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Microplastics in the cryosphere

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Abstract

Microplastics (MPs) have been detected throughout the cryosphere, from polar regions to mountain glaciers, highlighting their global reach and persistence. Predominantly found as fibers, MPs are highly mobile, transported by ocean currents and atmospheric winds across vast distances from human population centers. Whether in glaciers at temperate latitudes or in polar environments, the chemical composition of plastics reflects their use in a wide range of applications and their origin, either from local sources or transported from distant regions. In cold environments, plastic degradation slows down, leading to the long-term accumulation of MPs and associated chemical pollutants, either as additives or sorbed contaminants. This raises concerns about their eventual release into aquatic ecosystems as ice melts under the pressure of global warming. MPs may also contribute to climate change by reducing the albedo of ice and snow surfaces, thereby accelerating the melting of glaciers or permafrost. This effect has implications not only for fragile polar ecosystems but also for global oceanic circulation. Additionally, MPs interact with a broad range of cryosphere organisms, from invertebrates to large mammals, posing risks of bioaccumulation, biomagnification, and chemical toxicity. Although there is no doubt of increasing exposure to plastic, the risks associated to it remain poorly understood.

1. Introduction

Anthropogenic impact has reached all Earth's ecosystems, including the remote and isolated environments belonging to the cryosphere, where extreme cold keeps water frozen for most of the year. More specifically, the cryosphere refers to all parts of the Earth's surface where water exists in solid form. This includes glaciers and ice caps, such as those covering Greenland and Antarctica, frozen ocean water, primarily in the Arctic and Antarctic Oceans, permafrost, and frozen rivers and lakes. It also included seasonal and permanent snow cover of the mountains or mountain cryosphere¹. The mountain cryosphere is important due to its vulnerability to rapid environmental changes, which can result in significant downstream impacts on both the quantity and quality of water. Additionally, these areas are relatively close to large population centres². Figure 1 illustrates the location of the Global Cryosphere, defined as regions with a mean monthly temperature below zero in either January or July³.

The cryosphere is integral to Earth's climate system, impacting global temperatures by reflecting sunlight through its high albedo, influencing sea lev-

els, hydrological cycles, and regulating ocean currents and weather patterns. Changes within the cryosphere, such as the melting of glaciers and sea ice, serve as key indicators of climate change. For instance, sea ice in the Arctic and Southern Oceans plays a crucial role in regulating heat exchange between the ocean and atmosphere. Additionally, permafrost, soil and rock that remains frozen for at least two consecutive years acts as a major carbon reservoir⁴. It stores substantial amounts of organic material, and if thawed, this material could significantly affect global greenhouse gas concentrations⁵. Given its great influence on climate and ecosystem stability, the cryosphere has emerged as a research priority, with efforts dedicated to understanding its response to anthropogenic changes.

Microplastic pollution has been detected across all ecosystems and the cryosphere is not an exception with increasing evidence that reveals its presence even in these remote places and extreme conditions. As a legacy of marine pollution research, microplastics (MP) are defined as tiny plastic fragments, fibers, and films with their largest dimension below 5 mm⁶. MPs can be either primary, manufactured specifically in that size, or secondary, which are products of the fragmentation of larger pieces subjected to environmental stressors. An example of the former are production pellets, which often attract attention due to leaks in maritime transport and have already reached Antarctic shorelines⁷. Unlike primary microplastics, secondary microplastics result from the degradation

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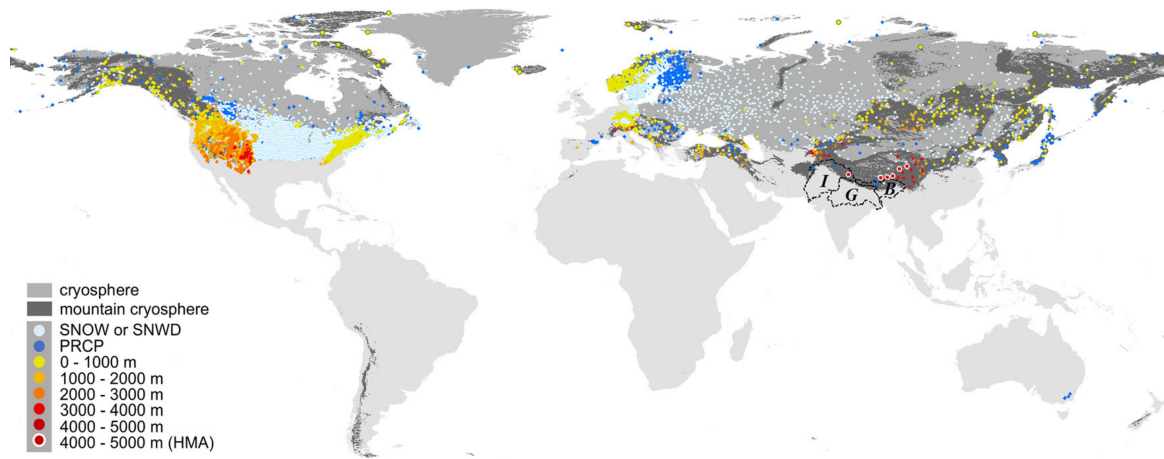


Figure 1: Global cryosphere marking as dots the weather stations in the Global Historical Climate Network. SNOW and SNWD refer to stations located in the lowland terrestrial cryosphere that report either the water content of snowfall or snow depth. PRCP indicates stations that reported precipitation but do not distinguish snow observations. I, G and B refer to the river basins of the Indus, Ganges, and Brahmaputra, respectively. (Reused from Pritchard, H. D. (2021). Global data gaps in our knowledge of the terrestrial cryosphere. *Frontiers in Climate*, 3, 689823, under a Creative Commons Attribution license).

of plastic waste, such as bottles, packaging, fishing nets, or other debris, breaking down into smaller pieces due to physical, chemical, or environmental factors like ultraviolet radiation, mechanical stress, or weathering. This process is facilitated by the loss of plastic additives that originally protected it from degradation.

