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Microplastics in the atmosphere and cryosphere in the circumpolar North: a case for multicompartment monitoring

Bonnie M. Hamilton[a], Liisa Jantunen[b], Melanie Bergmann[c], Katrin Vorkamp[d], Julian Aherne[e], Kerstin Magnusson[f], Dorte Herzke[g], Maria Granberg[f], Ingeborg G. Hallanger[h], Alessio Gomiero[i], and Ilka Peeken[c]

[a]Department of Ecology and Evolutionary Biology, University of Toronto, Toronto, ON M5S 3B2, Canada; [b]Air Quality Processes Research Section, Environment and Climate Change Canada, Egbert, ON L0L 1N0, Canada; [c]Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, 27570 Bremerhaven, Germany; [d]Department of Environmental Science, Aarhus University, DK-4000 Roskilde, Denmark; [e]School of the Environment, Trent University, Peterborough, ON K9L 0G2, Canada; [f]IVL Swedish Environmental Research Institute, Kristineberg Marine Research Station, 45178 Fiskebäckskil, Sweden; [g]NILU, Norwegian Institute for Air Research, Fram Centre, 9296 Tromsø, Norway; [h]Norwegian Polar Insitute, 4021, Tromsø, Norway; [i]Norwegian Research Centre, Department of Climate and Environment, 4021 Stavanger, Norway

Corresponding author: **Ilka Peeken** (email: ilka.peeken@awi.de)

Abstract

The atmosphere and cryosphere have recently garnered considerable attention due to their role in transporting microplastics to and within the Arctic, and between freshwater, marine, and terrestrial environments. While investigating either in isolation provides valuable insight on the fate of microplastics in the Arctic, monitoring both provides a more holistic view. Nonetheless, despite the recent scientific interest, fundamental knowledge on microplastic abundance and consistent monitoring efforts are lacking for these compartments. Here, we build upon the work of the Arctic Monitoring and Assessment Programme's Monitoring Guidelines for Litter and Microplastic to provide a roadmap for multicompartment monitoring of the atmosphere and cryosphere to support our understanding of the sources, pathways, and sinks of plastic pollution across the Arctic. Overall, we recommend the use of existing standard techniques for ice and atmospheric sampling and to build upon existing monitoring efforts in the Arctic to obtain a more comprehensive pan-Arctic view of microplastic pollution in these two compartments.

Key words: air, Arctic, atmospheric deposition, sea-ice, ice cores, atmospheric transport

Résumé

L'atmosphère et la cryosphère ont récemment fait l'objet d'une attention considérable en raison de leur rôle dans le transport des microplastiques vers et dans l'Arctique, et entre les environnements d'eau douce, marins et terrestres. Si l'étude isolée de l'une ou l'autre de ces sources fournit des informations importantes sur le devenir des microplastiques dans l'Arctique, la surveillance des deux permet d'obtenir une vision plus globale. Néanmoins, malgré le récent intérêt scientifique suscité, les connaissances fondamentales sur l'abondance des microplastiques et des efforts de surveillance cohérents font défaut pour ces compartiments. Les auteurs s'appuient ici sur les travaux du sur les travaux d'Arctic Monitoring and Assessment Programme (AMAP) pour la surveillance des déchets et des microplastiques pour fournir une feuille de route pour la surveillance multicompartiments de l'atmosphère et de la cryosphère, afin de mieux comprendre les sources, les voies de pénétration et les puits de la pollution plastique dans l'Arctique. Dans l'ensemble, ils recommandent d'utiliser des techniques standard existantes pour l'échantillonnage de la glace et de l'atmosphère et de s'appuyer sur les efforts de surveillance existants dans l'Arctique pour obtenir une vue panarctique plus complète de la pollution par les microplastiques dans ces deux compartiments. [Traduit par la Rédaction]

Mots-clés : air, Arctique, dépôt atmosphérique, glace de mer, carottes de glace, transport atmosphérique

Introduction

Plastic pollution including larger plastic litter and microplastics (≤5 mm) has been identified as an emerging concern in the Arctic (AMAP 2017; PAME 2019), especially given its inherent complexity of morphology (e.g., colour, shape, size), chemical composition (i.e., polymer type, additives), and associated chemicals (Rochman et al. 2019). Further, microplastics are ubiquitous and have been detected in numerous biotic and abiotic samples across the circumpolar North, including mammals (e.g., Moore et al. 2020; Carlsson et al. 2021), seabirds (e.g., Trevail et al. 2015; Baak et al. 2020), fish (e.g., Kühn et al. 2018; Morgana et al. 2018), invertebrates (e.g., Fang et al. 2018; Iannilli et al. 2019; Granberg et al. 2020), seawater (e.g., Tekman et al. 2020; Ross et al. 2021), wastewater (e.g., Herzke et al. 2021), sediment (e.g., Bergmann et al. 2017; Kanhai et al. 2019; Mu et al. 2019), sea-ice (e.g., Obbard et al. 2014; Peeken et al. 2018*a*), lake water (e.g., González-Pleiter et al. 2020), and atmospheric deposition (i.e., wet deposition (e.g., Bergmann et al. 2019) and dry-deposition (Hamilton et al. 2021)). Despite the widespread presence of microplastics in the Arctic, their sources remain poorly understood, including the relative importance of local and distant sources of microplastics (Hallanger and Gabrielsen 2018; PAME 2019; Herzke et al. 2021).

