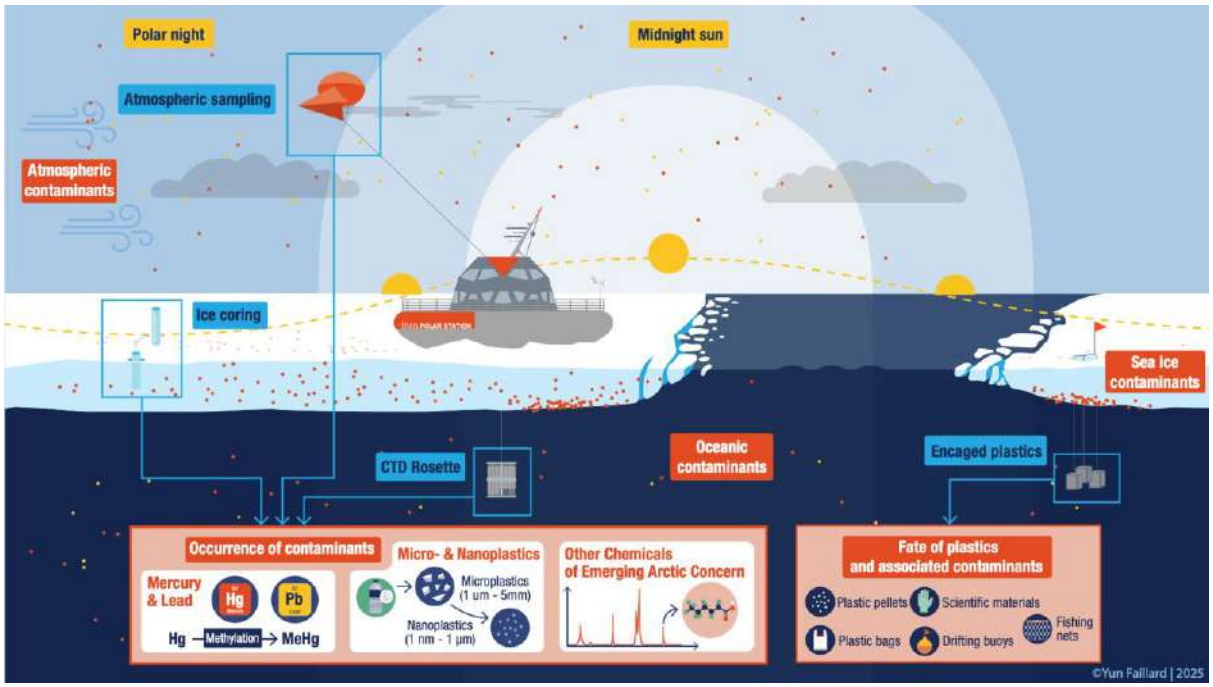

Figure 1: Overview of the use of the Tara Polar Station (*TPS*) facilities to assess seasonal and long-term contaminant monitoring in the central Arctic.

2.1. Mercury (Hg) and Lead (Pb)

The World Health Organization identifies Hg and Pb as pollutants of global concern due to their high toxicity and ability to disperse widely across the planet (AMAP/ UN Environnement, 2019). While initial seawater concentrations are low (Hg 1 and Pb 5 picomoles per liter), both elements are volatile and biomagnify orders of magnitude along the trophic web. Marine microbes transform Hg into the neurotoxin methylmercury (MeHg) which bioconcentrates in microalgae, bioaccumulates and biomagnifies in marine organisms, posing severe risks to both wildlife and human health (Sonke *et al.*, 2023; Tesán-Onrubia *et al.*, 2023).

Similarly, Pb is a potent neurotoxin, and isotopic measurements reveal that much of it is of anthropogenic origin (Cullen et McAlister, 2017; De Vera *et al.*, 2021).

The long atmospheric lifetime of Gaseous Elemental Mercury (GEM) of about 6 months enables its long-range transport from both natural and anthropogenic sources, leading to its deposition in remote and sensitive environments such as the Arctic (Dastoor, Angot, *et al.*, 2022). Lead shows comparable transport pathways where historic Pb aerosols, largely associated with leaded gasoline and smelting, were deposited in the Arctic through the atmosphere in the 20th century.

Inputs of Hg from rivers and erosion exceed atmospheric inputs, and are balanced by a net export to the Arctic Ocean and removal to deep waters and sediments (Petrova *et al.*, 2020; Tesán Onrubia *et al.*, 2020; Kohler, Kull, *et al.*, 2022). Similarly, for Pb, shelf and coastal processes (erosion, resuspension, sea ice and permafrost thaw) strongly influence dissolved Pb distributions along the margin (De Vera et al., 2021). As a result, the transpolar drift carries only a small part of the river-sourced Hg and Pb across the central Arctic Ocean to Fram Strait (Charette *et al.*, 2020). The combination of high river inputs, erosion, atmospheric deposition and the presence of sea ice result in a unique Hg distribution with elevated Hg levels in surface waters (Dastoor, Angot, et al., 2022). The stratified water column of the Arctic Ocean leads to another unique feature, where MeHg peaks at shallower depths (100 – 200 m) compared to other oceans (500 – 1000 m). The high MeHg levels near the surface might enhance bioconcentration into microalgae and explain the observed high biota Hg levels (Heimbürger *et al.*, 2015). For Pb, isotopic evidence shows anthropogenic contributions at nearly all depths, averaging ~60% of the total dissolved Pb, with signatures of Eurasian Pb detected even in deep waters (2000 – 2500 m), constraining ventilation ages of these water masses (De Vera *et al.*, 2021).

Recent studies have demonstrated that Hg concentrations in the Arctic Ocean exhibit strong seasonal variability (Kohler, Heimbürger-Boavida, *et al.*, 2022; Kohler *et al.*, 2024). Given the short residence times of Hg and Pb (3-10 years for Hg and only weeks for Pb in shelf waters due to particle reactivity), the Arctic Ocean is highly sensitive to external perturbations (Smith, Moran et Macdonald, 2003; Chen *et al.*, 2012; Kohler, Heimbürger-Boavida, *et al.*, 2022). However, year-round metal measurements within the central Arctic remain extremely limited. To date, the only dataset available over an annual cycle is for atmospheric Hg during the MOSAiC expedition (Angot *et al.*, 2022), while other monitoring efforts are largely restricted to summer research cruises and a few year-round ground-based observatories, such as Alert, the Villum Research Station, and the Zeppelin Observatory (Angot *et al.*, 2016). Year-

round observations of sea ice and water column metal concentrations are also absent for the central Arctic Ocean, leading to weak assumptions in metal biogeochemical cycling, and especially in undersampled seasons (Huang *et al.*, 2023; Kohler *et al.*, 2024). These spatial and temporal data gaps pose major obstacles to advancing our understanding of contaminant dynamics across Arctic systems under the influence of warming climate with anticipated complex effects (Chételat *et al.*, 2022).