The impact of plastic pollution pellets in remote regions can be significant. Due to their small size, they can easily be transported by ocean currents, often traveling vast distances to remote or previously pristine areas. Once in the environment, they can pose multiple risks to marine life, as they can be ingested by marine animals, including fish, seabirds, and marine mammals. This ingestion can lead to physical harm, digestive blockages, or poisoning, as the pellets can absorb toxic chemicals from the surrounding water⁸. Plastic pollution can be specially harmful for remote regions, affecting fragile ecosystems with persistent pollutants that may cause a long-term pollution issue, or transporting invasive species capable to alter the ecological equilibrium of highly sensitive areas. The following sections will present the latest findings in this emerging field and underline the need for further research into its global implications.

2. Cryosphere functions and importance

As indicated, the cryosphere is a vital component of Earth's climate system, not only because of its sensitivity to temperature changes, but also due to the essential services it provides (Figure 2). One of the

cryosphere's primary functions is regulating global temperatures through the reflection of solar radiation, a process known as the albedo. The cryosphere's high reflectivity helps maintain climate stability by reducing heat absorption at the Earth's surface. On average, only 12% of the Earth's surface is permanently covered by snow or ice; however, this percentage can increase to approximately 33% depending on seasonal variations⁹.

From a geophysical perspective, the contrast in albedo between different surface types underscores the cryosphere's significance. As an example, it has been estimated that the oceanic surface, that accounts for $3.6 \times 10^8 \text{ km}^2$ (72% of earth surface) has an albedo of approximately 0.07. In terms of absorption, this means that most of the incoming solar radiation is absorbed by open water surfaces. In contrast, frozen surfaces such as ice sheets, reflect a significant portion of solar energy back into the atmosphere. The albedo of snow and glaciers varies depending on factors like age, grain size, impurities (e.g., dust, soot), and moisture content. Typical values for fresh snow (very high albedo) are around 0.80 to 0.90, for aged snow between 0.40 and 0.70, and for glaciers between 0.30 to 0.50 depending on surface conditions with debris-covered or dirty ice reflecting less¹⁰. This reflective property acts like a mirror, contributing to local cooling and playing a crucial role in regulating global temperatures. Reductions in ice and snow cover lead to a reduction in planetary reflectivity, amplifying warming through a positive feedback loop. And there is clear evidence of this reduction year by year¹¹. In numbers it has been estimated the loss of even $102,000 \text{ km}^2$ per year in some places only

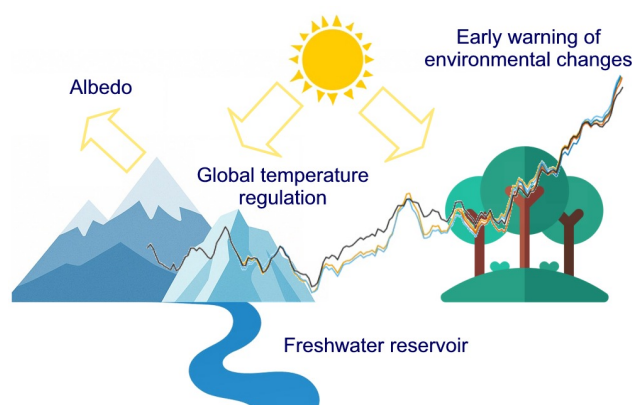


Figure 2: Importance of the cryosphere.

reduce by some gains that have been produced in the south hemisphere¹².

Beyond its essential role in regulating the Earth's climate, the solid cryosphere also serves as a vital source and long-term reservoir of freshwater. These frozen water stores supply drinking water, support agriculture, and sustain rivers and wetlands, particularly in regions where seasonal snowmelt and glacier runoff are critical for ecosystems and human populations downstream. As climate change continues to alter snow accumulation and melt patterns, understanding the cryosphere's contribution to freshwater supply becomes increasingly important for global water security. Antarctica alone holds approximately 75% of the world's available freshwater, stored in an estimated 27 million km³ of ice and snow¹³. This immense reservoir plays a key role in maintaining the global water balance, with far-reaching implications for sea level rise and freshwater availability. In addition to polar ice sheets, mountain snow cover represents a vital water source for numerous regions worldwide. Seasonal snowmelt from mountainous areas supplies freshwater to nearly one-sixth of the global population, sustaining ecosystems, agriculture, and human settlements¹.