Sources and pathways of microplastics have been reviewed by Browne (2015) and Li et al. (2020). We consider sources of plastics as their "origin of anthropogenic input into the environment". With regard to the Arctic, sources can thus be within or outside the Arctic, i.e., microplastics in the Arctic can be from local sources or be locally introduced via long-range transport. We consider pathways of microplastics as the physical transport process, e.g., with ocean currents (van Sebille et al. 2020) or via atmospheric transport (e.g., Allen et al. 2019), which moves microplastic particles in the environment. The majority of studies on the transport of microplastics have focused on ocean pathways (e.g., Lusher et al. 2015; Tekman et al. 2020). Ocean currents originating in the south have been proposed to function as conveyor belts, carrying microplastics from the more densely populated southern areas in Europe to the Arctic (Cózar et al. 2017; Tekman et al. 2020). Further, local sources, such as untreated wastewater, can cause considerable microplastic pollution, which may be regionally distributed within the aquatic environment (Herzke et al. 2021). In addition, the 2019 report of the Arctic Council Working Group on the Protection of the Marine Environment (PAME) identified atmospheric circulation as a potentially important transport pathway (PAME 2019). However, given the limited empirical data and lack of harmonised methodologies for sample collection, it is not yet possible to estimate the magnitude of atmospheric transport of microplastics to the Arctic. Similarly, little is known about microplastic abundance within the Arctic cryosphere, including land-fast ice, pack ice, and land-based ice (e.g., ice caps, ice fields, seasonal ice in freshwater lakes and rivers, glaciers). These ice types are of different origins and therefore likely to have different sources of microplastic contamination. Therefore, it is essential that we monitor the atmosphere and cryosphere to fully understand the fate and transport of microplastics into and within the Arctic, including the role of air and ice as a transport medium and, with regard to the cryosphere, as a reservoir for microplastics (Fig. 1).

The Arctic Monitoring and Assessment Program (AMAP) has outlined a multicompartment approach, which has the potential to improve our overall understanding of microplastic movement within the Arctic environment (AMAP 2021*a*). Here, we expand upon AMAP's Litter and Monitoring Guidelines for air, ice, and snow (AMAP 2021*b*) and discuss the strengths and limitations of monitoring microplastics in the atmosphere and cryosphere. Further, we highlight research gaps that should be prioritized for future monitoring efforts across the circumpolar North.

State of the science

Microplastic in the atmosphere and long-range transport

Although microplastics (e.g., microfibres, fragments, films, and foams) have been identified in both polar regions (Isobe et al. 2017; Waller et al. 2017; Peeken et al. 2018*b*; PAME 2019;), the majority of studies on microplastics in the atmosphere, ice, and snow have focused on Arctic environments (e.g., Obbard et al. 2014; Peeken et al. 2018*a*; Bergmann et al. 2019; Kanhai et al. 2020; Von Friesen et al. 2020; Brahney et al. 2021; Kim et al. 2021;). Like other atmospheric particles, microplastics are expected to undergo long-range transport via air currents followed by wet and dry deposition onto water and land (Allen et al. 2019). Compared to ocean currents, air masses can widely distribute microplastics, within a matter of hours or days (Stohl 2006). Liss (2020) suggests that the atmosphere may contribute as much as 10 million tonnes of microplastic per year to the oceans worldwide. This is comparable to estimates of riverine inputs of 5–13 million tonnes per year (Jambeck et al. 2015). Based on simulations of atmospheric transport of road wear particles, Evangeliou et al. (2020) estimated that 5%–10% of all tire and brake wear particles in the size fraction <10 μm (particulate matter 10 [PM_{10}]) emitted globally are transported to the Arctic. However, imperial estimations to confirm these measurements are lacking. Furthermore, nanoplastic particles from tire wear were recently detected in a 14 m deep Greenland firn core (). Microplastic particles can undergo physical changes during atmospheric transport, including fragmentation, UV degradation, and chemical weathering. Cai et al. (2017) recorded signs of degradation such as grooves, pits, fractures, and flakes on microplastic particles collected in atmospheric deposition and suggested that they were caused by collision and friction, as well as chemical weathering due to the high irradiation levels in the atmosphere. Fragmentation during transport likely increases the potential for long-range transport (Biber et al. 2019).

The strong seasonal changes in the Arctic may also impact the transport of airborne microplastic, e.g., changes in air mass transport, the presence or absence of UV light, as well as its intensity (Allen et al. 2020). The polar sunrise and Arctic haze season are known to create reactive environments that could both enhance the deposition of microplastics and cause fragmentation, which may result in long-range transport of smaller particles. Thus, monitoring of airborne microplastics should ideally take place throughout the year, similar to other contaminants (Wong et al. 2021).

