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Current status and future perspectives of microplastic pollution in typical cryospheric regions

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ABSTRACT

The cryosphere is the term used to describe the frozen areas of the Earth, including all forms of snow and ice, which are primarily influenced by anthropogenic pollutants through atmospheric transport. In this review, we described the current status of newly emergent pollutant-microplastics-in the snow and ice of typical cryospheric regions (e.g., Arctic, Antarctic, Alps, Tibetan Plateau, and Andes), discussed their transport pathways, and provided perspectives for future research. A brief summary of snow and ice sampling, pretreatment, and the identification of microplastics in cryospheric regions suggested that standard procedures were inadequate and urgently required improvement. Microplastics were widely distributed in snow and ice across the typical cryospheric regions, indicating the ubiquitous distribution of microplastics in such environments. However, the abundance, size distribution, shape, and polymer composition of the microplastics in snow and ice showed significant differences. Sea ice was especially important for the temporal storage, transport, and release of microplastics in the Arctic and Antarctic. Microplastics in land snow cover and mountain glaciers emphasized the importance of atmospheric transport in the transferal of microplastics to cryospheric regions. In particular, the non-polar cryospheric regions (e.g., Tibetan Plateau, Andes, or Alps) were highlighted as important receptors of mid-latitude emissions of microplastics, which might indicate a future climatic risk considering the ability of microplastics to absorb radiation and accelerate the melting of snow. Microplastics retrieved from mountain glacier ice cores may also provide new insights into the historical variations of anthropogenic pollutants. The potential impact of microplastics in snow and ice on the carbon cycle and the climatic risk needs to be further addressed in the future.

1. Introduction

The Earth's cryosphere comprises different forms of snow and ice (Barry and Gan, 2011; Qin et al., 2018; Fountain et al., 2012) that are usually located in high-latitude (e.g., the Arctic and Antarctica) and high-altitude areas (e.g., the Tibetan Plateau (also known as the Third Pole), Alps, and Andes). In typical cryospheric regions, glaciers, snow cover, and sea ice provide effective and distinctive matrices with which to study anthropogenic pollutants (e.g., black carbon (BC), mercury, persistent organic pollutants) and their potential environmental impacts (Kang et al., 2019; Skiles et al., 2019; Wang et al., 2017). The warming climate has resulted in rapid shrinkage of the cryosphere (e.g., glacier

Abbreviations: Polymers, Abbreviations; acrylonitrile butadiene styrene, ABS; ethylene vinyl acetate, EVA; polyamide, PA, also called nylon; polycarbonate, PC; polylactic acid, PCA; polycaprolactone, PCL; polychloro-prene, PCP; polyethylene, PE; polyethylene chlorinated, PE-C; polyester, PES; polyethylene oxidized, PE-O; Polyethylene terephthalate, PET; polyimide, PI; polylactide acid, PLA; methyl methacrylate, PMMA; polyolefin, PO; polyacetal, POM; polypropylene, PP; propylene carbonate, PPC; polystyrene, PS; polysulfone, PSF; polytetrafluoroethylene, PTFE; Polyurethane, PU; polyvinyl chloride, PVC.

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and ice sheet retreat, snow cover decline, permafrost thaw, and a decrease in the extent of the Arctic sea ice) (Huss and Hock, 2018; IPCC, 2019; Yao et al., 2012; Mercier, 2021), which could result in the release of pollutants from the frozen state, leading to potential environmental risks (Chen et al., 2019a; Mu et al., 2020; Miner et al., 2018; Obbard et al., 2014).

As an emerging and widespread anthropogenic pollutant, microplastics, first reported by Thompson (2004), are becoming an invisible environmental and human health threat that is significantly affecting marine and terrestrial ecosystems globally (Bergmann et al., 2015; de Souza Machado et al., 2017; Hale et al., 2020; Hartmann et al., 2019; Rilling and Lehmann, 2020; Wright et al., 2020a; Zeng, 2018; Zhou et al., 2021). Since the 1950s, plastics have been increasingly commercialized and are ubiquitous in our lives because of their versatility, stability, light weight, and low production costs (Carpenter and Smith, 1972). However, since the 1970s, plastic pollution has garnered significant interest from the public, scientists, and policymakers (PlasticsEurope, 2019). The global plastic production reached almost 360 million tons in 2018, with an annual growth rate of ~8% over the period 1950–2015 (Borrelle et al., 2017; Geyer et al., 2017; PlasticsEurope, 2019), and an estimated future production that is expected to increase to 1.1 billion tons by 2050 (Geyer, 2020). Multiple factors are involved in the microplastic cycle, influencing the fate, transport, and impact of microplastics in the Earth's ecosystems (Allen et al., 2019, 2020; Bakir et al., 2012; Bank and Hansson, 2019; Brahney et al., 2020; Bergmann et al., 2019; Evangeliou et al., 2020; Galloway et al., 2021; Horton and Dixon, 2018; Liu et al., 2020; Mai et al., 2020; Wright et al., 2020b; Yang et al., 2015; Zhang et al., 2020a). These impacts include characteristics such as the sorption of chemicals, the ecocorona, biofilm growth, photo- or mechanical degradation or fragmentation, microbial degradation of plastic debris, and environmental conditions (such as precipitation and air or water currents).