This reliance on mountain snowmelt is particularly critical in arid and semi-arid regions, where glacial and seasonal snowpacks act as primary water sources. However, current climate models project near-surface warming due to increasing greenhouse gas concentrations, which is disrupting snow-dominated hydrological systems. As a result, peak runoff is shifting to earlier in the year, toward winter and early spring, reducing water availability during summer and autumn when demand is highest. In regions with limited storage capacity, this runoff is often lost to the oceans, threatening long-term water security for a significant portion of the global population¹⁴.

Polar regions are particularly vulnerable to climate change due to their heightened sensitivity to variations in temperature and atmospheric conditions. As

a result, these areas often act as early warning systems, providing valuable insights into broader global environmental shifts. A well-established trend is the significant loss of glacier mass, which has been extensively documented in various studies, such as the World Glacier Monitoring Service reports¹⁴. If the ice in these regions were to melt entirely, it could result in a rise in global sea levels by approximately 0.32 ± 0.08 meters, according to the available estimations¹⁶. This process, while gradual, could have far-reaching implications for coastal areas and low-lying regions around the world. Similarly, Arctic ice cover has also been subject to extensive monitoring for decades¹⁷. Over the past forty years, satellite data and observational records reveal a troubling loss of more than 2.6 million km² of ice. This dramatic reduction in ice mass has profound and far-reaching consequences, not only for the delicate ecosystems that depend on this ice but also for the global climate system, disrupting weather patterns and contributing to further temperature changes. In summary, the cryosphere acts as a critical observatory for detecting environmental shifts. Even small changes in temperature can trigger substantial alterations in ice extent, permafrost stability, and ocean circulation patterns. This heightened sensitivity, coupled with the cryosphere's essential role in regulating global climate processes, underscores its significance as a focal point for scientific research.

3. Occurrence of microplastics in the cryosphere

MPs have emerged as a global environmental concern, with their widespread distribution and potential ecological impacts thoroughly examined throughout this book. The cryosphere is no exception. MPs have been detected even in the most remote polar regions, underscoring the extent to which human-

derived pollution has permeated ecosystems across the planet. This broad dispersion raises pressing questions about the mechanisms driving their transport, their accumulation in ice and snow, and the ecological consequences of their eventual release into marine environments. Understanding the complexity of these processes demands an integrated approach that accounts for the dynamic interactions between atmospheric, oceanic, and cryosphere systems. This is currently the focus of active research, with a growing body of literature, now exceeding 300 scientific publications, dedicated to understanding the role of microplastics in cryosphere environments and the various pathways through which these particles reach the polar regions.

MPs are transported over vast distances via atmospheric currents, where wind borne particles are deposited onto ice and snow through precipitation or dry deposition. Similarly, ocean currents and riverine systems convey MPs from densely populated regions into remote polar waters, where they accumulate in surface layers and deep sea sediments. Once entrapped within the cryosphere, these particles can remain stored for decades before being released back into the environment as the ice melts, completing a cycle of sequestration and redistribution. This widespread dispersion raises urgent questions about the mechanisms driving their transport, their accumulation within ice and snow, and the ecological consequences following their eventual release into marine ecosystems. Addressing the complexity of these processes requires an integrated approach that considers the interplay between atmospheric, oceanic, and cryosphere dynamics.

3.1. Accumulation and storage in ice, snow, and glaciers

Table 1 presents a selection of recent findings on the occurrence of MPs in polar snow, sea ice, glaciers, marine sediments, as well as in the air and biota of these remote regions. Most studies revealed the prevalence of synthetic fibers such as polyester (PES), sometimes identified as poly (ethylene terephthalate), PET, although it is difficult to discriminate among polyesters using spectroscopic analysis, especially when dealing with environmental samples or weathered fibers. Fibers in general are difficult to assess. For example, the study carried out by Bergmann et al. in ice floes drifting in the Arctic and in different locations on Svalbard revealed considerable abundance of fibers the composition of which could not be determined. Instead, MPs from a variety of synthetic polymers including varnish of acrylic/polyurethane composition and several types of rubber (ethylene-propylene-diene rubber and nitrile butadiene rubber)¹⁸. Yu et

al. collected particles from surface snow in the Inner Mongolia Plateau, including a residential area, the vicinity of a thermal power plant, and suburban areas and found mostly fibers, as usual in most atmospheric deposition studied and with similar composition dominated by PES/PET and PE fibers¹⁹. In an study conducted on snow samples in the Canadian Arctic, the authors also found a high proportion (up to 100%) of fibers, many of which were cellulosic with evidence suggesting a non-natural origin²⁰. These types of materials are commonly found in atmospheric samples and include regenerated cellulose fibers (such as rayon/viscose, Tencel, or modal), which are generally considered semisynthetic. They also include other anthropogenic cellulosic pollutants, such as cellulose fibers incorporated into textiles, which often show signs of industrial processing, including non-natural colors or textures²¹.