In addition to current gaps, ongoing and future ecosystem changes are expected to further modify metal and contaminant cycling in the Arctic. Thawing permafrost is projected to mobilize large quantities of Hg and Pb previously stored in frozen soils, increasing fluxes to aquatic systems (Schaefer *et al.*, 2020). At the same time, the increasing frequency and intensity of wildfires across northern high latitudes are releasing previously stored metals to the atmosphere (Kumar *et al.*, 2018), while accelerating coastal erosion can remobilize legacy Pb and Hg deposited during peak 20th-century industrial emissions (Rogalla *et al.*, 2025), introducing additional important and growing sources of re-emission. Collectively, these emerging sources underscore the need for improved monitoring and modeling efforts to anticipate how Hg and Pb dynamics and exposure risks may evolve in a rapidly changing Arctic.

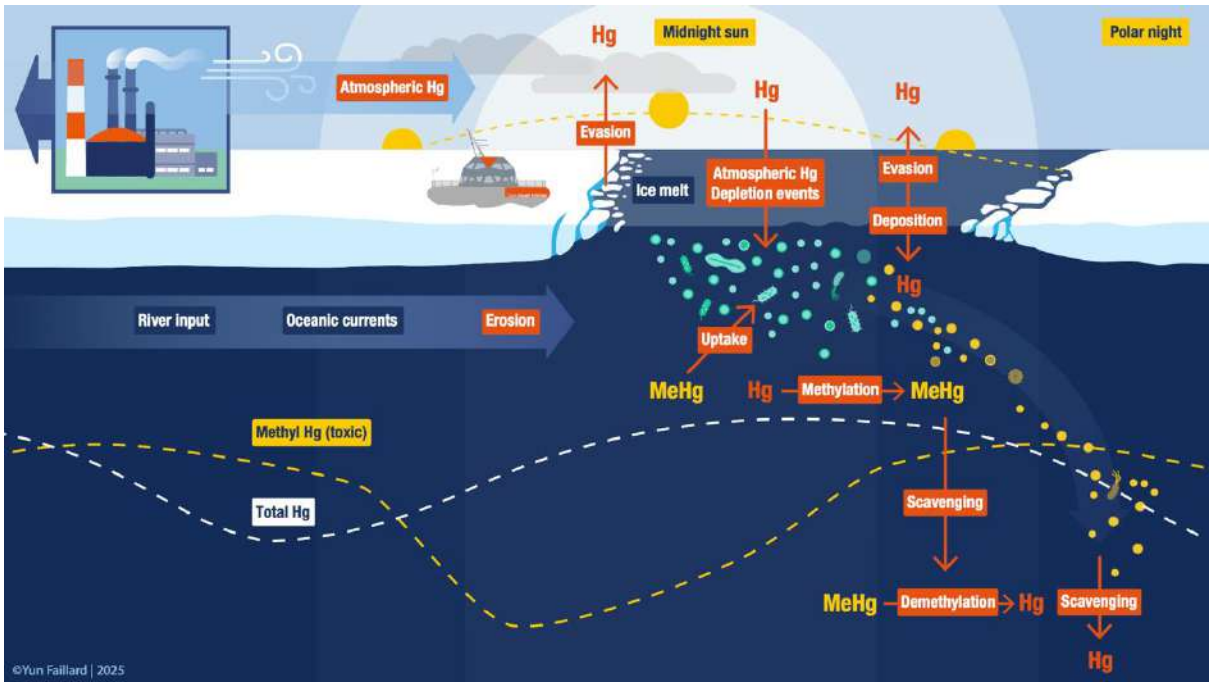

Figure 2: Proposed seasonal changes of arctic mercury (Hg) cycling (adapted from Kohler et al., 2024).

2.2. Plastics and associated chemicals

Plastic pollution has become a critical environmental issue due to the exponential rise in plastic production since the 1950s (Sonke *et al.*, 2025). Plastics in the form of macroplastics (>5 mm), microplastics (1 µm–5 mm), and nanoplastics (<1 µm) have been detected across all Arctic compartments—including the atmosphere, sea ice, ocean water, and sediments (Kanhai *et al.*, 2020; Trainic *et al.*, 2020; Bergmann *et al.*, 2022; Materić *et al.*, 2022; Parga Martínez *et al.*, 2024). Sea ice has been shown to concentrate microplastics at levels 100 to 1,000 times higher than those found in the underlying seawater (Kanhai *et al.*, 2020). A recent study also reported substantial quantities of nanoplastics in snow collected from Greenland, suggesting atmospheric transport as a key vector for plastic pollution in the Arctic (Materić *et al.*, 2022). Additionally, the seasonal release of nanoplastics from melting sea ice and their accumulation at the ocean surface contribute to their redistribution through Arctic oceanic circulation (Pradel *et al.*, 2021).

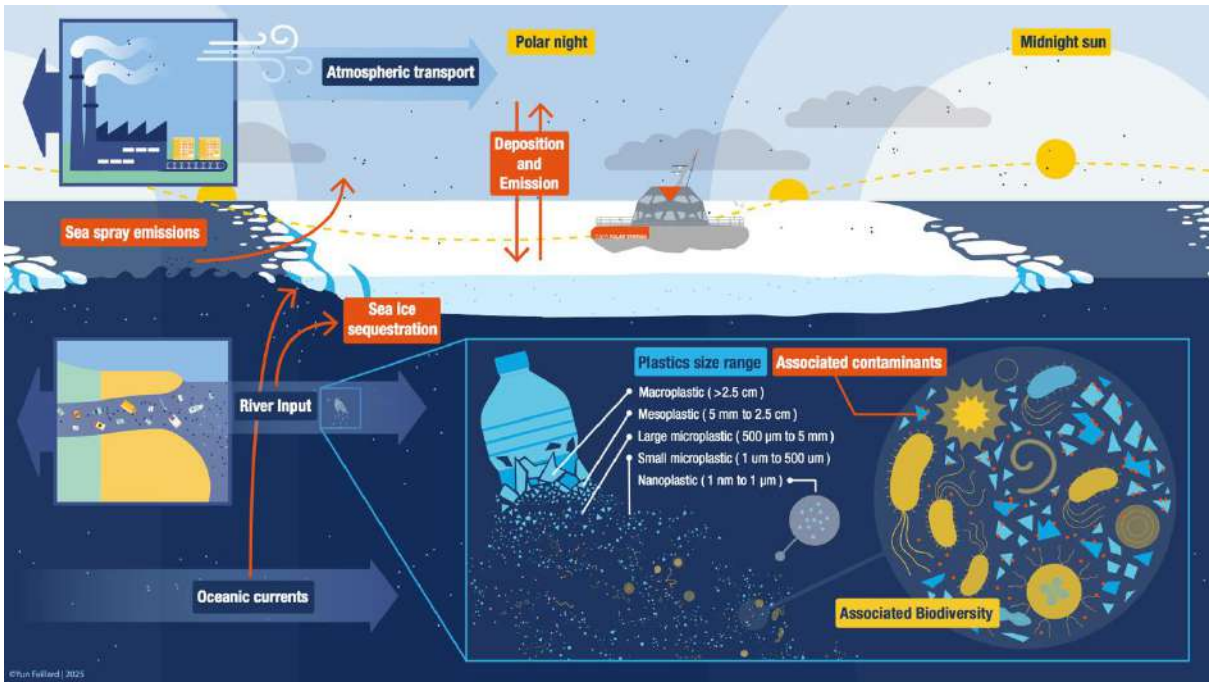

Figure 3: Seasonal variation and transport of fragmented plastic debris (micro and nanoplastics) and associated organic and inorganic pollutants in the central Arctic.