Recent studies have shown that microplastics can reach remote and pristine areas in which there are very few local sources of plastic, via atmospheric transport (Allen et al., 2019; Brahney et al., 2020; Stefánsson et al., 2021). Microplastics have also been reported in the snow and ice from typical cryospheric regions with little direct anthropogenic input, such as in the Arctic, Antarctic, Alps, and Mt. Everest (Bergmann et al., 2019; González-Pleiter et al., 2020; Napper et al., 2020), further highlighting the fact that plastic pollution has reached even the most remote areas of the Earth (Bergmann et al., 2019; Zhang et al., 2021). Simulation of global emissions indicated that deposited road microplastics (such as that from brake and tire wear) were concentrated in eastern US, northern Europe, and urbanized areas of eastern China, the Middle East, and Latin America (Evangeliou et al., 2020) (Fig. S1a and b). It was estimated that vehicle tire wear contributed approximately 5–10% of the particulate matter ($PM_{2.5}$) that reached the global ocean and 3–7% of that found in urban air (Kole et al., 2017). Simulations revealed similar spatial distributions of atmospheric BC and PM_{10} particles, with high emissions of BC and PM_{10} in East/South Asia, eastern America, and western Europe (EDGAR, https://data.jrc.ec.europa.eu/collection/edgar) (Fig. S1c-d). Research conducted in coastal areas has indicated that the high concentrations of suspended atmospheric microplastics in terrestrial inflowing air masses were an important source of microplastic pollution in the oceans (Liu et al., 2019; Szewc et al., 2021). A recent study revealed that atmospheric microplastics in the western US were derived mainly from road dust, the ocean, and agricultural soil dust based on the atmospheric transport model (Brahney et al., 2020). These results revealed that the atmospheric transport of microplastics was an important pathway by which microplastics reach coastal ocean areas or Arctic regions, providing a new perspective for understanding the plastic cycle (Bergmann et al., 2019; Brahney et al., 2020; Evangeliou et al., 2020; Liu et al., 2020).

The source, transport, and potential impact of microplastics in marine and freshwater environments have been extensively studied and reviewed (Bergmann et al., 2015; Wagner and Lambert, 2018; Zeng, 2018). The importance of the atmospheric transport of microplastics to remote areas has also been highlighted (Allen et al., 2019; Bergmann et al., 2019; Evangeliou et al., 2020; Zhang et al., 2019, 2021), although the source, transport, and impacts have been less intensively investigated. Recent research has highlighted the presence of microplastics in the snow and ice of remote cryospheric regions, with focus on the distribution, abundance, sources, and transport of microplastics in snow and ice (Bergmann et al., 2019; Parolini et al., 2021; Stefánsson et al., 2021; Zhang et al., 2021). However, in-depth exploration of the occurrence, behavior, and fate of microplastics in the cryosphere lacks comprehensive evaluation compared to that conducted in the marine or atmospheric environments (Brahney et al., 2020; Hale et al., 2020; Lima et al., 2021; Zeng, 2018). This review is a synthesis of the literature that focuses on the presence of microplastics in the snow and ice of typical cryospheric regions that are far from human activities, including the Arctic, Antarctic, High Mountain Asia (Tibetan Plateau), the Alps, Rocky Mountains, and the Andes, and is an attempt to characterize the current knowledge of microplastics in the cryosphere (Fig. 1 and Text S1). The features of microplastics are discussed along with the impact of microplastics, transport, and deposition from source to sink. We will also explore the study of microplastics in typical cryospheric regions from the perspective of future research.

2. Brief summary of microplastic identification in snow and ice

2.1. Sampling and pretreatment of snow and ice

The protocols that are used in microplastic studies include sampling, pretreatment, and analysis (Table 1). Studies in the remote cryospheric regions are still limited, and the protocols used for collecting and pretreating snow and ice before the measurement of microplastics is diverse and unstandardized. Surface snow samples are usually retrieved with a steel spoon and placed into pre-cleaned glass or metal containers by operators that are dressed in 100% cotton clothes, and sampling is performed downwind (Bergmann et al., 2019; Parolini et al., 2021) (Table 1). Snow samples have been collected from the surface of the Andes glacier before being placed into pre-cleaned plastic bags, washed three times with Milli-Q water (18 MΩ cm), and dried at room temperature (Cabrera et al., 2020). Sea ice cores are generally drilled with a stainless steel corer (usually 9 cm in diameter) and transported into plastic bags, with sections from the exterior surface of sea ice cores removed using a ceramic knife or razor blades, before the interior sections are melted and filtered for analysis (Table 1).

To concentrate microplastics from samples, diverse types of filters are used in sample preparation prior to analysis, following a range of different measurement methods (Table 1). Aluminum oxide filters, nitrocellulose membranes, glass microfiber filters, or PTFE filters with different pore size (0.2 μm, 0.45 μm, 0.7 μm, or 1 μm) are usually used. Saturated sodium chloride (NaCl) solutions are generally used for density separation of microplastics from snow and ice samples, and H_2O_2 solutions have been used to remove the organic matter and biofilms that are attached to the plastic surface (Ambrosini et al., 2019; Parolini et al., 2021; Peeken et al., 2018). Density separation is a particularly effective way to separate synthetic polymers from supraglacial debris or cryoconite sediments (Ambrosini et al., 2019).