Few studies have addressed the trajectory or transport pathways of microplastics in the atmosphere. Nonetheless, they generally note that microfibres are the most common

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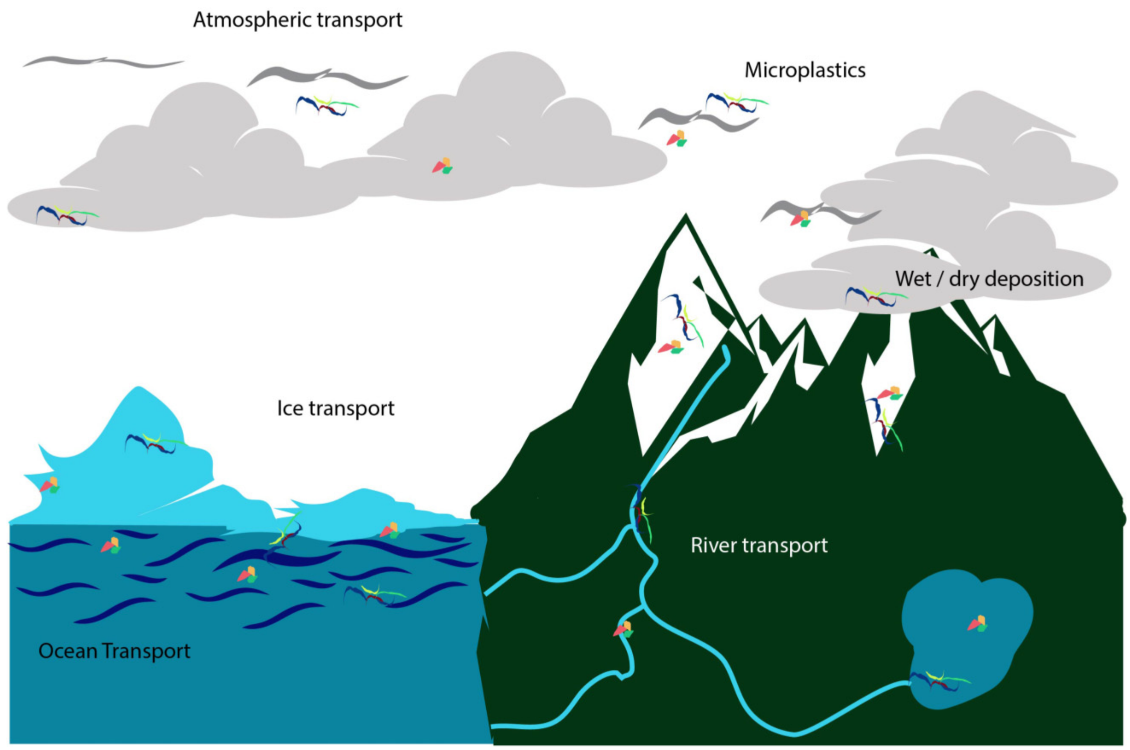
Fig. 1. Graphic depicting the atmosphere and cryosphere compartments and transport pathways of microplastics into and within the Arctic.



shape identified in atmospheric deposition samples (e.g., Dris et al. 2016; Cai et al. 2017; Bullard et al. 2021). In addition, Wright et al. (2020) showed a predominance of microfibres in microplastic bulk deposition in London (UK) and estimated travel distances of 12 and 60 km for nonfibrous and fibrous materials, respectively, with an influence area of fibrous microplastics from 640 to 8700 km^2. Using the air mass trajectory analysis, Allen et al. (2019) estimated a travel distance of 95 km for microplastics observed in the Pyrenees. Notwithstanding these few studies, the atmospheric transport of microplastics has been widely noted as a gap in knowledge (e.g., Allen et al. 2019; Wright et al. 2020; Zhang et al. 2020; Bullard et al. 2021).

Microplastics in the cryosphere

Cryosphere matrices (e.g., sea-ice, land-fast ice, ice caps, ice fields, glaciers, etc.) tend to sequester microplastics and act as temporary storage and regional transport vector (Obbard et al. 2014; Peeken et al. 2018*a*; von Friesen et al. 2020; Kanhai et al. 2020; Ásmundsdóttir and Scholz 2020; Kim et al. 2021). The mechanism of microplastic sequestration is likely dependent upon the origin of the ice (e.g., seasonal sea-ice versus ice fields created by snowpack). Atmospheric deposition (e.g., wet and (or) dry deposition), as a pathway for microplastics into Arctic sea-ice, was suggested by Geilfus et al. (2019), who found high microplastic concentrations in the surface layer of an open sea-ice tank experiment. However, when measuring in situ sea-ice cores from the Baltic Sea, they could not corroborate these experimental results (Geilfus et al. 2019). The Baltic findings are in line with observations of Arctic sea-ice cores, which generally lack high concentrations of microplastics in the surface (Peeken et al. 2018*a*; Kanhai et al. 2020). This is further supported by Kim et al. (2021), who showed that less than 1% of observed microplastics entrapped in sea-ice could be related to snowfall in the western Arctic Ocean, while the remaining proportion was a result of microplastics sequestered from seawater. In contrast, Bergmann et al. (2019) recorded comparably higher concentrations of microplastic in Eurasian Arctic snow, which might be explained by more polluted air masses or analytical differences.