The study by Jones-Williams et al., conducted at the Union and Schanz glaciers, as well as the South Pole, not only reported particle counts ranging from 73 to 3,099 MPs/L but also calculated mass concentrations using two-dimensional images²². The mass concentrations ranged from $3.6 \pm 2.3 \mu\text{g/L}$ (South Pole) to $32.2 \pm 31.0 \mu\text{g/L}$ (Union Glaciers), which is considered high, especially for such remote locations. Similarly, Rosso et al., using geometrical approximations, reported mass concentration of MPs in snow recovered from Svalbard archipelago between $24.7 \pm 7 \mu\text{g/L}$ and $206.5 \pm 20 \mu\text{g/L}$. Surprisingly, these concentrations are comparable and even much higher to those found in treated wastewater²³. High concentrations of nanoplastics (NPs) have also been reported using thermal desorption-mass spectrometry (Proton Transfer Reaction-Mass Spectrometry) in water samples extracted from a firn core in Greenland and a sea ice core in Antarctica. In these samples, Materić et al. identified several synthetic polymers and tire wear particles, with concentrations reaching up to $52.3 \mu\text{g/L}$ ²⁴.

3.2. Release and redistribution from melting ice

The cryosphere serves as a temporary reservoir for MPs, trapping them during the formation of sea ice, snow, and glaciers from atmospheric, marine, and fluvial sources. As indicated before, the available studies have confirmed that remote sea ice contains high MP concentrations. This occurs because, during sea ice formation, particles from the water column become trapped. Global warming accelerates glacier and sea ice melting, releasing previously sequestered MPs into adjacent ecosystems. This release is particularly marked in regions with strong seasonal melting, where MP liberation may coincide

Table 1. Selection of recent findings of MPs in the cryosphere.

Location	Occurrence, size and typology	Main polymers	Reference
Snow over ice floes and Svalbard islands	0 to 14,400 items/L (only fragments); 11-475 μm 80% $\leq$ 25 μm	Varnish (ACR, PU), rubber, EVA	Bergmann et al. ¹⁸
Mount Everest	30 items/L; fibers with 36-3,800 μm length, and 18-2,000 μm diameter	PES (56%, ACR (31%), PA (9%), and PP (5%)	Napper et al. ⁶⁴
Ross Island	29.4 $\pm$ 4.7 items/L; size 50-3510 μm (av. 606 μm ; fibers (61%, mostly blue and pink, av. size 850 μm); fragments all $\leq$ 1000 μm (av. 200 μm)	PET (41% of the polymers), ACR and copolymers, PVC, PA, PE and alkyd resins	Aves et al. ³⁵
Teide, Tenerife, Canary Islands, Spain	51 $\pm$ 72 items/L (99.3% fibers in pristine zone and 167 $\pm$ 104 items/L (95% fibers) in accessible areas; av. length 1188 μm and 892 μm , respectively	Cellulose (62.7%), PES (20.9%), ACR (6.3%)	Villanova-Solano et al. ⁶⁵
Hokkaido, Japan	150 to 4200 items/L; mostly < 100 μm ; deposition fragments dominant for fine particles (< 100 μm ; fibers in larger sizes (expressed as length)	Alkid resins, EVA, PE, and minor amounts of rubber, PA, PU, ACR, and PVC	Ohno and Iizuka ⁶⁶
Snow in Svalbard archipelago	535 $\pm$ 32 to 3400 $\pm$ 810 items/L; size 20-750 μm , mostly <100 μm	PTFE (most abundant), PS, PU, PA, PS	Rosso et al. ⁶⁷
Inner Mongolia Plateau, China	68 $\pm$ 10 to 199 $\pm$ 22 items/L; fibers 63.0-89.4%	PP, PET/PES, PVC	Yu et al. ¹⁹
Antarctica (Union Glacier, Schanz Glacier, and the South Pole)	73 to 3099 items/L (av. 817 $\pm$ 310); fragments 79%, fibers 21%; 95% < 50 μm	PA (55.5%), PET (12.3%), PE (10.9%), synthetic rubber (10.3%), and minor amounts of varnish (ACR, PU), PP, cellulose PVC and others	Jones-Williams et al. ⁶⁸
Arctic Canadian territory, glaciers and sea ice	5-30 items/L; fibers (95-100%; 0.1-17 mm (av. 1.45 mm)	PES/PET (8-22%), rayon (1-18%), cellulose (3-7%)	Yu et al. ²⁰
Arctic sea ice, between Russia, Greenland and Canada	38-234 items/m ³ of ice; fibers up to 2 mm length, fragments mostly in the 20-200 μm range	Rayon (54%, PES (21%), PA (16%), PP (3%), and PS, ACR and PE (2% each)	Obbard et al. ⁶⁹
Italian Alps	74.4 $\pm$ 28.3 items/g (fibers 65.2%, fragments 34.8%)	PES, PA, PE and PP	Ambrosini et al. ³⁰
Antarctica, ice melt in Byers Peninsula (Livingston Island)	0.95 (0.47-1.43) items/1000 m ³ ; fibers and films, 400-3546 μm (av. 1118 μm), and 10-1026 μm (av. 199 μm), respectively	PES, ACR and PTFE	González-Pleiter et al. ³⁶

Table 1 (cont.). Selection of recent findings of MPs in the cryosphere.