A means of ensuring that samples are uncontaminated is also required. Parallel samples are generally used to evaluate the sampling procedure in the field. It should be noted that obtaining blanks in the process of field sampling is difficult. Therefore, representative blank samples are generally produced in the laboratory by filling PVC and PE containers or similar glass jars with Milli-Q water or tap water (Bergmann et al., 2019) and the resulting blanks are processed in the same way as the snow samples.

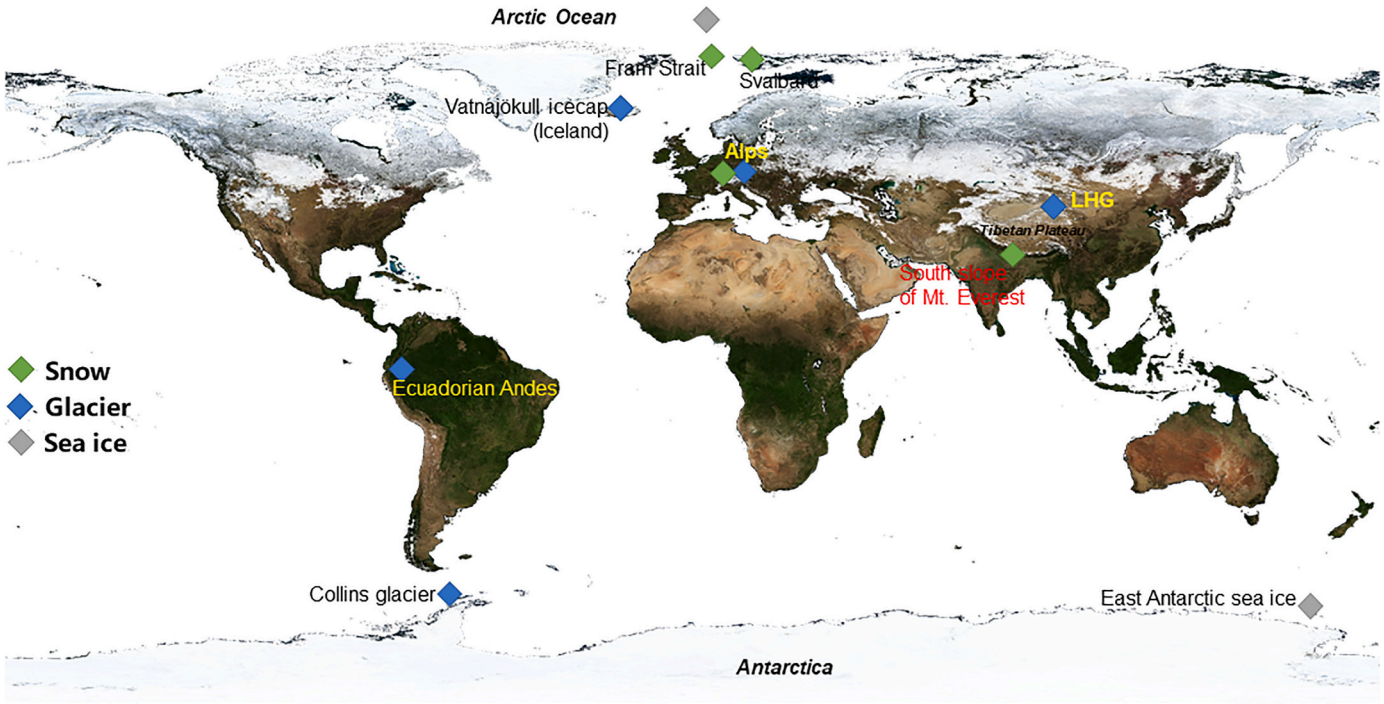

Fig. 1. Microplastic studies in the snow and ice in the typical cryospheric regions. Note: LHG-Laohugou glacier No.12 in Qilian Mountains. Detailed information about the related studies is given in Table 3.

2.2. Identification

Several methods have been developed to identify microplastics in the environment and have been reviewed in previous studies (Hendrickson et al., 2018; Mai et al., 2018; Wagner and Lambert, 2018; Zhang et al., 2020a) (Table 2). The identification of microplastics in snow and ice is similar to that of microplastics in other environmental matrices (Table 1). Current state-of-the-art methods described in the literature include spectroscopic techniques such as Fourier transform infrared (FTIR) and Raman spectroscopy (Araujo et al., 2018; Käppler et al., 2018; Primpke et al., 2018; Zhang et al., 2020a). The benefits of these methods are that they are non-destructive, require a minimal amount of sample, and provide information on the chemical composition (type of plastic polymer), shape, and size distribution of microplastic particles. Micro-Raman has been shown to be effective in the characterization of microplastics down to 1 μm in size (Huppertsberg and Knepper, 2018; Käppler et al., 2016; Anger et al., 2018; Araujo et al., 2018) with published findings reporting samples as small as ~2 μm discovered in environmental samples (Wright et al., 2020a, 2020b; Allen et al., 2020). Raman spectroscopy can be affected by additives such as pigments in the plastic or biofilms on the particle surfaces (Anger et al., 2018). Furthermore, BC or dust particles that are attached to the plastic may absorb near-complete infrared light or laser energy, potentially resulting in underestimation or bias in the microplastic results (Wagner et al., 2018).