Microplastics identified in land-based snowpack and ice (e.g., ice caps, ice fields) are a direct result of both wet and dry atmospheric deposition (Ambrosini et al. 2019; Bergmann et al. 2019; Geilfus et al. 2019; Cabrera et al. 2020; Materić et al. 2020; Kim et al. 2021; Stefánsson et al. 2021). There is evidence of microplastics in glacial debris from the Forni Glacier, Italian Alps, by Ambrosini et al. (2019) at concentrations comparable to those found in European marine and coastal sediments (Gomiero et al. 2019; Haave et al. 2019). Microplastics recently observed in snow covering the Vatnajökull ice cap in Iceland also suggest their presence in compacted deeper glacial layers (Stefánsson et al. 2021). Furthermore, Materić et al. (2022) identified nanoplastics in the Greenland ice sheet and attributed these findings to long-range transport as the source (Materić et al. 2022). In concert, organic contaminants, transported to polar regions in the gaseous phase or associated with particles, have been found in multiyear high-altitude ice caps and ice fields, where atmospheric deposition is the main source of contaminant transport (e.g., Hermanson et al. 2010; Gao et al. 2020; Na et al.

2020; Xie et al. 2020; Hermanson et al. 2021). These sites have yet to be investigated for microplastics.

Another important feature of Arctic sea-ice is its seasonal cycle of growth and melt. For example, the European Arctic margin is influenced by drift ice formed on the Siberian shelves and carried by ocean currents to the Fram Strait via the Transpolar Drift (Serreze et al. 1989). Studying various sea-ice cores along the Transpolar Drift, Peeken et al. (2018*a*) could show that ocean currents had a unique microplastic fingerprint, which was reflected in their sea-ice. In addition, similar polymer compositions and plastic shapes between the western Arctic Ocean and the Arctic Central Basin suggest a strong connectivity between these two basins and a considerable input of microplastics through the Pacific inflow in the Bering Street into the Arctic basin (Kim et al. 2021). Upon entering the major outflow gateways of the Arctic, microplastics are likely released from the marginal ice zone (Obbard et al. 2014; Peeken et al. 2018*a*; Von Friesen et al. 2020; Kim et al. 2021). Displacement of microplastics from the marginal ice zone into deep-sea sediments at the HAUSGARTEN observatory in the Fram Strait was proposed by Bergmann et al. (2017) and further corroborated by modelling of microplastic pathways in Fram Strait sediments and water (Tekman et al. 2020). Furthermore, Fang et al. (2018) observed high microplastic concentrations in benthic organisms caught below the ice covered Pacific inflow gateway (Fang et al. 2018). Given the marked reduction in age, thickness, and extent of Arctic sea-ice cover in recent decades (Polyakov et al. 2012; Stroeve et al. 2012), it is likely that sequestered microplastic will be increasingly released by the major outflow gateways into Arctic and subarctic pelagic water systems. In a warming Arctic, the occurrence, movement, and freeze/thaw cycles of ice can be anticipated to play an even stronger role in the link between the atmospheric, aquatic, and terrestrial environments with regard to microplastic accumulation and transport.

These studies, although limited in number, already indicate the presence of microplastics both in the atmosphere and cryosphere, with implications for transport to and distribution within the Arctic. Considering the rapid changes in the Arctic cryosphere (Ásmundsdóttir and Scholz 2020), ice may play a dynamic role in the storage, transport, and release of microplastics. However, published knowledge on the connectivity between the role of ocean currents and atmospheric input of microplastic in the Arctic is lacking. Future monitoring studies should include multicompartment monitoring to enhance our understanding of the linkages and governing factors controlling the exchange of microplastic between compartments and to obtain a better understanding of sources and pathways of microplastic in the Arctic.

Sampling methods and challenges

Sampling the atmosphere

Although the monitoring of air and ice is important for a holistic understanding of microplastic occurrence in the Arctic, sample collection faces practical challenges. The routine collection of air samples for microplastics in the Arctic is limited because of the remoteness, harsh climatic conditions (e.g., wind, frigid temperatures), and limited access to power (AMAP 2021*b*). However, there is a growing knowledge base on the atmospheric sampling of microplastics that can provide examples of appropriate sampling strategies. In general, atmospheric studies on microplastics have used traditional air and precipitation monitoring methods, such as active air samplers, bulk deposition samplers (Dris et al. 2016; Allen et al. 2020; Roblin et al. 2020), wet-only deposition samplers (Brahney et al. 2020; Roblin et al. 2020), dry dust collectors (Brahney et al. 2020), and snow samplers (Fig. 2). Nonetheless, the strong wind conditions in the Arctic are a challenge compared to less exposed regions.