Location	Occurrence, size and typology	Main polymers	Reference
Vatnajökull ice cap, Iceland	4 plastic fragments 30-3000 µm, and two plastic fibers 1300 µm and 3000 µm	PU, PVC, PA	Stefánsson et al. ⁷⁰
Arctic and Antarctic	13.2 µg/L (Greenland) and 52.3 µg/L (Antarctic Sea ice); nanoplastics, <1 µm	PE, PP, PET, PVC and tyre wear particles	Materić et al. ²⁴
Arctic (coastal sea ice, Alaska)	38.4-485.5 items/L (av. 221 ± 140; mostly fragments 10-50 µm	PA (12.8%), PE (21.1%), PET (8.8%), PP (6.1%), PU (8.6%) and rubber (12.7%)	Zhang et al. ⁷¹
Northwestern Himalayas, (Kolahai and Thajwas glaciers, sediments)	1 item/L (Kolahai) to 151 items/L (Thajwas); 31-953 µm; fibers (62.1%, fragments (23.2%), beads and pellets (10.2%), films (4.5%)	PET (18%), PP (17%), PA (14.3%), PS (13%), PE (10.3%), PVC (8.6%), PEG (6.7%)	Dar and Gani ³¹
Antarctica Bransfield strait and bottom sediments)	sediments 0.09 items/g (0-0.2 items/g); water 7.0 items/L (0-16 items/L); mostly fibers	Cellulose, PET and PAN	De la Torre et al. ²⁷
Antarctica (Coastal areas and Ross Island)	87.2-283.6 items/g; mainly 20-50 µm	30 MP types identified, PET and PVC dominant	He et al. ⁷²
Arctic (marine sediments, Chukchi Sea)	674-1942 items/kg (av. 1145 ± 578); 14.7-4955 µm; fibers (92-98 %)	PE (42.6%), rayon (19.3%), PES (16.2%), celluloid, PA, PP, PVC, and ACR	Zhang et al. ⁷³
Arctic (sediments, Svalbard Air)	0.7-2.2 items/g; fibers predominant (75%); 0.04-4 mm (65% ≤ 1 mm)	PET/PES; PAN, PE, polyisobutylene	Lloyd-Jones et al. ²⁶
Antarctica (Victoria Land)	1.7 ± 1.1 items m ⁻² day ⁻¹ (deposition rate); fragments (95%); 53\$ in the 5-10 µm	PP (31%), PE (19%), PC (12%), PS, PES, PET (~6% each)	Illuminati et al. ²⁴
Antarctica (King George Island)	Deposition rate (passive samplers) not given; fibers (81.4%); lengths 50-2000 µm, width 10-30 µm. (90% length 50-1000 µm)	Cellulose, PES, PA, PAN, PE, PP	Rodríguez Pirani et al. ⁷⁴
Arctic (Greenland)	2433 ± 1235 items m ⁻² day ⁻¹ (deposition rate); fibers (81%), fragments (18%), films (1%)	Cellulose (45%), PP (10%)	Hamilton et al. ⁷⁵

with enhanced biological activity, increasing the risk of ingestion by marine and terrestrial organisms. In the Arctic, the decline in ice cover leads to significant MP discharge into oceans, rivers, and polar lakes, reintroducing them into global circulation. Once released, MPs are carried by ocean currents, wind, and rivers, spreading across ecosystems and contributing to widespread contamination, including in beach sediments and terrestrial habitats. It has been shown that MPs can be transported via major Arctic oceanic currents such as the Transpolar Drift and the Beaufort Gyre²⁵. Recent research emphasizes the importance of this redistribution in shaping pollution patterns in remote regions^{26,27}.

Furthermore, exposure to temperature fluctuations in cold environments may accelerate the fragmentation of microplastics. This process leads to the release of both adsorbed chemical compounds and the plastics' inherent constituents, while also generating smaller, more elusive nanoplastics (NPs), which may pose heightened toxicological risks due to their increased bioavailability and reactivity. NPs pose a unique challenge due to their extremely small size, which allows them to penetrate tissues more easily and potentially disrupt cellular processes²⁸. Moreover, their detection in environmental samples remains analytically demanding, leading to significant underestimations of their true concentration and impact in cryosphere and other ecosystems.

The phenomena of MP accumulation and release are not confined solely to polar environments. A similar dynamic occurs in continental glacier systems found in non-polar regions, where MPs are primarily deposited via atmospheric transport from urban and industrial areas²⁹. For instance, Ambrosini et al. found 74.4 MPs/kg of sediment in the supraglacial debris of the Forni Glacier (Italian Alps), equivalent to 131-162 million MPs in the entire glacier-levels comparable to those in marine and coastal sediments. These MPs likely originate from local human activities or are transported by wind³⁰. As these frozen reservoirs undergo seasonal melting, they release not only microplastics (MPs) but also associated contaminants into freshwater systems, potentially affecting aquifers and local water supplies, with long-term implications for human health.

3.3. Transport mechanisms: atmospheric, oceanic, and riverine pathways

The origin of microplastics (MPs) in remote environments has long been debated, with various transport pathways proposed for their delivery to the cryosphere. The atmosphere is considered a primary conduit, as MPs, due to their small size and low density, can remain airborne for extended periods and

travel thousands of kilometers before being deposited through precipitation or dry deposition. This mechanism helps explain the presence of small particles and fibers with chemical compositions inconsistent with local sources³¹. Several studies have emphasized precipitation as a key deposition mechanism in polar regions^{32,33}. Illuminati et al. measured plastic deposition in Antarctica using passive samplers and HYSPLIT back-trajectory models, estimating a deposition rate of 1.7 ± 1.1 items $m^{-2} day^{-1}$. Their analysis indicated that air masses reaching Larsen Glacier and Tourmaline Plateau likely originated from the Antarctic Plateau³⁴.