Recently, the rapid, automated analysis of microplastics via laser direct infrared spectroscopy (LDIR) has been developed, which has the same manual limit of detection as FITR (10 μm), but can resolve particles down to 6 μm in size and identify particles as small as 3 μm using Agilent Technologies Clarity software and ATR analysis (Agilent Technologies, 2019; Scircle et al., 2020). This method can eliminate the influence of manipulative errors with the use of particle finder software and carry out total particle analysis without the mistakes in particle selection that are often associated with human operation. LDIR also has high efficiency and operability, laying a foundation for the standardization of microplastic testing methods.

Methods of thermal extraction desorption (TED) or pyrolysis (Pyr) coupled with mass spectrometry (GC–MS) have also been proposed and implemented to identify plastic particles (Table 2) such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) (Käppler et al., 2018; Zhang et al., 2020b). Thermal desorption-proton transfer reaction-mass spectrometry (TD-PTR-MS) can be used to analyze various complex organic mixtures in the environment, combining high sensitivity with high mass resolution (>1 ng mL^{-1} for most types of polymer) (Materić et al., 2020). This method can identify the chemicals from which polymers are constructed at the level of the chemical formula, rather than utilizing a vibrational fingerprint such as that used in FTIR and Raman methods. The high sensitivity of this technique provides quantitative information on low-concentration organics and shows the highest sensitivity and resolution for identifying environmental microplastics so far (Materić et al., 2020). Matrix-assisted laser desorption/ionization-time-of-flight mass spectrometry (MALDI-TOF MS) is a powerful technique that can be used in the ionization and detection of intact molecules with high molecular weights (Badía et al., 2011; Lin et al., 2020), and can also be used to identify nano- and microplastics (Wu et al., 2020). Meanwhile, TD-PTR-MS or MALDI-TOF MS measurements can report the mass concentrations of polymers (Ambrosini et al., 2019) that may be affecting the Earth's carbon cycle as emergent components (Stubbins et al., 2021).

All the above methods involve the thermal desorption analysis of microplastics and are destructive to the plastic particles. To date, analyzing the full range of microplastics in terms of size (down to 1 μm and smaller) and composition remains a challenge, both in terms of quantitative characterization of particles (particle counts) and mass.

3. Features of microplastics in the cryospheric regions

3.1. Size distributions

Studies of microplastics in snow and ice have so far focused on the Arctic, Alps, Tibetan Plateau, Andes, and Antarctica, the typical cryospheric regions (Fig. 1). As shown in Table 3 and Fig. 2, the size and abundance of microplastics detected in snow and ice varied greatly in different regions. However, it should be noted that the size distribution

Table 1
Summary of the main methodologies on microplastics studied in snow and ice in the typical cryospheric regions.

Study areas	Sample types	Sampling methods/ tools/storage containers	Filtration	Density separation	Organic matter removing	Measurement and reporting	References
Arctic and Europe	Surface snow	Surface snow was sampled with a prerinsed mug, a steel spoon, or a soup ladle and transferred into containers made of PVC, PE, or glass jars.	A specific volume of the sample, ranging between 0.2 and 100% of the calculated volume for full area coverage, was filtered onto aluminum oxide filters (Ø = 25 mm; pore size = 0.2 μm; Anodisc, Whatman, Germany).	N/A	N/A	FTIR microscope Abundance (item L-1), size (≥11 μm), composition, shapes	Bergmann et al., 2019
Vatnajökull ice cap in southeast Iceland	Snow cores	Two snow cores (3 m long) were drilled by a PICO hand coring drill/ auger. The cores were carefully packed into aluminum foil, and were kept frozen until they were melted in the laboratory.	The samples melted and filled into clean glass containers were filtered into three size fractions: >800 μm, 800–180 μm, and 180–50 μm by using stainless steel mesh with 150 mm diameter.	N/A	N/A	Microscope+μRaman spectroscopy Abundance (items per sample), composition, shapes	Stefánsson et al., 2021
Arctic	Sea ice	The 1 m to 3.5 m Sea ice cores were drilled. The exterior sections were removed with razor blades, and then the interior sections were melted directly in pre-cleaned glass bottles	The meltwater were filtered through Millipore nitrocellulose membranes (pore size = 0.22 μm).	N/A	N/A	Microscope+FTIR Abundance, size, colors, shapes, composition	Obbard et al., 2014
Arctic	Sea ice	Snow was removed before drilling the sea ice cores. Nitrile gloves were used. The cores were drilled with a Kovacs 9 cm diameter corer, and were transported into plastic bags (polyethylene tube films and stored at −20 °C. Ice cores were cut individually into horizons ranging from 10 to 35 cm using a bone saw. To exclude sample contamination from sampling the surface of the ice core horizon was removed by a stainless steel grater.	The remaining ice cores were melted in glass preserving jars at room temperature and then concentrated onto aluminum oxide filters (Ø = 47 mm; pore size 0.2 = μm; Anodisc, Whatman, Germany).	N/A	35% H_2O_2	Imaging FTIR Abundance (item L^{-1}), Size (≥11 μm), composition (17 polymers)	Peeken et al., 2018
Baltic Sea	Sea ice	Sea ice cores were sampled using a ceramic knife and a Kovacs Mark II coring system with internal diameter 9 cm; Ice samples were wrapped in aluminum foil to avoid cross-contamination and kept frozen until further analysis.	Sea ice cores were cut into 2 to 4 cm sections in a cold room laboratory (−20 °C), scraped with a ceramic knife, and melted at room temperature in glass beakers; the meltwater were filtered using glass microfiber filters pore size = 0.7 μm; Whatman GF/F,) to remain particles.	N/A	N/A	Camera +FTIR Abundance (item L^{-1}), size (>63 μm)	Geilfus et al., 2019
Arctic	Sea ice	Pieces of free-floating sea ice was sampled directly using a metal boat book and a green plastic basket connected to a white rope, and were immediately placed in pre-rinsed (three times with filtered seawater, GF/F, 0.7 μm, Whatman) plastic buckets (white or	The melted sea ice were filtered using 10 μm filters (Nucleopore, Track-Etch Membrane, Polycarbonate, Whatman) and glass microfiber filter (pore size = 0.7 μm; Whatman GF/F).	N/A	N/A	Stereomicroscope+FTIR Abundance (item L^{-1}), size (>50 μm), colors, shapes, composition	Von Friesen et al., 2020