Sampling methods that allow continuous measurements throughout the year are beneficial for atmospheric microplastic research; however, the lack of electrical infrastructure can make continuous active air sampling a challenge. One solution is to use existing Arctic research stations for atmospheric monitoring. The stations used for contaminant monitoring were recently described by Wong et al. (2021) and include the Zeppelin Observatory on Svalbard, Alert and Little Fox Lake in Canada, Villum Research Station in Greenland, Stórhöfði in Iceland, Pallas in Finland and Andøya in Northern Norway. The study also included the stations Amderma and Tiksi in Northern Russia (Wong et al. 2021). However, extending current sampling programs to microplastics will require adjustments to equipment and procedures, as well as dedicated quality assurance/quality control (QA/QC) protocols for microplastics. Sampling sites colocated with meteorological measurements will provide valuable supporting information of high relevance for data interpretation, such as wind speed, wind direction, precipitation, and temperature. These data can provide insights into seasonal variability of microplastic concentrations due to changes in wind patterns or short-term transport events. Alternatively, passive sampling methods can be employed as a screening method to determine microplastics in an area at a given time. Passive sampling methods for plastic particles have been explored and developed as a way to increase spatial coverage, provide a relative comparison between different areas, and evaluate relative atmospheric deposition at a particular time (Pienaar et al. 2015). As they are usually more easily operated than active samplers, passive sampling methods (e.g., moss bags, Petri dishes) can engage local communities and further enhance capacity building in the field of microplastic monitoring. In this context, moss and lichen biomonitoring appears to be a cost-effective tool to study airborne contamination including microplastic deposition (Roblin and Aherne 2020; Loppi et al. 2021) and through the use of moss or lichen bags (Temple et al. 1981) they may be particularly suitable during winter conditions. When compared with snow samples, moss bags are considered to provide a more homogeneous and better controlled sampling method (Salo et al. 2016).

Sampling the cryosphere

While various glacial coring programs are ongoing in the Arctic, primarily targeting climate reconstruction (e.g., Weißbach et al. 2016), there are currently no land-based cryosphere coring campaigns for microplastic (i.e., glaciers,

Fig. 2. Sampling equipment for atmospheric microplastics: photographs showing (from left to right) active air sampling (with sampling head), wet deposition only sampling, NILU bulk deposition collector, and passive air sampling (including moss bags).

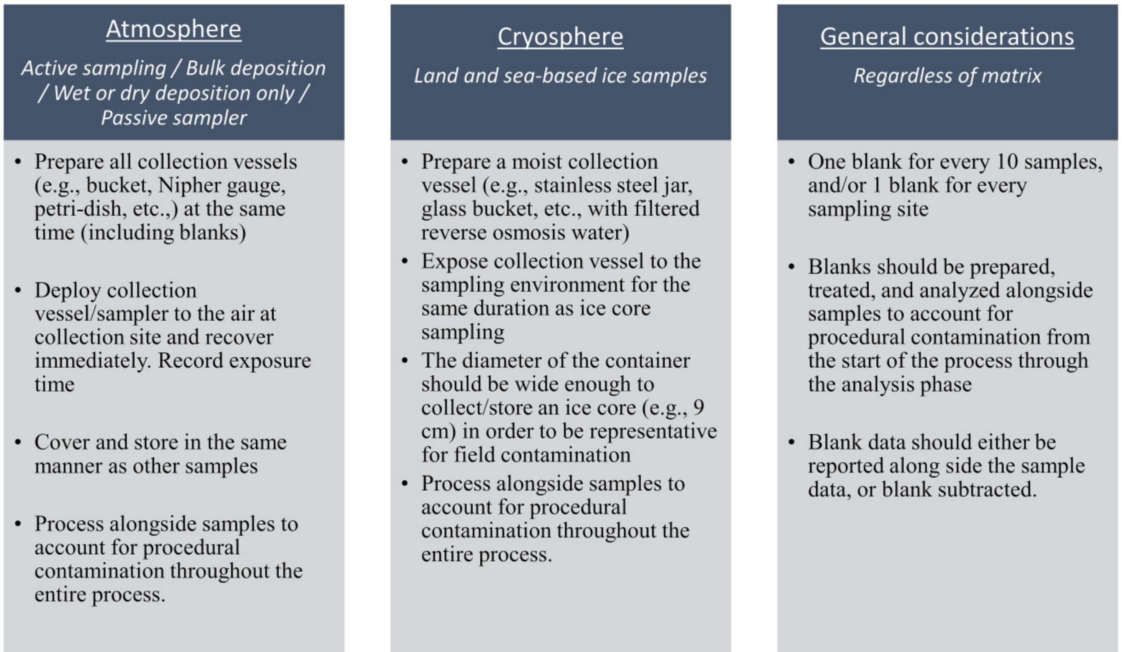
ice caps, ice fields) in the circumpolar North, although legacy samples from such campaigns have been analysed (). However, sea-ice sampling has been described for the Arctic, and several studies evaluating plastics have used traditional coring techniques (e.g., Kovac corers; Obbard et al. 2014; Peeken at al. 2018*a*), which can be applied to sea-ice sampling. Monitoring programs that have a particular interest in mass-based abundance of microplastics in sea-ice or potential impacts of microplastic on ice-based organisms are encouraged to collect several replicate cores from the same ice floe. Furthermore, additional sea-ice cores can provide valuable ancillary data for temperature, salinity, black carbon content, and biological parameters (e.g., chlorophyll, cell counts) to provide a more holistic view of the sampled sea-ice and thus evaluate how microplastics might affect ecosystem services. Specific markers, such as rare Earth elements, are helpful for elucidating the history of the sampled sea-ice (e.g., riverine input; Laukert et al. 2017). Sampling ice caps, ice fields, and glaciers also requires drilling tools (e.g., US Ice Drilling and Design Operations hand auger (76 mm) and further handling is similar to that of sea-ice cores (e.g., Materić, et al. 2022)). When evaluating ice from glaciers, ice fields, ice caps, etc., it is important to take replicate cores for high-resolution age-depth data. Moreover, replicates are highly recommended for more robust data to compensate for heterogeneous distribution within both land and sea-based ice samples.