In addition to long-range atmospheric transport, local sources have also been documented. Aves et al. reported an average of 29 items/L in snow samples from Ross Island, mostly PET fibers consistent with clothing and equipment used at nearby research stations³⁵. Similarly, González-Pleiter et al. identified synthetic fibers (PES and ACR) and PTFE films in ice melt from an Antarctic Specially Protected Area in Byers Peninsula, further supporting the presence of locally sourced MPs³⁶.

Beyond atmospheric pathways, ocean currents and riverine systems also play a significant role in MP transport. Rivers carry large amounts of plastic pollution from urban and industrialized areas into the ocean, where MPs are redistributed globally. High concentrations of MPs have been documented in Arctic waters, attributed to both oceanic circulation and local inputs, with measurements ranging from thousands of particles per liter to substantial fiber counts. Once in marine environments, MPs may remain suspended in the water column, settle into deep-sea sediments, or become temporarily trapped in sea ice and glacial systems, only to be re-released during seasonal melting cycles.

4. Fate and impact of microplastics in the cryosphere

4.1. Physical effects

The presence of MPs in the cryosphere produces not only the expected chemical damages but also significant physical alterations. One key example is the reduction of albedo, a phenomenon related to MPs confirmed in various compartments including ice and snow^{37,38}. Emerging sources, such as tire wear, add heavy metals and other chemicals while generating particles that absorb solar radiation, thereby further reducing the albedo of ice and snow (Figure 3). This reduced surface reflectivity increases heat absorption in affected areas and accelerates melting processes³⁹. Consequently, it has been suggested that

MP particles can contribute to glacier retreat and raise concerns about long-term glacier mass loss and sea-level rise under ongoing climate change³¹.

Beyond albedo reduction, MPs may also affect the internal structure of ice and snow by modifying their permeability, thermal conductivity, density, and mechanical stability. More specifically, the presence of MPs could affect the permafrost soil layer by reducing its permeability, which may lead to greater water retention and increased evaporation over time. Increased freeze-thaw cycles may cause fine particles to aggregate altering soil structure and promoting the clumping of soil particles and MPs in a feed-back cycle⁴⁰.

The scientific community is actively investigating these impacts to determine the extent to which MPs can alter these characteristics, which, over time, could lead to shifts in global climate patterns and the dynamics of polar ecosystems. It has been shown that MPs can act as nucleation sites for hail or snow formation, as evidenced by the presence of both natural and synthetic fibers in the cores of hailstones, suggesting that MPs could be a significant factor in hail growth⁴¹. Although reports of MPs in hailstones are rare, their plastic content is expected to resemble that found in snow⁴².

4.2. Occurrence of microplastics in cryosphere biota

Some recent articles report the presence of MPs in species from different trophic levels in polar environments (Table 2). Moore et al. studied the gastrointestinal tracts of seven beluga whales (*Delphinapterus leucas*) and found that every individual contained between 18 and 147 MPs, with a variety of compositions, predominantly PES fibers⁴³. Another study reported the presence of plastics in the stomachs of marine mammals (spotted seals, *Phoca largha*) hunted by native communities in the Chukchi and Beaufort Seas of the Pacific Arctic. Although no spectroscopic characterization was performed, visual analysis revealed the presence of plastic items in all specimens⁴⁴. It has also been shown that the stomach of Antarctic krill (*Euphausia superba*) contains MPs, small enough to make determinations difficult but that could have been quantified in the range of 0 to 0.4 items/individual^{45,46}. The presence of plastic in Antarctic krill provides evidence of plastic entering the trophic chain at a low level, making it available for transfer to higher predators and illustrating the potential for bioaccumulation and ecosystem-wide effects.

Several fish and bird species from Arctic and Antarctic environments have also been shown to harbour plastics. As in the case of spotted seals, a consid-

erable variety of plastics, mostly fibers and increasing in older fish, were found in most of the captured specimens of Alaska pollock (*Gadus chalcogrammus*), indicating the prevalence of MPs in the Bering Sea⁴⁷. The northern fulmar (*Fulmarus glacialis*) is a classic indicator species for monitoring plastic pollution, as it is known to ingest large quantities of plastics. Collart et al. investigated the presence of plastics in the stomachs of fulmar fledglings from Kongsfjorden in the Svalbard archipelago. They found that all birds had ingested plastic, with an average of 46 items per bird (items > 1 mm), including 14 industrial pellets, representing a mass of 0.31 ± 0.24 g per bird⁴⁸. Similar findings have been reported elsewhere, with some specimens (3.4%) having more than 0.1 g of plastic in their stomachs. This is close to the OSPAR Ecological Quality Objective (EcoQO) target for plastic ingestion in northern fulmars, which recommends that no more than 10% of individuals should have more than 0.1 g of plastic in their stomachs⁴⁹.