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Table 1 (*continued*)

Study areas	Sample types	Sampling methods/ tools/storage containers	Filtration	Density separation	Organic matter removing	Measurement and reporting	References
		dark blue) and left to thaw covered in clean aluminum foil in the onboard laboratory.					
Arctic	Sea ice	Overlying snow was removed. Sea ice cores were collected using a stainless-steel core barrel of 12.5 cm diameter, and then ice cores were placed into clean bags (polyethylene) and transported to the laboratory.	The outer surface of each ice core was scraped off using a boomerang scraper. A stainless-steel hand saw was then used to cut each ice core into 10 cm vertical subsections. Subsections were placed into individual clean Ziploc bags (polyethylene) and allowed to melt for 24–48 h, then filtered with glass microfiber paper (Ø = 47 mm; pore size = 1.2 μm; Whatman GF/C).	N/A	N/A	Microscope+FTIR spectroscopy Abundance (item L^{-1}), Size (≥100 μm), composition	Kanhai et al., 2020
Italian Alps	Supraglacial debris	Cryoconite samples and sparse and fine (<2 mm) supraglacial debris were collected. To avoid contamination, samples were collected in glass jars with a gardening metal shovel or a metal laboratory spoon. Jars and sampling tools were accurately cleaned with acetone before sampling.	Extraction of microplastic items from supraglacial and cryoconite debris samples was performed under a laminar-flow hood. About 50 g sediments were mixed with 300 mL of NaCl solution, and stirred for 15 min., and then filtered using glass fiber filters (Ø = 47 mm; pore size = 0.45 μm; Whatman GF/A).	Saturated NaCl solution (density = 1.2 g cm^{3}; 365 g L^{1})	digested with H_2O_2 (15%) overnight	Microscope+FTIR Abundance (items kg^{-1} dw), colors, composition	Ambrosini et al., 2019
Western Italian Alps	Snow	Snow sampling was performed by appropriately trained operators with a stainless steel spoon, scraping the surface of snow accumulation, and transferred to 2 L glass jars. Both the spoon and the glassware were previously washed with acetone. Three independent samples per each location were collected. Samples were transported to the laboratory and were maintained at 4 °C in the dark until the analysis.	Snow samples were melt and filtered through cellulose filters (Ø = 47 mm; pore size = 1 μm); wrapped in tinfoil until analyses to avoid laboratory contamination	Saturated NaCl (365 g L^{-1})	H_2O_2 (30%).	Stereomicroscope+μFTIR Abundance (item L^{-1}), composition	Parolini et al., 2021
Austria Alps	Surface snow/ snowpit,	Snow profile was performed in 20 cm sections, which were taken with a stainless steel cylinder. The outer 1 cm of the surface was shaved off with a clean ceramic knife, and the rest was melted in a microwave and mixed with a clean glass stick. Surface snow (the first 10–15 cm) was placed in a pre-cleaned glass bottle.	The snow meltwater was filtered through a PTFE filter (pore size = 0.2 μm) to separate microplastics from nanoplastics.	N/A	N/A	TD-PTR-MS Abundance (ng L^{-1}), composition	Materić et al., 2020
Carnic Alps	Winter season surface snow	Surface snow was placed in a pre-cleaned glass bottle (750 mL), and	Snow samples were dissolved at room temperature in closed	NaCl oversaturated	Creon enzyme (37 °C; TRISbuffered pH)	Stereomicroscopy+μFTIR Abundance (item L^{-1})	Pastorino et al., 2020

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Table 1 (*continued*)