QA/QC practices

In general, field sampling carries the risk of contamination, which should be reflected in sampling protocols, i.e., field techniques should be employed that prevent procedural contamination during the collection of cryosphere and atmospheric samples. For example, samples should be taken against the prevailing wind direction. Field technicians in warmer weather should not use gloves and in colder weather should wear natural fibres (i.e., wool, leather, or cotton) for hands and head. Field sheets should record the material types and colours being worn including footwear while sampling. if possible, clothing of field technicians should be analysed as a means of QA/QC. Likewise, laboratory facilities with controlled, particle free environments and techniques must be ensured for the processing of the samples. Laboratory technicians should wear cotton laboratory coats and work within a clean room and laminar air flow hood when available.

Procedural laboratory and field blanks are of the utmost importance to evaluate method quality and provide accurate data, especially given that plastic particle counts are often quite low in Arctic regions. During field sampling, procedural blanks (e.g., one for every 10 samples, or at least one per sampling site) should undergo the exact same processing as a field sample. For example, when taking active air samples, an additional sampling head (Fig. 2) should be taken to the field, loaded in the air sampling apparatus, attached to the pump, and allowed to draw air for < 30 seconds. Similarly, for passive samplers, blanks should be brought to the field, deployed, and immediately retrieved. Blanks should be covered, stored, transported, processed, and analysed in the same way as the environmental samples. This way, procedural contamination throughout the entire sampling and analysis process can be evaluated and results can be corrected or flagged accordingly (Fig. 3). For ice sampling, entire cores or individual sections should be cut with a stainless steel, noncoated

Fig. 3. Preparation of procedural blanks and general considerations for proper quality assurance/quality control methods for atmosphere and cryosphere sampling.



blade (e.g., bone saw). The outer part of the core (i.e., firn) should be cleaned with a nonplastic, noncoated grater (e.g., stainless steel, ceramic) to ensure the removal of any surface contamination. Ice core or snow melting should occur in a precleaned, sealed stainless-steel or glass jar to further prevent procedural contamination. Plastic airborne contamination in the sample preparation area should be monitored and reported alongside the results of the environmental samples.

Furthermore, it is imperative that particle specification methods are included for all compartments when reporting results (i.e., polymer type, colour, shape, length, and diameter). Sample analyses should have multiple lines of evidence, such as microscopy (stereo or fluorescence) and chemical identification techniques to determine polymer type (e.g., Raman spectroscopy, Fourier Transform Infrared (FTIR), Laser Direct Infrared (LDIR) imaging, pyrolysis/gas chromatography-mass spectrometry (GC-MS)). Further, external quality control schemes are being developed for microplastics and should be utilized, e.g., Quality Assurance of Information for Marine Environmental Monitoring in Europe (QUASIMEME; van Mourik et al. 2021).

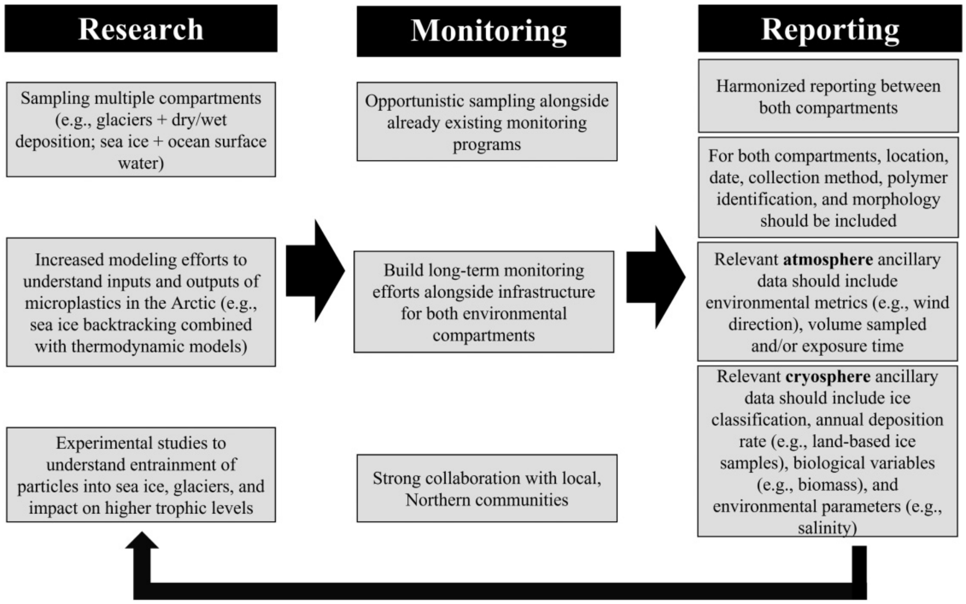
Recommendations for future monitoring and research priorities

Atmosphere and cryosphere microplastic research is still in its infancy, which poses challenges for standardised monitoring (Fig. 4). Furthermore, the resulting data gaps hamper our understanding of transport processes and the role of local and distant sources. Since the various components of the cryosphere are quite different, research and monitoring strategies need to be adapted to each, while still allowing connections between the compartments. While ice caps and Arctic lakes are strongly impacted by atmospheric deposition (Fig. 1; e.g., Luoto et al. 2019), the marine and riverine cryosphere might be more influenced by the plastic particle load of the underlying water currents (Fig. 1; e.g., Peeken et al. 2018 *a*). While atmospheric deposition is shown to be a contributing factor of microplastics in various water bodies, it remains a challenge to quantify its importance; thus, active air monitoring at dedicated locations is necessary to provide insight into the role of atmospheric deposition.