4.3. Potential biological impacts

Microplastics not only accumulate in the cryosphere but also act as vectors for other contaminants, highlighting the significant risks they pose. This concept has been well documented in other compartments and is increasingly explored in cryosphere environments^{50–52}. Studies have revealed that MPs in snow and ice frequently contain traces of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorine pesticides^{53,54}. Furthermore, it is a well-known fact that MPs can adsorb pharmaceuticals, antibiotics, and other chemicals, thereby increasing their potential to harm polar flora and fauna when ingested and transferred along the food chain. Emerging anthropogenic threats, such as tire wear and pandemic related waste, further intensify MP pollution in these fragile environments adding more contaminants to the mixture¹².

Generally, microplastics degrade more slowly in polar environments compared to temperate or tropical regions, primarily due to the combined effects of low temperature and low solar irradiation. Due to the low temperature, degradation processes like photooxidation, hydrolysis, and thermal breakdown proceed at a reduced rate. Reduced solar irradiation during dark periods and the smaller angle of solar incidence limit ultraviolet exposure, which is a key driver of photodegradation. Additionally, cold temperatures slow down microbial activity involved in plastic breakdown. Cold-adapted microbes may be less effective at breaking down plastics than microbes in warmer environments, and microbial communities capable of biodegrading plastics are generally less

Table 2. Evidence of MP contamination in cryosphere biota.

Location	Species	Occurrence, size and typology	Polymers	Reference
Beaufort Sea	Beluga whale (<i>Delphinapterus leucas</i>)	18-147 items/specimen (av. 97 ± 42); fibers, 49%; mostly MPs <2 mm	PET, PE, PS, PP, ACR, PA, PVC and rubber	Moore et al. ⁴³
Teno River draining into the Barents Sea	Alaska pollock (<i>Gadus chalcogrammus</i>)	0-14 items/specimen (av. 2.7 ± 2.8 or 0.06 ± 0.05 items/g); positive in 85% of the specimens; fibers 80.5%; 100-500 μ m most abundant category	Rayon (56.7%), PE (15.3%), PET (13.5%) and minor amounts of PES, PVC, PP, PC and PA	Ding et al. ⁴⁷
Ross Sea	Emerald rockcod (<i>Trematomus bernacchii</i>)	1.4 ± 0.7 items/specimen; positive 70% percent of the specimens; all fibers	PES (9 items), PET (3 items), PP (2 items)	Micalizzi et al. ⁷⁶
Teno River, North Lapland	European grayling (<i>Thymallus thymallus</i>)	13 plastics in 50 percent of fish; 1.3 ± 1.7 items/specimen (range: 0-5); > 90% MPs; fragments 62%; fibers 23%; av. length 1.06 ± 2.27 mm	PE (75%) and PVC (25%)	Pedà et al. ⁷⁷
Svalbard Islands	Northern fulmar (<i>Fullmaurs glacialis</i>)	35 items/bird (median), range 8-139; fragments ≥ 1 mm	PE (65%) and PP (27%), PS, PA, ACR, PET, PU and rubber	Collard et al. ⁴⁸
Southern Ocean near the Antarctic Peninsula	Antarctic krill (<i>Euphausia superba</i>)	0.17-0.27 items/specimen, av. 0.23 ± 0.44 ; 22.7% of specimens had plastic; mostly >0.25 mm	PP, PS, PA and PVC	Feng et al. ⁴⁵
Southern Ocean near the Antarctic Peninsula	Antarctic krill (<i>Euphausia superba</i>)	0 -0.4 items/specimen	Rubber, chlorinated PE, PA, varnish (PU / ACR) and others	Primpke et al. ⁴⁶
Baffin Island, Nunavut, Canada	Northern fulmar (<i>Fullmaurs glacialis</i>)	0–0.15 g/bird, with plastic in 62% of the specimens; fragments ≤ 1 mm	Visual identification; no spectroscopic analysis	Hanifen et al. ⁷⁸
Bering and Chukchi seas	Spotted seal (<i>Phoca largha</i>)	97% presence in stomachs; fibers 99.5%; 190 items <5 mm (90%)	Visual identification; no spectroscopic analysis	Sletten et al. ⁴⁴

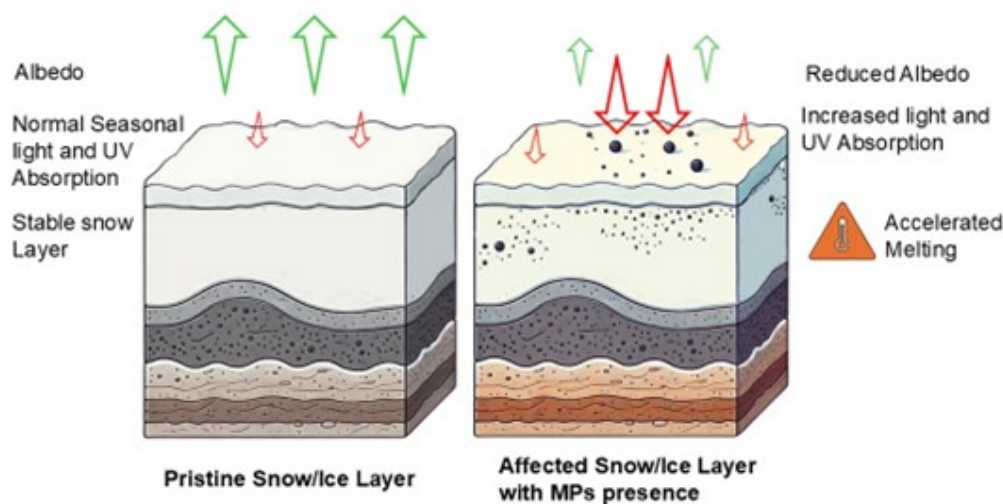


Figure 3: Schematic comparison of snow/ice layers with and without microplastic contamination. The pristine snow (left) exhibits high albedo, reflecting most incoming solar radiation, while the contaminated snow (right) shows reduced albedo due to the presence of microplastics, leading to increased absorption of solar and UV radiation and contributing to accelerated surface melting.