The physical impacts of macroplastic pollution on human health, biodiversity, and ecosystem integrity are often plainly visible. In contrast, the risks posed by plastic-associated

chemicals and micro- (MPs) and nanoplastics (NPs), along with the psychological, sociocultural, and economic consequences of plastic pollution, are far less apparent. Yet, these invisible threats represent a significant challenge to both environmental and public health. According to the most recent assessment on plastic chemicals (Wagner *et al.*, 2025), more than 16,000 substances have been identified in association with plastic materials, over 4,200 of which are considered substances of concern due to their persistence, bioaccumulation potential, mobility, and/or toxicity –classified as PBT (Persistent, Bioaccumulative, and Toxic) or PMT (Persistent, Mobile, and Toxic). Once ingested or inhaled, microplastics and nanoplastics can release toxic substances such as additives and monomers, which may disrupt endocrine function and elevate the risk of neurodevelopmental disorders, reproductive abnormalities, infertility, cardiovascular disease, and cancer (Landrigan *et al.*, 2024).

NPs represent the invisible fraction of plastic pollution, yet their impact may be far from negligible. Emerging evidence suggests that Arctic NPs can be more extensively deposited, transported, and reactive than their microscale counterparts. In particular, studies of atmospheric particle size distributions at High Arctic sites have revealed a strong predominance of particles smaller than 1 μm (Freud *et al.*, 2017; Dall'Osto *et al.*, 2019). The detection of NPs in snow and at high altitudes (Bergmann *et al.*, 2019; Materić *et al.*, 2022) further indicates their capacity for long-range atmospheric transport and deposition. Regarding oceanic transport, the first evidence of a significant prevalence of NPs over microplastics in surface waters was reported in 2017 and 2018 in the southern Atlantic (Ter Halle *et al.*, 2017; Davranche *et al.*, 2020), suggesting a wide distribution and high mobility within marine systems. In the Arctic Ocean, NPs have recently been detected in remote regions previously considered pristine. Concentrations in the central Arctic Ocean range from 14 ng L^{-1} in surface seawater to up to 300 ng L^{-1} in the top layer of sea ice (Cai, Guilmette and Gigault, under revision).

Due to their extremely small size, detecting and quantifying NPs requires advanced and highly sensitive technologies. This challenge is exacerbated by the fact that natural nanoparticles and submicron mineral or organic particles are poorly retained by conventional sampling methods and sediment traps. As a result, there remains a significant knowledge gap regarding their occurrence, transport, fate, and accumulation in the Arctic Ocean. This gap is largely due to current limitations in analytical methodologies for detecting NPs at (ultra)-trace concentrations. Despite their nanoscale—which makes them highly reactive with marine biota, particularly primary producers—the ecological implications of NPs remain poorly understood. Several studies underscore the importance of considering small (submicron-range) particles,

including NPs, in the functioning of the biological carbon pump (Henson, Yool et Sanders, 2015), a process that may be especially relevant in the Arctic Ocean under specific seasonal or environmental conditions. The upcoming Tara Polaris expeditions is expected to address these knowledge gaps by enabling targeted sampling and interdisciplinary investigation of NPs dynamics in the Arctic Ocean.

All together, MPs/NPs can adsorb various organic contaminants because of their large specific surface area and hydrophobicity (Wang *et al.*, 2024). Evidence of virulent pathogens residing in the plastisphere from plastic debris that serves as a raft for the long-distance dispersal of species (Philip *et al.*, 2025). Mounting evidence suggests that plastic pollution affects organisms across the entire Arctic food web, with far-reaching consequences for both marine and terrestrial ecosystems. These impacts also extend to Indigenous Arctic communities, whose health and livelihoods depend on vulnerable Arctic species increasingly threatened by this pervasive form of pollution.

The atmosphere is thought to play an important role in transport of MPs/NPs (and associated chemicals and microbes) to and within the Arctic, including both long-range transport from lower latitudes and local transport from regional sources such as human activity and marine plastics (Bergmann *et al.*, 2022). As MP/NP particles are highly size- and shape-dependent in their transport behavior, atmospheric modeling efforts must account for particle-specific aerodynamic properties, hygroscopicity, and degradation dynamics to accurately represent atmospheric lifetimes and deposition patterns. Currently, atmospheric chemical transport models for MP/NP, such as GEOS-Chem (Fu *et al.*, 2023), rely heavily on observations from lower latitudes, as Arctic observations are extremely sparse. Long-term year-round plastic observations from Tara Polaris expeditions across the air-snow-sea ice-ocean continuum will help reduce uncertainties in simulated emissions, transport, deposition, and aging processes within the Arctic and provide insights into seasonal variations (Nicolaus *et al.*, submitted). Improved atmospheric models in turn will inform interpretation of Tara Polaris data by allowing source apportionment analysis of Arctic plastics (Schmale *et al.*, 2025). This type of analysis has been informative for other pollutants such as Hg (Dastoor, Wilson, *et al.*, 2022), but studies to date have been limited by the sparsity of MP/NP observations in the Arctic. Integrating Tara Polaris observations into atmospheric chemical transport models or Lagrangian particle dispersion frameworks, such as FLEXPART, will also allow for the evaluation of transport processes and the impact of polar meteorological phenomena such as the polar vortex. Combining models with time-series data from Tara Polaris expeditions may be particularly helpful for identifying links to freeze/thaw cycle processes or

seasonal trends in the origin of Arctic air masses. Multi-compartment plastic models, such as GBM-Plastics (Sonke *et al.*, 2022), that simulate exchanges between the atmosphere, snow, sea ice, and ocean will be especially useful for tracing MP/NP cycling across interfaces. Data-informed models will also play a key role in projecting changes under future scenarios of climate change and increased shipping and other anthropogenic activity in the Arctic.

2.3. Other chemicals of emerging Arctic concern

Other CEACs cover a diverse group of contaminants, including novel flame retardants, current-use pesticides, pharmaceuticals and personal care products (PPCPs), plastic additives, e.g. phthalate esters (PAEs), organophosphate esters (OPEs) and UV filters (Xie *et al.*, 2022). In contrast to well-studied persistent organic pollutants (POPs), most CEACs have only recently been identified as contaminants, and information on their sources, environmental behavior, and effects on Arctic ecosystems remains limited. Their continuous release from global production and use, together with riverine inputs, atmospheric transport, and oceanic currents, makes their presence in remote Arctic environments a growing concern (Li, Kallenborn et Zhang, 2024). Climate change is expected to enhance their mobility through increased precipitation, sea ice loss, and permafrost thaw, potentially influencing their transport, transformation, and accumulation (Hung *et al.*, 2022). Understanding the occurrence and pathways of CEACs is essential for evaluating their risks to Arctic environments and food webs.

Among CEACs, PFASs are of particular concern due to their widespread use, persistence, and potential for long-range transport. PFASs are a large class of synthetic fluorinated chemicals valued for their water- and grease-resistant properties and widely used in industrial applications and consumer products. Their exceptional chemical stability, driven by strong C–F bonds, results in extreme environmental persistence and widespread distribution (Kwiatkowski *et al.*, 2020). Over the past two decades, PFASs have been detected in remote regions far from primary emission sources, including the Arctic, highlighting their potential for long-range environmental transport and persistence (Xie et Kallenborn, 2023).