Study areas	Sample types	Sampling methods/ tools/storage containers	Filtration	Density separation	Organic matter removing	Measurement and reporting	References
		four replicates (3 L) were obtained from each site. To prevent potential contamination, personnel moved against the wind and took samples of the snow in front of them using their bare hands and a pre-cleaned steel spoon.	glass bottles without pretreatment. Meltwater samples were filtered with a paper fiber filter disk (pore diameter = 6 μm), stored in glass Petri dishes, dried overnight at 40 °C, and dyed with Rose-Bengal.	pre-filtered solution			
Tibetan Plateau	Glacier surface snow	surface snow was collected by using glass jars and a steel spoon to prevent potential contamination	Snow meltwater was filtered using aluminum oxide filter (Ø = 47 mm; pore size = 0.2 μm; Anodisc, Whatman, Germany).	Saturated NaCl (density = 1.2 g cm ^{3}; 365 g L^{-1})	H_2O_2 (15%)	FTIR+Raman Abundance (item L^{-1}), size (≥11 μm), composition	Zhang et al., 2021
Mt. Everest, Southern slope of Central Himalayas	Snow t	Snow sample was collected and placed into stainless steel metal containers.	Snow meltwater was filtered using glass microfiber filter papers (pore size = 0.6 μm, Whatman).	N/A	N/A	FTIR Abundance (item L^{-1}), colors, size(>30 μm), composition	Napper et al., 2020
Ecuadorian Andes	Glacier snow and ice core	Surface snow samples was collected by plastic bags, and ice core was drilled by ice coring gear. The mountaineering crew, trained to avoid MP contamination, remained downwind to the sampling points. The samples were stored in a freezer at −18 °C until analysis.	Cellulose nitrate filters (Ø = 47 mm; pore size = 0.45 μm)	20 mL of NaCl (1.2 kg cm^{-3}), centrifugation (3000 rpm)	N/A	Microscope Abundance (item L^{-1}), size (60 μm), colors, fiber and fragment	Cabrera et al., 2020
East Antarctica	Sea ice	The sea ice cores were collected using trace metal and organic carbon clean-sampling methods, e.g., an electro-polished stainlesssteel corer was used for drilling, sea ice core was triple-bagged in acid-cleaned plastic bags for transport and freezer storage (−18 °C). clean suit was worn for all ice-core processing and stored in a bag when not in use to avoid atmospheric particle contamination.	Samples were filtered using aluminum oxide filter (Ø = 25 mm; pore size = 0.2 μm; Anodisc, Whatman, Germany).	N/A	Filtered were overlaid with 40 mL H_2O_2 (35%) at room temperature and incubated overnight	μFTIR Abundance (item L^{-1})	Kelly et al., 2020
Collins Glacier, Antarctica	Ice surface that constitute part of the ablation zone of Collins glacier	Squares of ice surface (1 m^2) were collected used previously cleaned containers, which were cleaned with Milli-Q water, wrapped in aluminum foil and heated to 300 °C for 4 h to remove organic matter.	N/A	N/A	N/A	ATR-FTIR and μFTIR Abandance (items per surface unit), Deposition (items per surface unit and day)	Gonzalez-Pleiter, 2021

of microplastics obtained in different studies depended more on the sampling and analytical methods used than on a real global estimate, as suggested by the results in this section, which was a summary of information from the published literatures.

Overall, the number of microplastic particles observed in a sample generally decreases as the particle size increased (Bergmann et al., 2019). However, the limitations in sampling and instrumental methodology mean that little was known about microplastics that were smaller than 10 μm. Microplastics in snow and ice were generally smaller than 50 μm (Fig. 2), with plastic fibers dominating (Bergmann et al., 2019; Peeken et al., 2018; Zhang et al., 2021). Microplastics detected in snow from the Laohugou glacier No.12 (LHG) on the northeastern Tibetan Plateau showed that approximately 38% of microplastics were < 25 μm, while more than 80% were < 50 μm (Fig. 3a). Fibers with lengths of >1 mm have also been found in snow from the Mt. Everest Balcony (8840 m a.s.l.) (Napper et al., 2020). Approximately 80% of the microplastics found in snow from the Arctic have been <25 μm, with 98% <100 μm, which is consistent with the

Table 2
A brief summary of the updated methods to identify microplastics in snow and ice from the related studies.