diverse and active in polar regions⁵⁵. Accordingly, cryosphere environments significantly slow down the degradation of chemical pollutants contained in plastics, thereby preserving these substances. In essence, the freezing conditions ‘pause’ the degradation of these sensitive contaminants. As a result, the cryosphere becomes a long-term reservoir for such pollutants, and its eventual melting can release these accumulated contaminants into downstream ecosystems in a perfect condition. A unique characteristic of these environments not found elsewhere.

Microplastics provide a stable surface for the attachment of harmful microorganisms and algae⁵⁶. When these particles are ingested by marine organisms, they not only serve as physical contaminants but also carry harmful biological agents that might otherwise not be as easily absorbed by aquatic species. This is particularly concerning because the ability of MPs to transport multiple pollutants makes them dangerous environmental contaminants in addition to their direct physical impacts. With the warming of polar seas, a double concern arises, not only do the temperatures increase the toxicity of algal blooms, but they also lead to the movement of toxic substances to areas previously less affected⁵⁷. This can expand the geographic range of harmful toxins and impact previously stable ecosystems. Warming can also increase the frequency and intensity of these blooms, escalating the chances of large-scale ecological disruptions, particularly in the Arctic and Antarctic ecosystems, which are ecologically sensitive. This process may contribute to diseases and disrupt trophic balances within marine food webs, ultimately impacting ecosystem health⁵⁸.

The bioaccumulation of MPs in the cryosphere

biota is a growing concern. MPs, along with the contaminants they adsorb, tend to accumulate in basal trophic levels such as zooplankton and are transferred through the food web via predation. This process can lead to biomagnification, resulting in higher concentrations of pollutants in apex predators like marine mammals and seabirds. Combined with the pressures of climate change and habitat loss, these plastic-related toxins pose a significant risk to the long-term stability and resilience of polar ecosystems. Trophic transfer of MPs has been demonstrated in fish^{59,60}, and similar findings have been observed in Adélie penguins^{61,62}. However, there is insufficient evidence of MPs translocating to internal tissues like the liver or muscles. In addition, reports of MP ingestion by seals and whales suggest plastic pollution reaches higher trophic levels⁴⁴. Although recent investigations found no MPs in the scats of Antarctic fur seals, the potential for bioaccumulation remains a concern, given the presence of MPs in organisms throughout the trophic chain, from zooplankton and fish to seabirds and marine mammals⁶³.

Other effects remain poorly understood. MPs may disrupt the ecological balance of microorganisms in the cryosphere, particularly photosynthetic organisms such as microalgae and cyanobacteria, which form the base of the food chain, as well as the primary consumers that depend on them. Higher trophic levels, such as polar bears, accumulate persistent non-polar pollutants, including perfluoroalkyl substances, polychlorinated biphenyls, and organochlorine pesticides, which have occasionally been linked to plastic pollution. However, the connection between plastics and the accumulation of these pollutants in lipid tissues has not yet been fully established. The inter-

nalization of plastic fragments into tissues is highly controversial and would likely be relevant only for sub-micron particles (NPs), or at most, particles in the low micrometer range. However, current analytical capabilities for detecting such particles in tissues remain very limited.

5. Final remarks and outlook

MPs have been detected in all cryosphere environments. Findings consistently show that fibers are the predominant shape, which aligns with their greater mobility under the influence of marine currents and winds. The composition of MPs indicates that they originate either from local human activities or are transported over long distances from densely populated areas.

In cold environments, MPs, as well as the chemical pollutants they contain as additives or sorbed substances, degrade very slowly. This persistence leads to their accumulation and raises concerns about their eventual release into rivers and oceans, where they could exacerbate existing pollution. The threat is particularly significant in the context of global warming, which is expected to accelerate the melting of ice caps, permafrost, and glaciers.

MPs may also reduce the albedo (reflectivity) of icy surfaces, diminishing their ability to reflect sunlight and thereby accelerating melting. This phenomenon affects not only polar regions but also glaciers in temperate climates. The resulting increase in melt-water could disrupt ocean circulation and destabilize thermohaline currents, potentially impacting climate systems on a global scale.

Within the cryosphere, MPs interact with a wide range of organisms, from invertebrates and fish to birds and large mammals. Over time, this exposure may lead to bioaccumulation and biomagnification, as well as adverse effects stemming from both the particles themselves and the toxic chemicals they carry. Although plastic exposure has been linked to metabolic disruption, impaired nutrient absorption, oxidative stress, and endocrine interference, the risks associated with long-term exposure to environmentally relevant concentrations remain largely unknown.

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