In the Arctic, PFASs have been reported in multiple compartments. Volatile precursors, such as fluorotelomer alcohols (FTOHs), undergo long-range atmospheric transport and oxidation to form stable perfluoroalkyl acids (PFAAs), which are subsequently deposited via wet and dry deposition. Measurements in Arctic air and snow have confirmed the presence of both neutral precursors and ionic PFAS, indicating active atmospheric input and seasonal deposition cycles. Snow and sea ice act as temporary reservoirs, storing PFAS during winter

and releasing them during melt events, thereby influencing coastal seawater concentrations. Arctic seawater contains a mixture of legacy PFAS, including PFOS (Perfluorooctane sulfonic acid) and PFOA (Perfluorooctanoic acid), as well as emerging compounds that reflect changes in global production and regulation. Several novel PFASs have been found in the environment and biota in the past ten years, such as hexafluoropropylene oxide dimer acid (HFPO-DA) in seawater and snow, 6:2, 8:2 fluorotelomersulfonate (6:2 and 8:2 FTS) in runoff near airports, 6:2 chlorinated polyfluorinated ether sulfonate (6:2 Cl-PFESA) in lake water and polar bears (Xie *et al.*, 2022).

Ocean currents transport PFAS from industrialized regions into the Arctic Ocean, where they can persist and undergo vertical mixing and exchange with sediments. Sea spray aerosols may further contribute to the re-emission of PFAS from the ocean surface back to the atmosphere, suggesting a dynamic exchange between compartments (Johansson *et al.*, 2019). Understanding the occurrence and transport pathways of PFAS across air, seawater, snow, and ice is therefore essential for assessing exposure risks for Arctic ecosystems (MacInnis *et al.*, 2019).

3. Technical approach and challenges

Sampling in the central Arctic Ocean is complicated by several factors. The region's remoteness and harsh climate make access difficult, requiring substantial resources and specialized equipment for sample collection. Sea ice cover further complicates sampling efforts (Zhang *et al.* 2024). Additionally, the need for large volumes of seawater to detect trace levels of contaminants poses logistical challenges, especially when using low-volume sampling techniques for contaminants like Hg and CEAC. Detection of contaminants in Arctic samples is equally challenging. The presence of diverse pollutants, including Hg, Pb, microplastics, and associated contaminants, requires a wide array of analytical techniques. Moreover, the extremely low initial concentrations of some contaminants in Arctic waters and the atmosphere demand highly sensitive analytical techniques for reliable detection. Researchers must also contend with potential contamination during sampling, transportation, and analysis, necessitating stringent protocols to ensure data integrity (Coelho *et al.*, 2022). Addressing these challenges is crucial for understanding the extent of Arctic Ocean contamination and its potential impacts on ecosystems and human health. Table 1 summarizes proposed measurements on the *TPS* during the Tara Polaris expeditions.

Table 1: Summary table of proposed contaminant measurements on the *TPS* during the Tara Polaris expeditions.

Compartment / Medium	Target contaminants	Sampling & analytical methods	Frequency / duration	Contamination control
Atmosphere	-Gaseous elemental mercury (GEM) -Aerosols for MPs/NPs, total and dissolved Pb, Hg -PFAS and CEAC	-Lumex RA-915 AM monitor -Pumps and filtration -High volume Air sampler	Continuous	Algorithms to flag *TPS* contamination; compare with aerosol & gas tracers
Snow	Hg speciation, total and dissolved Pb MPs/NPs	Surface and layer sampling; filtration for MPs/NPs	Event-based	Distance from ship, procedural blanks
Sea ice	Hg speciation, total and dissolved Pb and Pb isotopes, MPs/NPs	Ice cores, sectioned 10–20 cm; brine via "sack hole"; filtration for MPs/NPs	Biweekly for Hg, monthly for MPs/NPs	Distance from ship, clean tools, vacuum sealing for volatile Hg; procedural blanks
Seawater	Hg speciation, total and dissolved Pb and Pb isotopes, MPs/NPs	Trace-metal clean bottles, peristaltic pumps; filtration for MPs/NPs	Monthly CTD; dedicated Hg species sampling in summer	Glass or Teflon vials; procedural blanks
Atmosphere, sea ice, seawater	Plastic degradation and sorption of contaminants	Incubation of nurdles, nets, packaging, scientific plastics	Exposure over months; sampling monthly	Cotton lab coats, no plastic gloves; replicate samples, blanks
Atmosphere, snow, seawater	PFAS and CEAC	High volume Air sampler PP/glass bottles for seawater and snow and ice melting water	Air sampling weekly, seawater sampling every two weeks, snow sampling monthly	Distance from ship, no plastic tubing, with nitrile glove, procedural blanks

3.1. Mercury and lead monitoring and experiments on the *TPS*

Continuous and high-temporal resolution measurements of gaseous elemental mercury (GEM) in the atmosphere are essential to understand air–sea exchange processes and long-range pollutant transport in the polar environment. Given the duration of the drift campaigns (up to 1.5 years), the measurements will be performed by a Lumex RA-915 AM Hg monitor (Lumex Ltd., St. Petersburg, Russia), which uses atomic absorption spectrometry with Zeeman background correction. Unlike the widely used Tekran 2537 analyzer, the Lumex does not require carrier gas and demands less frequent maintenance, making it more suitable for year-

round deployment on *TPS*. Previous intercomparison studies (Brown *et al.*, 2010) conducted under the European Committee for Standardization (CEN EN 15852) showed good agreement between the Lumex RA-915 AM and the Tekran 2537, validating the reliability of the Lumex for ambient GEM monitoring. Furthermore, its predecessor, the Lumex RA-915+, was successfully deployed in the Global Mercury Observation System (GMOS) network at stations in Russia and Suriname (Sprovieri *et al.*, 2016). Given that the *TPS* is a potential source of local contamination (e.g., through ship exhaust, cooking activities, waste treatment), atmospheric GEM data will be complemented by other trace gas and aerosol measurements (e.g., CO_2, particle number, wind direction and speed) to help identify and filter out local contamination events. This approach is already being developed for broader atmospheric monitoring efforts on *TPS* (Schmale *et al.*, 2025). Algorithms like those described by Beck et al. (2022) will be employed to flag local contamination. During test campaigns, additional surveys will assess the spatial footprint of *TPS* emissions to optimize placement of inlets and samplers. Systems to make measurements (aerosols, meteorology) away from the *TPS* on the sea ice are also being explored (Schmale *et al.*, 2025).

This would complement snow and sea ice sampling that will take place in a dedicated area away from major shipborne Hg and Pb contamination sources. Snow will be sampled using acid-washed plastic equipment from the snow surface, in layers if possible, and sea ice will be sampled using a stainless-steel Kovacs 9 cm ice corer. Onsite, each core will be sectioned in 10 – 20 cm intervals, shaved with an acid-cleaned ceramic knife and stored in clean plastic bags. Brine will be sampled using the "sack hole" method (Cossa *et al.*, 2011) with acid-cleaned tubing and syringes for subsampling. Core sections to be analyzed for gaseous Hg species will be collected into bags and vacuum sealed, to ensure no loss of volatiles. Onboard, samples will be melted either at 4 °C or at room temperature, with subsampling into cleaned bottles. Samples will be processed onboard through purging, decanting, and preservation for onshore Hg speciation and Pb isotope analysis. Purging for gaseous Hg speciation will take place whenever experienced personnel is onboard with adequate human resources. Snow, sea ice, and brine will be collected at biweekly intervals in order to ensure adequate time resolution over the deployment period and within personnel capabilities.