The relative contributions of different pathways to the marine environment, including ocean transport, riverine inflows, atmospheric deposition, and biological transport, might differ between locations, seasons, and for different types of plastics. This needs further research to be properly quantified; however, reliable and comparable methods are essential and should be a primary area of development. Experiences and lessons learned from better-developed research on marine microplastics can be used and adapted to address questions relating to microplastics in other environmental compartments (e.g., QA/QC, quantification, and identification techniques). This involves building upon already existing monitoring infrastructure and co-creating monitoring programs with Northern partners that address local interests towards Northern led research.

Plastic pollution of the Arctic environment directly affects Arctic communities, as microplastics have the potential to accumulate in Arctic food chains (Moore et al. 2022). In addition, microplastics in the air could also be inhaled by local Arctic community members, especially in areas prone to sea spray (Allen et al. 2020). The monitoring needs for plastic pollution across the Arctic provide opportunities for Indigenous and community-based produced and co-produced

Fig. 4. Flow chart highlighting recommendations for monitoring, reporting, and future research priorities for microplastic sampling in the Arctic atmosphere and cryosphere.



research and long-term monitoring programs, including sampling campaigns with appropriate QA/QC schemes. For example, Hamilton et al. (2021) used simple passive air sampling methods (i.e., Petri dishes lined with double sided sticky tape) deployed by local partners in Nunavut, Canada. The deployment of these samplers was used in part to determine atmospheric deposition (i.e., dry dust deposition), but they were also used as a pilot project to determine feasibility and usability in collaboration with local partners. Working together to produce manageable and replicable monitoring methods that are guided and led by Indigenous researchers is crucial as we work toward a strategic monitoring effort across the circumpolar North. Opportunities of aligning monitoring priorities in the field of litter and microplastics with interests of northern and Indigenous communities and co-developing monitoring strategies have been discussed by Provencher et al. (this Collection). The National (Canada) Inuit Strategy for Research produced by the Inuit Tapiriit Kanatami (ITK) organization, representing about 65 000 Inuit in the Canadian Arctic, has presented a National Inuit Strategy for Research (ITK 2018). While each Indigenous group and local communities across the Arctic will be different with varying research priorities and interests, these principles could also be applied outside Canada, across the circumpolar North, with an emphasis on community collaboration and co-production of monitoring efforts moving forward.

Contaminant monitoring infrastructure exists across the Arctic (e.g., Provencher et al. this Collection; AMAP 2017; Wong et al. 2021; Hamilton et al. 2022), which could be built upon in an effort to create a similar circumpolar monitoring program for plastic pollution in the atmosphere and cryosphere. The Arctic air monitoring stations are equipped with active air samplers that collect a variety of organic contaminants (e.g., flame retardants, pesticides, polychlorinated biphenyls), which could be expanded to include plastic particles (Wong et al. 2021). At Villum Research Station in Greenland, a pilot project has been initiated on microplastic determinations in snow samples, with a strong focus on QA/QC protocols. There is also a network of air quality stations, close to or within the Arctic. For example, in Nunavut there are stations in Arviat, Iqaluit, and Kugluktuk. At these stations, gasses and particles (e.g., ozone, nitrogen dioxide, and $PM_{2.5}$) are routinely monitored and provide potential sites that could be expanded for microplastics research. Further, the European Monitoring and Evaluation Program (EMEP) includes monitoring sites across the European Arctic that could be expanded upon to include microplastic sampling.

Despite the growing interest regarding microplastic pollution in sea-ice (e.g., Obbard et al. 2014; Peeken et al. 2018*a*; von Friesen et al. 2020; Kim et al. 2021), there are currently no established research or monitoring sites for sea-ice (PAME 2019). Monitoring could be implemented at existing research stations by collecting extra cores for microplastic. For example, current regular sea-ice sampling occurs in the Hudson Bay, Cambridge Bay, and in Northern Baffin Bay, Canada. Another targeted area could be Northeast Greenland in the outflow of sea-ice from the Arctic Ocean as well as Young Sound (e.g., Daneborg/Zackenberg stations 74°N), where it is possible to collect drifting sea-ice during the summer months. Additionally, regular sampling campaigns like the ones occurring in Fram Strait (FRAM Pollution Observatory as part of HAUSGARTEN Observatory) could monitor the outflow of Arctic sea-ice and study the processes at the interface between the ocean and the atmosphere by ship-based sampling. However, it is imperative to include extensive QA/QC protocols during ship-based sampling due to the high potential for ship-based contamination (Leistenschneider et al. 2021). Selected fjords near Svalbard or reoccurring Central Arctic research vessel expeditions could include additional sea-ice core sampling and air sampling programs for microplastics. Furthermore, collaborations with existing research programs could be fostered to acquire additional (legacy) ice cores for plastic contamination from established ice monitoring programs (e.g., US National Science Ice Core Facility, Canadian Ice Core Laboratory, EGrip and NGrip on Greenland).