Methods	Main characteristics	Measurement	Reference
Spectrometry			
μFT-IR (micro Fourier transform infrared spectroscopy)	Infrared spectra of the sample recording its characteristics vibrational bands. Non-destructive of plastic particles. Allowing the detection of particles down to 11 μm.	Polymer compositions, size MPs with nontransparent or less than 20 μm are difficult to be analyzed.	Bergmann et al., 2019 Peeken et al., 2018 Primpke et al., 2018
μRaman (Micro-Raman spectroscopy)	Raman spectra of the sample recording its characteristics vibrational bands. Non-destructive of plastic particles. Time-consuming and affected by biological, organic, and inorganic impurities. Effective in MP characterization down to 1 μm.	Polymer compositions, size, shapes. Particle size distribution information.	Allen et al., 2019 Araujo et al., 2018 Stefánsson et al., 2021
SE-Raman (Surface Enhanced Raman Spectroscopy)	The Raman signal can be significantly enhanced in a very small spatial region (<10 nm) that activated by an assembly of metallic nanoparticles.	Identification of polystyrene nanoplastics.	Zhou et al., 2020
LDIR (laser direct infrared spectroscopy)	The LDIR analyzer was run in trans-reflectance mode, where the system directs IR laser light hrough the sample (particle), and the light was then reflected back to the reflective slide through the particle as it exited. A full spectrum of each particle covering the range of the instrument is collected and compared to the spectral library in real time.	Polymer compositions, size fraction.	Scircle et al., 2020
Thermal connected to Mass Spectrometry			
MALDI-TOF MS (Matrix-Assisted Laser Desorption/ Ionization-Time-of-Flight Mass Spectrometry)	The cups were mechanically crushed into fine powders in liquid nitrogen by a grinder. The powders were dissolved in THF. Micro- or nano-plastics extracted from sediments.	Polymers and its molecular can be detected by mass spectrum. Get the weight of each polymer.	Wu et al., 2020
TD-PTR-MS (Thermal Desorption−Proton Transfer Reaction−Mass Spectrometry)	The thermal degradation of each polymer (which produces different degradation products at different temperatures) was integrated in the analysis.	Different polymers of plastics express various unique features (pointed by arrows), can be used for the identification. Using calibration	Materić et al., 2020
Pyr-MS (pyrolyzer-mass spectrometry) or Pyr-GC–MS (pyrolyze-gas chromatography-spectrometry)	For the observation of nanoplastic (<1.2 μm) by preconcentrations. Destructive of the plastic particles. Inorganic additives cannot be detected. This method is not limited by the color, shape, size, and thickness of MPs samples compared with FT-IR and Raman.	Enables rapid identification and weight-related quantification of MPs.	Käppler et al., 2018 Zhang et al., 2020b

distributions observed in snow from Europe (Bergmann et al., 2019) (Fig. 3b). On average, 67% of the plastic particles in Arctic sea ice were within the currently smallest detectable size class of ≥11 μm (Fig. 3c). In general, the predominant microplastics in water matrices have been identified at 200–500 μm in size (Picó et al., 2020), while lake water was generally dominated by microplastic particles that were <500 μm in size (Fig. 2) (Mao et al., 2020). The fiber length distribution in oceanic surface waters showed a peak in abundance of ~800–900 μm and a pronounced absence below 400 μm (Rist et al., 2020; Suaria et al., 2020; Zeng et al., 2018). The predominant length of microplastic fibers in the atmosphere of remote areas ranged from 100 to 200 and 200–300 μm (Fig. 3d) (Allen et al., 2019), while the most abundant lengths reported in urban cities were 400–500 μm (Fig. 3e) (Wright et al., 2020b). Comparison of the plastic particles found in urban areas to those from remote areas suggested that cryospheric microplastics comprised a smaller fraction of the general atmospheric microplastics; meanwhile, atmospheric microplastic particles were generally notably smaller in size than aquatic microplastics, suggesting a smaller proportion of microplastic particles than atmospheric microplastics in the cryosphere (Fig. 2) (Zhang et al., 2020a). However, the relationship between the size of microplastics and their atmospheric residence time/deposition strength and the rate at which different microplastics deposited were still poorly understood (Brahney et al., 2020). Uniform sampling and pretreatment (including the use of the same filters with the same pore size, density separation, and analytical methods) are required in order to accurately compare the microplastics found in snow and ice on a global basis.

3.2. Abundance

Currently, no general understanding of the abundance of microplastics in snow and ice has been established because of the limited data. The abundance of microplastics reported in the surface snow and snowpits of Alpine glaciers has been calculated to be 5.4–27.4 ng mL^{-1} (polyethylene terephthalate fibers, PET) (Materić et al., 2020). Meanwhile, the concentration of microplastics with particle sizes ≥11 μm in Arctic snow (9.8×10^3 items L^{-1}) was significantly lower than that found in snow from Europe (24.6×10^3 items L^{-1}) (Table 3) (Bergmann et al., 2019). However, microplastic particles that were found in the firn cores of the Vatnajökull Ice Cap in Iceland were identified to contain 2–5 items per sample with the size of the plastic fragments ranging from 30 to 3000 μm (Stefánsson et al., 2021).

Table 3
The characteristics of microplastics in snow and ice in typical cryospheric regions synthesized from the published literatures.