Seawater total Hg and Pb concentrations are in the low picomolar to 10's of picomolar range, respectively, and require trace metal clean sampling methods (Heimbürger *et al.*, 2015; De Vera *et al.*, 2021). Rubber bungees are less elastic in the cold arctic waters and often cause Niskin or GOFLO bottles to malfunction. Stainless steel operated bottles such as OTE, Niskin X or PRISTINE are the better choice. If the *TPS* moon pool shows signs of rust or corrosion

an ice camp with messenger-on-line operated bottles might be the better choice. Alternatively peristaltic or compressed air-driven Teflon pumps (ASTI) could be an interesting alternative. Total Hg (tHg) should be sampled into glass vials to allow for long storage and not acidified onboard to prevent potential contamination. Methylmercury (MeHg) is less contamination prone and could be sampled from the standard CTD Niskin bottles, for which a deep profile is desirable. Filtration of 10 L of sea water from the standard CTD Niskin bottles through a GF/F or quartz filter could be used to quantify particulate Hg (pHg) on suspended matter. Beyond THg, MeHg and pHg, other Hg species such as dissolved gaseous Hg, monomethyl- and dimethylHg would be useful but require more onboard operations by dedicated Hg scientists during the shorter summer legs (Kleindienst et al. 2023). A major concern is contamination with $HgCl_2$ which is often used to preserve biological samples. $HgCl_2$ amendments have to be done in dedicated well-separated areas to avoid a general contamination of *TPS*. Trace-clean sampling, handling and storage for Hg remains challenging and possible onboard contamination can only be tested in the home labs.

Lead and Pb isotope samples are to be filtered using 0.2-µm Acropak filters (Pall Corporation) into rigorously cleaned 1-2 L low density polyethylene bottles (LDPE) according to GEOTRACES protocols (Cookbook version 4.0 available at https://www.geotraces.org/methods-cookbook/). The samples are then to be acidified to pH 1.7 with 12-M, high-purity HCl and processed for Pb isotope measurements according to Conway et al. (2013).

3.2. Plastic monitoring and experiments on the TPS

MPs/NPs sampling will be undertaken across the air-sea ice-ocean continuum in order to understand mass balance and ecosystem exposure. Aerosols (300 LPM SAS3100 pumps) and wet deposition (rain, snowfall) will be sampled manually and event-based using aluminum buckets. Annual sea ice cores will be taken around May while surface and subsurface ocean samples (5 L) will be taken from the CTD on a monthly basis. To avoid shipping large volumes of water, all snow, ice, and sea water samples will be filtered onboard using Teflon filters. Filters from aerosol and aqueous samples will be stored at -20 °C until transfer to land for extraction of MPs/NPs and analysis by micro-Raman and FTIR spectroscopy. Compared to macro- and micro-sized plastic particles, there are relatively few studies reporting the distribution of NPs in Arctic environments. This main limitation is principally due to the lack of analytical strategies to sample, identify and quantify trace-level concentration of anthropogenic carbon-based particles in various sea-ice, seawater and sediment matrices.

During Tara Polaris expeditions we will use a combination of state-of-the-art sampling and analytical techniques to overcome these limitations (Gigault and Davranche, 2025). Specifically, we plan to deploy a tangential flow ultrafiltration system directly at sea to isolate NPs from large volumes of seawater and/or sea-ice melt.

MPs and NPs sampling must avoid contamination from polymers in clothing, paint and plastic items onboard. Basic sampling equipment typically consists of glass bottles for water, and Teflon or stainless-steel filtration and sampling tools. Cotton lab coats will be worn in the field and onboard and use of plastic gloves avoided. Aerosol and snow sampling and ice coring will be done at 100 – 200 m distance from *TPS*, if personnel safety permits, to avoid vessel contamination. Microplastic filtration of seawater, melted snow and ice will be done onboard in a closed system filtration circuit, not exposed to indoor airborne dust.

To control for potential contamination and ensure data integrity, rigorous blank protocols will be implemented at every stage of the sampling and analysis process. Procedural blanks will be prepared by processing ultrapure water (Milli-Q or equivalent) through the entire sampling and filtration setup—on board and in the lab—under identical conditions to environmental samples. These blanks will be collected in parallel during field operations to assess airborne contamination, cross-contamination from sampling containers, filters, or tubing, and background signals from instruments.

The long-term transformation of known plastic items and the adsorption of chemical and biological contaminants on their surface under the extreme conditions of the central Arctic will be investigated through a series of experiments. Plastic items will be exposed to the atmosphere, sea ice, and seawater near the *TPS* for several months. These items will include (i) plastic products commonly found as marine debris, such as industrial plastic pellets (nurdles) or plastic packaging; (ii) drifting buoys used to monitor sea surface temperature and ocean currents; (iii) fishing nets and lines; and (iv) scientific materials like pipette tips, surgical masks and disposable gloves. For some of these products, both conventional and biodegradable plastics (when available) will be tested to assess their degradation and behavior under Arctic conditions. Sufficient samples will be incubated in the various environments (sea ice, sea water, atmosphere) to satisfy the quantities required for the analyses that will follow regular sampling. Samples will be taken at least bimonthly, frozen and sent to partner laboratories.

Changes in physical properties will be analyzed by transmission electron microscopy (TEM), saturated-excitation image scanning microscopy (SAX), X-ray photoelectron spectroscopy (XPS) and Differential scanning calorimetry (DSC) (Ter Halle *et al.*, 2017). Chemical changes will be evaluated by Nuclear Magnetic Resonance (NMR), Fourier

transform infrared spectroscopy (FTIR), and Gel permeation chromatography (GPC). The biofilm living on plastics (plastisphere, including pathogens) will be analyzed by uncultured-based approaches for further OMICs analysis (metagenomic, metatranscriptomic, metabolomic) (Ghiglione *et al.*, 2025). Both direct and indirect multivariate statistical analyses will be employed to assess the relationships between physical, chemical, and biological patterns and the behavior of plastic products under central Arctic conditions.

The sorption of POPs and heavy metals will be monitored on all types of exposed items in order to assess to what extent the nature of the material influences the transfer of contaminants. The quantification of POPs in exposed plastics will be carried out by extraction followed by high-resolution mass spectrometry analysis (coupled with either HPLC or GC depending on the compound families being targeted). Targeted analyses will be performed to quantify around sixty endocrine-disrupting chemicals (such as phthalates, bisphenols, PCBs, and UV filters). Non-targeted analyses will be conducted to identify a broad range of compounds present in a sample without any prior assumptions about their nature. Additionally, the characterization of the bacterial biofilm developed on plastics will help assess the extent to which the biofilm contributes to the adsorption of chemical pollutants on the plastic materials.

3.3. Other chemicals of emerging Arctic concern monitoring and experiments in the TPS

PFASs and other CEACs will be investigated along the TPS transect at air–seawater and snow–ocean interfaces to quantify fluxes between compartments and evaluate the potential re-emission of these chemicals under Arctic warming conditions.