Estimates for the contribution of long-range atmospheric transport of microplastics versus local sources are lacking for both the marine and the terrestrial cryosphere. In contrast to previous assumptions, there are now indications that local sources play a role in the overall microplastic pollution in the Arctic ocean. For example, recent studies by Ross et al. (2021), Von Friesen et al. (2020), and Herzke et al. (2021) showed higher concentrations of anthropogenic microparticles close to wastewater outlets and in the marginal sea-ice zone. Currently, over four million people live in the Arctic (Heleniak and Bogoyavlensky 2015) and most have no access to proper waste management or wastewater treatment. Thus, plastic debris from openly exposed waste disposal sites (e.g., open-pit landfills, open-pit burning) and microplastic from treated and untreated wastewater enters the marine environment continuously (Magnusson et al. 2016; Granberg et al. 2019; Herzke et al. 2021) and could be a local source for ice contamination and atmospheric deposition. Other local microplastic pollution sources in the Arctic are related to shipping, fisheries, and tourism (PAME 2019). Typical polymers of these activities like varnish, polyamide, and polyethylene were traced to very small microplastic particles in Arctic sea-ice (Peeken et al. 2018*a*). Thus, the estimate of local sources should be an integral part of future monitoring activities, which could include community-based assessments of plastic pollution (e.g., monitoring ice caps close to local communities or ice samples in a gradient along wastewater effluent outlets).

River systems are another critical pathway that connects the freshwater, marine and terrestrial compartments, and should be monitored for plastic inputs in the Arctic (Frank et al. 2021; Yakushev et al. 2021). Understanding the role of riverine transport can be important in understanding the fate of microplastics, particularly in the cryosphere. For example, since a large fraction of Arctic sea-ice is created on shallow shelves (e.g., Laukert et al. 2017) or as anchor ice on the actual seafloor in shallow areas (Reimnitz et al. 1987), microplastic with riverine origin or resident in sediment can easily be transported as far from its sources as Fram Strait (Peeken et al. 2018*a*; Tekman et al. 2020). Given that 11% of the global riverine discharge enters the Arctic Ocean (Fichot et al. 2013), Russian and Canadian rivers likely constitute important pathways for microplastic to the Arctic Ocean (Yakushev et al. 2021). Recent estimates suggest that previous studies overestimated the worldwide input of plastic from rivers, implying much longer residence time of plastic particles in the surface ocean (Weiss et al. 2021). Nonetheless, river systems should be included in future monitoring activities, especially given the fact that most of the Arctic rivers have a freezing cycle, which might further enhance the fragmentation of plastic litter and lead to fast speeds of river currents in the melting season, which could promote particle transport to river deltas. This information can be used to fuel 2-D and 3-D simulations of particle transport trajectories, which have previously been used to identify the pathways of various polymer types in the Arctic (Tekman et al. 2020). This will also improve 1-D thermodynamic models, which together with the backtracking of sea-ice floes are a good tool to track the incorporation of various polymer types during sea-ice growth (Peeken et al. 2018*a*). Furthermore, robust models can improve our ability to evaluate any increasing accumulation of microplastics in the Arctic over time on the scale of several decades, as well as studying the role of winter convection for downwelling processes of microplastic to the seafloor and thus interconnecting with this compartment (Bergmann et al. 2017).

Conclusion

In addition to the specific monitoring methods highlighted in the AMAP Litter and Monitoring Guidelines (AMAP 2021*b*), a multicompartment monitoring approach can provide a more comprehensive understanding of microplastics in the pan-Arctic, including their transport to and distribution within the Arctic. Monitoring efforts should include multicompartment sampling when appropriate, combining sampling of glaciers and atmospheric deposition, or sea-ice and surface water, supplemented with relevant ancillary data for each compartment. To propel this area of research out of its exploratory phase, and to create and sustain monitoring research efforts, opportunistic sampling alongside existing monitoring programs is recommended. Furthermore, knowledge sharing and collaboration with local communities, with an emphasis on community research priorities, is crucial in creating successful and robust long-term monitoring programs across the circumpolar North. Ultimately, a holistic monitoring approach that includes multiple knowledge streams will increase our understanding of the inputs and outputs of microplastics in various environmental compartments across the Arctic.

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Author information

Author ORCIDs

Bonnie M. Hamilton https://orcid.org/0000-0002-4721-9451
Ilka Peeken https://orcid.org/0000-0003-1531-1664

Author contributions

BMH: conceptualization, first draft writing, figure creation, editing, and writing; LMJ: conceptualization, first draft writing, editing, and writing; MB, KV, JA, MG, IGH, AG, and DH: editing and writing in two rounds of drafts; IP: conceptualization, first draft writing, editing, and writing.

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