Air samples will be collected using high-volume samplers (MINJIE, Geesthacht, Germany) equipped with pre-combusted quartz fiber filters (QF/F) for particulate collection, followed by polyurethane foam/XAD-2 (PUF/XAD-2) cartridges to capture gaseous neutral and ionic PFASs and CEACs. Snow deposition will be sampled manually on an event basis using pre-cleaned stainless-steel containers. Samples will be transferred into pre-cleaned polypropylene and glass bottles and stored cold until analysis.

Surface and subsurface seawater will be sampled monthly with CTD rosettes using 1 L polypropylene and glass bottles. To reduce shipping volumes, snow, ice melt, and seawater samples will be filtered onboard through pre-combusted glass fiber filters (47 mm GF/F). Dissolved ionic PFASs will be concentrated on pre-conditioned Oasis-WAX cartridges, while neutral PFASs will be retained on HLB cartridges. Filters, SPE cartridges, and sorbents will be

wrapped in pre-baked aluminum foil or sealed in aluminum bags, stored at −20 °C, and shipped on dry ice for subsequent extraction and quantification by LC-MS/MS or GC-MS.

Where large sample volumes are needed, ultrafine filtration and tangential-flow filtration will be applied directly at sea to concentrate trace PFASs from seawater and sea-ice melt, following established nanoparticle isolation protocols.

4. Connection to other Tara Polaris themes

4.1. Towards central Arctic ecotoxicology : linking contaminants to microbial communities monitoring

The various contaminants present in the central Arctic Ocean pose potential threats to its unique microbial communities, and in particular Bacteria, Archaea and viruses. These communities play essential roles in Arctic ecosystems, influencing biogeochemical cycles, food webs, and climate feedback mechanisms (Edwards *et al.*, 2020). As the Arctic experiences rapid transformations driven by global warming, understanding how contaminants affect microbial life is crucial for anticipating and mitigating broader ecological impacts. We will adopt a microbial ecotoxicology framework (Ghiglione *et al.*, 2016) to explore the ecological effects of contaminants at the planktonic level, including their influence on key ecosystem functions, and the reciprocal role of microbial communities in the ecodynamics of pollutants—namely their sourcing, transfer, degradation, and transformation. First, the effects of various contaminants on microbial biodiversity in the Arctic Ocean will be studied. As the Arctic Ocean undergoes profound changes driven by climate change, planktonic communities are expanding their range northwards (Ardyna et Arrigo, 2020; Negrete-García *et al.*, 2024). Our focus will be on: (i) assessing changes in microbial community composition in response to different contaminants, (ii) identifying vulnerable species and potential shifts in dominant taxa, and (iii) evaluating the impact of contaminants on rare microbial taxa, which have been shown to be sample site-specific rather than region-specific (Carter-Gates *et al.*, 2020).

In addition, the research will examine how contaminants influence the functional ecology of Arctic microorganisms, using functional responses as indicators of overall ecosystem health (Geoffroy *et al.*, submitted). This is a critical approach, as microorganisms deliver essential ecosystem services, including nutrient cycling, carbon sequestration, and primary production (Edwards *et al.*, 2021). In addition to investigating trophic levels and interactions, we will evaluate the extent to which contaminant-induced functional changes in microbial communities could disrupt biogeochemical cycles at both regional and global scales.

Second, the project will investigate the capacity of Arctic microbial communities to degrade and transform a range of environmental contaminants. Specifically, this component of the study will aim to: (i) identify microbial taxa capable of degrading or transforming key pollutants, such as Hg, plastics and other CEAC; (ii) assess the efficiency of microbial biodegradation processes under Arctic environmental conditions; and (iii) examine potential shifts in microbial community composition toward taxa better adapted to the degradation of specific contaminants. In parallel, the research will explore the role of microbial biodiversity in supporting ecosystem resilience under contaminant stress. We will examine the functional redundancy within microbial communities to determine their capacity to maintain critical ecosystem functions despite disturbance. We will also evaluate the potential for temperate-adapted microbial taxa to replace cold-water species under scenarios of increasing Atlantic influence and contaminant influx. Finally, we will investigate the persistence of dominant cold-adapted eukaryotic taxa and assess whether rare, cold-specialist species may be replaced by taxa better adapted to warmer conditions.

This integrative approach will yield valuable insights into the intricate relationships among contaminants, microbial diversity, and ecosystem functioning in the Arctic Ocean. By deepening our understanding of these dynamics, we aim to improve our ability to predict and mitigate the ecological impacts of pollution and climate change in this highly sensitive and rapidly changing environment.

4.2. Linking contaminants to atmosphere sea ice–ocean–biosphere interactions

During the Tara Polaris expeditions, the research on contaminants will be closely integrated with the activities on the atmosphere–biosphere interactions (Schmale et al. 2025), with a particular focus on the role of local biological sources in the Arctic Ocean as ice-nucleating particles (INPs) and cloud condensation nuclei (CCN) influencing low-level Arctic cloud formation (Schmale *et al.*, 2025). This will be investigated by collecting regular surface-based *in situ* measurements and vertical profiling using tethered balloon-borne measurements, both conducted throughout an annual cycle. Continuous, year-round data on aerosol composition, complemented by isotope analyses, will advance our understanding of both natural (including biological) and anthropogenic sources of aerosols—including MPs and NPs—over the central Arctic Ocean. An aerosol lidar will also scan the lowest 1 km to provide information about the vertical and horizontal extent of aerosols and their sources (and clouds), complementing the *in situ* measurements. This data, together with air mass and source origin modeling, will contribute to diagnosing contaminant sources. Aerosol-cloud climate feedbacks,

including changes in cloud properties and the surface radiation budget, and photosynthetically active radiation (PAR) will also be examined, with implications for Hg photochemistry and plastic degradation.

The research planned is also linked to other activities on sea ice (Vancoppenolle *et al.,* 2025) and ocean microbiomes and physical processes (Geoffroy *et al.,* 2025). Analysis of snow samples or aerosol composition and isotopes will provide information about biological and anthropogenic sources that can complement contaminant measurements (Vancoppenolle *et al.*, 2025). In addition to routine contaminant/aerosol deposition sampling of the snow/ice pack, dedicated measurement campaigns may also investigate aerosol dry deposition processes in detail (e.g., eddy covariance flux tower measurements on the ice) or photochemical cycling involving Hg, ozone and halogens (atmosphere, snow pack, ocean). Phytoplankton and zooplankton sampling for contaminant concentrations, in addition to water samples and isotopes providing contaminant seascapes across the different basins and water masses of the CAO, will be collected in close collaboration with the ocean group. Observations of currents speed and direction, as well as water mass origins, will help understanding the transport and connectivity of contaminants within the ocean. Numerical modeling, for example, using WRF-Chem (e.g., Ahmed *et al.*, 2023), of the long-range atmospheric transport of anthropogenic and natural (e.g., boreal fires) sources of aerosol and trace gases, and their deposition onto the sea ice/ocean, as well as local sources emitted from the snow/ice (e.g., halogens) and ocean (e.g., sea-salt aerosols, shipping emissions) will also contribute to elucidating anthropogenic sources of contaminants in the Arctic atmosphere, sea ice and ocean.

5. Foreseen outcomes

The long-term outcomes of the Tara Polaris year-round campaigns in the central Arctic Ocean will be multifaceted. A comprehensive contaminant profile will be established for the region, providing seasonal and long-term monitoring of key pollutants such as Hg, plastics and other chemicals of emerging Arctic concern across the atmosphere, cryosphere, and hydrosphere. This will create a baseline dataset for future comparative studies under climate change and intensifying human activity, while also serving as a valuable input to improve regional and global contaminant models. This contaminant profile will further be monitored over 10 consecutive drifts covering ca. 20 years, allowing to track changes and validate models.

Year-round observations will yield insights into seasonal and spatial variability, enabling a better understanding of contaminants dynamics, their sources, and their transport-sink relationships through atmospheric deposition, ocean currents, and ice drift. At the same time,

the campaigns will drive advancements in Arctic monitoring methodologies, including optimized sampling protocols for extreme, remote environments and the development of a scalable monitoring framework that could be replicated at other polar sites.

By applying integrative approaches such as the exposome and microbial ecotoxicology, we will link contaminant exposure to ecological risk, identifying molecular and ecosystem-level responses and providing early warning indicators of ecosystem stress. These insights will directly inform policy and regulatory frameworks, contributing new knowledge to international agreements such as AMAP, the Stockholm and Minamata Conventions, and the forthcoming global Plastics Treaty, while also generating recommendations for regulatory action on contaminant use, emissions, and waste management.

Furthermore, the campaigns will shed light on climate-contaminant interactions, clarifying how climate-driven processes such as ice melt and ocean circulation module contaminant transport and bioavailability, and helping predict risks under future climate scenarios. Finally, the *TPS* will become a hub for capacity building and international collaboration, serving as a reference site for Arctic contaminant research and fostering shared protocols, interdisciplinary training opportunities, and a strengthened global network of polar scientists.

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Author contributions

All co-authors had substantial contributions to conception and design, drafting the article or revising it critically for important intellectual content, as well as final approval of the version to be published.

Competing Interests

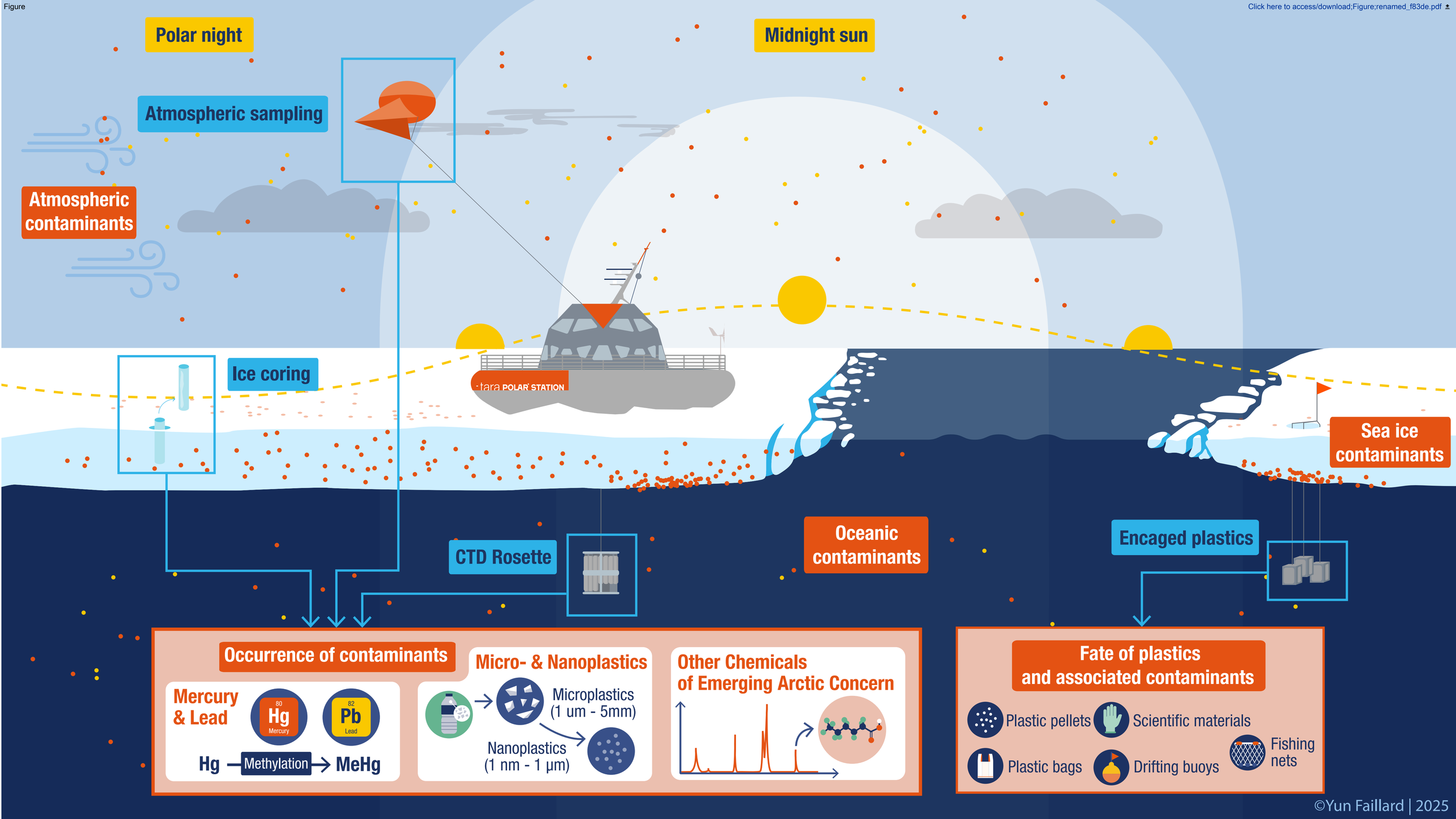
The authors have no relevant financial or non-financial interests to disclose.

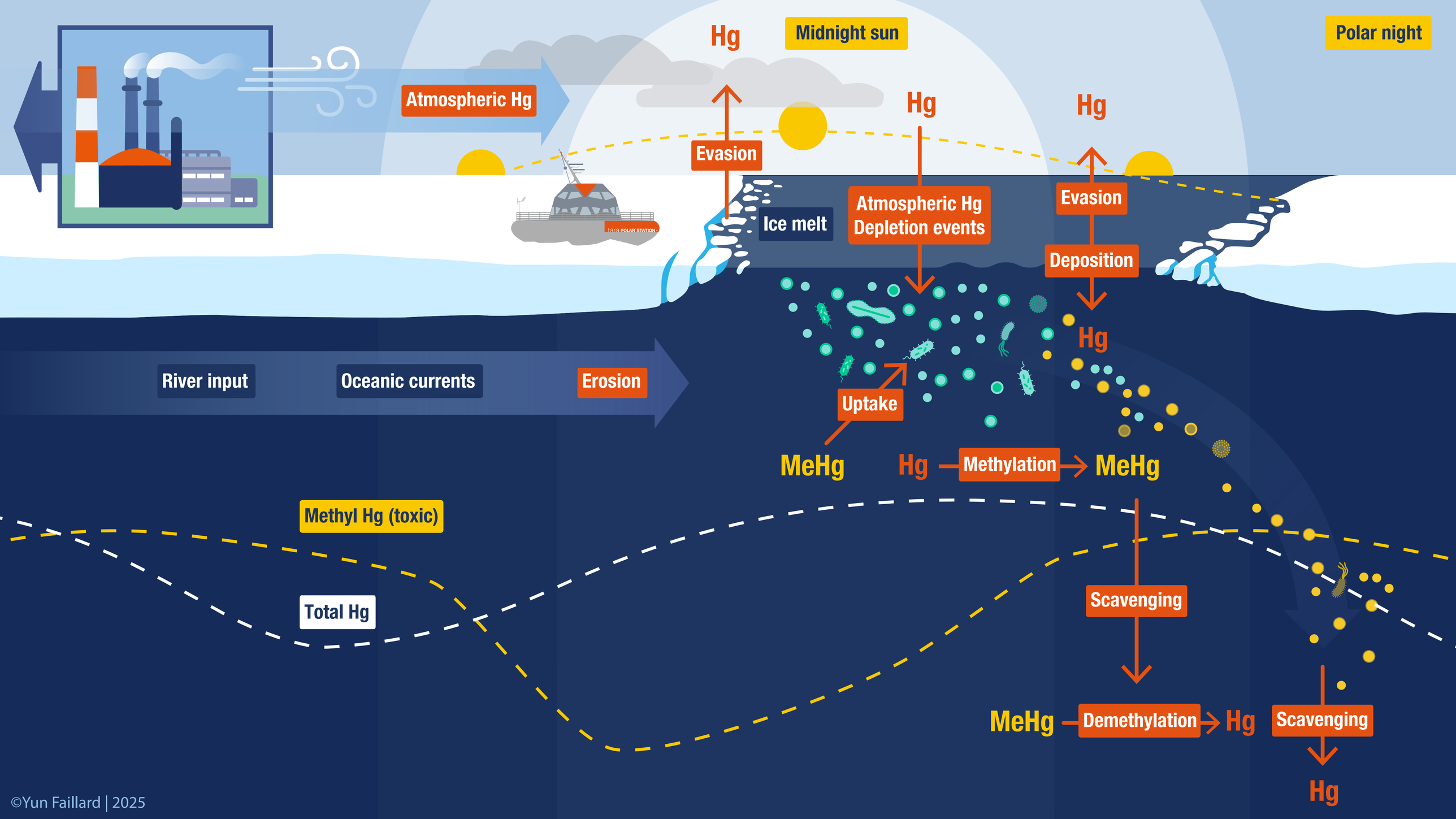
Availability of data and materials

The datasets and materials used and/or analyzed during the current study are available on reasonable request.

List of figures

Figure




Hg
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Atmospheric Hg
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Hg
Hg
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MeHg
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Scavenging
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Hg
Scavenging
Hg
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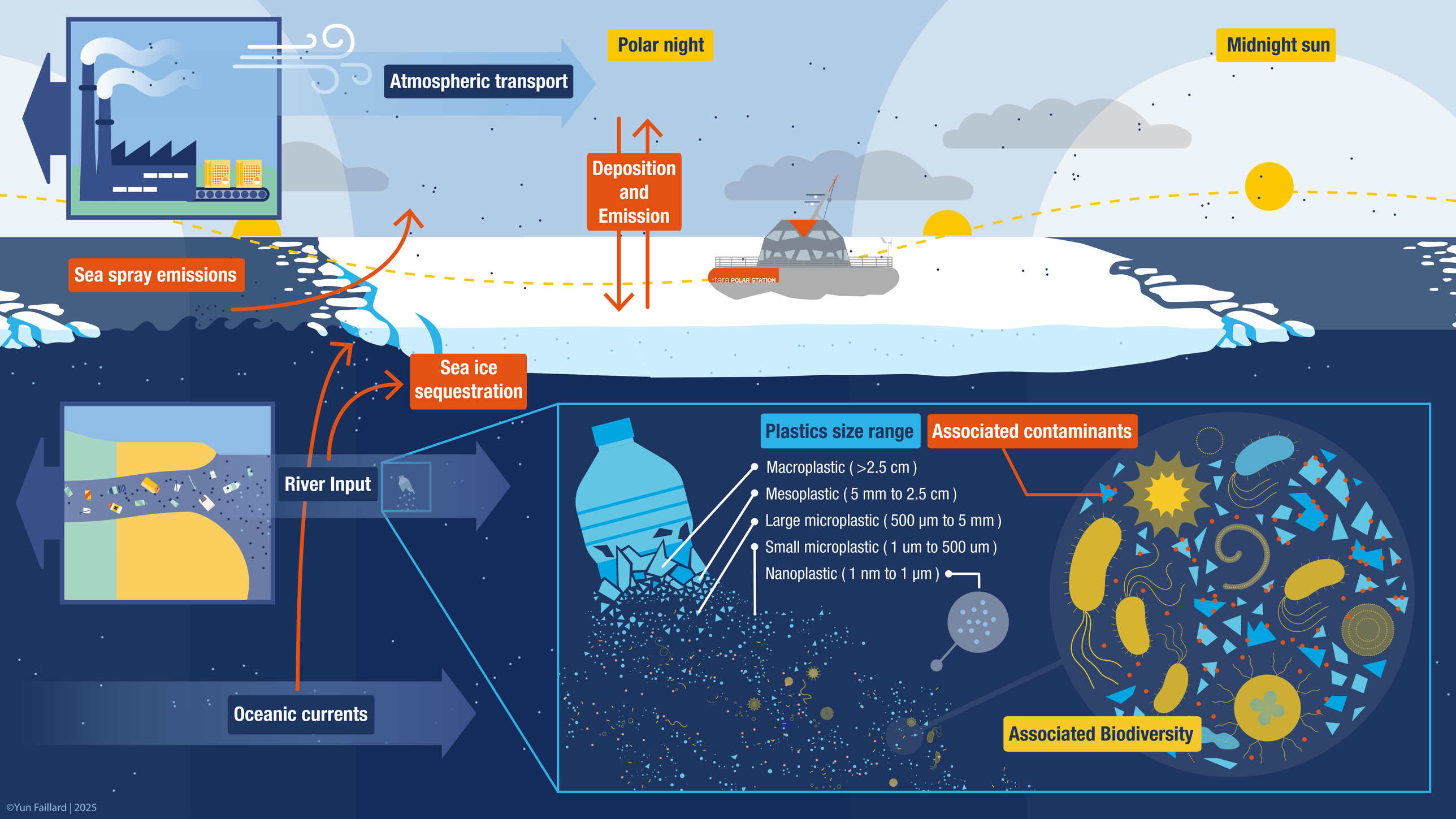
Polar night
Midnight sun
Atmospheric transport
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Sea spray emissions
Sea ice sequestration
River Input
Oceanic currents
Plastics size range
Macroplastic (>2.5 cm)
Mesoplastic (5 mm to 2.5 cm)
Large microplastic (500 µm to 5 mm)
Small microplastic (1 um to 500 um)
Nanoplastic (1 nm to 1 µm)
Associated contaminants
Associated Biodiversity
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