Study area	Sample types	MPs abundance	Dominant size or range (μm)	Dominant polymers	Method	References
Arctic						
Svalbard and Fram Strait	Snow	9.8×10^3 items L^{-1} (range: 0 to 14.4×10^3 items L^{-1})	<25 μm (80%) (range: 11–475 μm)	Acrylates/PU/varnish/ lacquer	μFTIR	Bergmann et al., 2019
Fram Strait	Drifting sea ice Lan-locked ice	2×10^3 items L^{-1} 6×10^2 items L^{-1}			μFTIR	Bergmann et al., 2017
Arctic Ocean	Sea ice	38–234 items L^{-1}	(range: 20 μm −2 mm)	Rayon (54%), PET (21%), PA (16%), PP(3%)	Microscope+FTIR	Obbard et al., 2014
Central Arctic	Sea ice	1.1×10^3 to 1.2×10^4 items L^{-1}	<25 μm (80%)	PE (48%), varnish, PA, EVA, CE, PES, PP	FTIR	Peeken et al., 2018
Arctic Ocean	Sea ice	2–17 items L^{-1}	Range: 0.1–5 mm	PET(57%), PA(19%), PU(6%), PAN(6%), styrene/acrylates (6%), PVC(5%)	FTIR	Kanhai et al., 2020
Arctic Svalbard	Free-floating sea ice	158 items L^{-1}	Range: >50 μm	PET, paint, PA, low-density PE, urethane alkyd, acrylic, PU	FTIR	Von Friesen et al., 2020
Baltic Sea of Arctic and experiments	Sea ice	Upper layer (top 1 cm) of sea ice core: 758–39,600 items L^{-1} Below the first centimeter of sea ice: 180–527 items L^{-1}	<250 μm		FTIR	Geilfus et al., 2019
Arctic regions	Snow	Road Microplastics: 1–10 ng kg^{-1} (PM2.5) 4–80 mg kg^{-1} (PM10)			Simulations	Evangeliou et al., 2020
Vatnajökull Ice Cap, Iceland	Snow cores	2–5 items per sample	Fragment: 30–3000 μm Fibers: 1300–3000 μm	PU, PVC, PA, ABS	Stereomicroscope + Raman	Stefánsson et al., 2021
Europe						
Heligoland, Bremen, Bavaria, Tschuggen, and Davos	Snow	24.6×10^3 items L^{-1} (range: 190 to 154×10^3 items L^{-1})	Longer than Arctic snow	PA, varnish, rubber, EVA, and PE	μFTIR	Bergmann et al., 2019
Forni glacier, Italian Alps	Supraglacial debris	74.4 ± 28.3 items kg^{-1} dw		PET, PA, PE, PP	μFTIR	Ambrosini et al., 2019
Snow, western Italian Alps	Snow	2.32 ± 0.96 items L^{-1}	Average: 339 μm (range: 50–1910 μm)	PE, PET, HDPE, PES, PP, PU	Stereomicroscope +μFTIR	Parolini et al., 2021
Sonnblick Observatory, Austria Alps	Surface snow/ snowpit	5.4–27.4 ng mL^{-1}		PET fibers	TD-PTR-MS	Materić et al., 2020
Carnic Alps, Italy	Winter season snow	0.11 items L^{-1}		PET	μFTIR	Pastorino et al., 2020
Tibetan Plateau						
LHG glacier No.12, Qilian Mountains	Glacier snow	~ 650–920 items L^{-1}	<25 μm (38%) <50 μm (80%)	PET, rubber, PA, PP, PU, PSPC, Varnish	μFTIR	Zhang et al., 2021
Southern slope of Mt. Everest	snow	30 items L^{-1}	Detection >30 μm	PET, PMMA, nylon, PP	Stereomicroscope + FTIR	Napper et al., 2020
South America						
Antisana glacier, Ecuadorian Andes	Glacier	101 items L^{-1} (surface snow) 2–17 items L^{-1} (ice core)	60-2500 μm		Microscope	Cabrera et al., 2020
Antarctica						
Collins Glacier, King George Island	The ablation zone of glacier	EPS: 0.17–0.33 items m^{-2} PET: 0.25 items m^{-2}	2292 to 12,628 μm		FTIR or μFTIR	González-Pleiter et al., 2021
East Antarctica	Sea ice	11.7 items L^{-1}	<50 μm (60%) <100 μm (90%)	PET, PP, PA	FTIR	Kelly et al., 2020

The winter snow in the Carnic Alps region originated in the ocean and was reported to contain very low levels of microplastics (0.11 items L^{-1}, with fragments measuring 75 × 200 μm) (Pastorino et al., 2020), which was much lower than that found in surface snow from the Swiss and Bavarian Alps (Bergmann et al., 2019). The microplastic concentrations in Tibetan glacier snow has been calculated at 800–1100 items L^{-1} (Table 3), which was much higher than that reported in snow from the southern slopes of Mt. Everest (~30 items L^{-1}) (Napper et al., 2020). Microplastics have been measured in both the surface snow and ice core samples from the Andes glacier, with average concentrations of 101 and 2–17 items L^{-1} (with sizes >60 μm), respectively (Cabrera et al., 2020). The occurrence of microplastics (~74 items kg^{-1} dry weight) found in the subglacial debris was within the range of microplastic contamination observed in the marine and coastal sediments of Europe (Ambrosini et al., 2019). However, these differences may be attributed to the different methods used to sample, filter, and measure the microplastics (Table 3).

In addition, the cryoconite holes that form at the ice–atmosphere interface of glaciers or in the presence of meltwater can accumulate and concentrate anthropogenic contaminants, including microplastics (Baccolo et al., 2020). The first cryoconite study of microplastics was reported in an Alpine Fornie Glacier, with 70.5 items kg^{-1} (Ambrosini et al., 2019). Historical variations in microplastic concentrations have also been reported in lake and marine sediments and with the oceanic Continuous Plankton Recorder (Turner et al., 2019; Ostle et al., 2019). However, until now, only one ice core (8 m length) has been drilled and

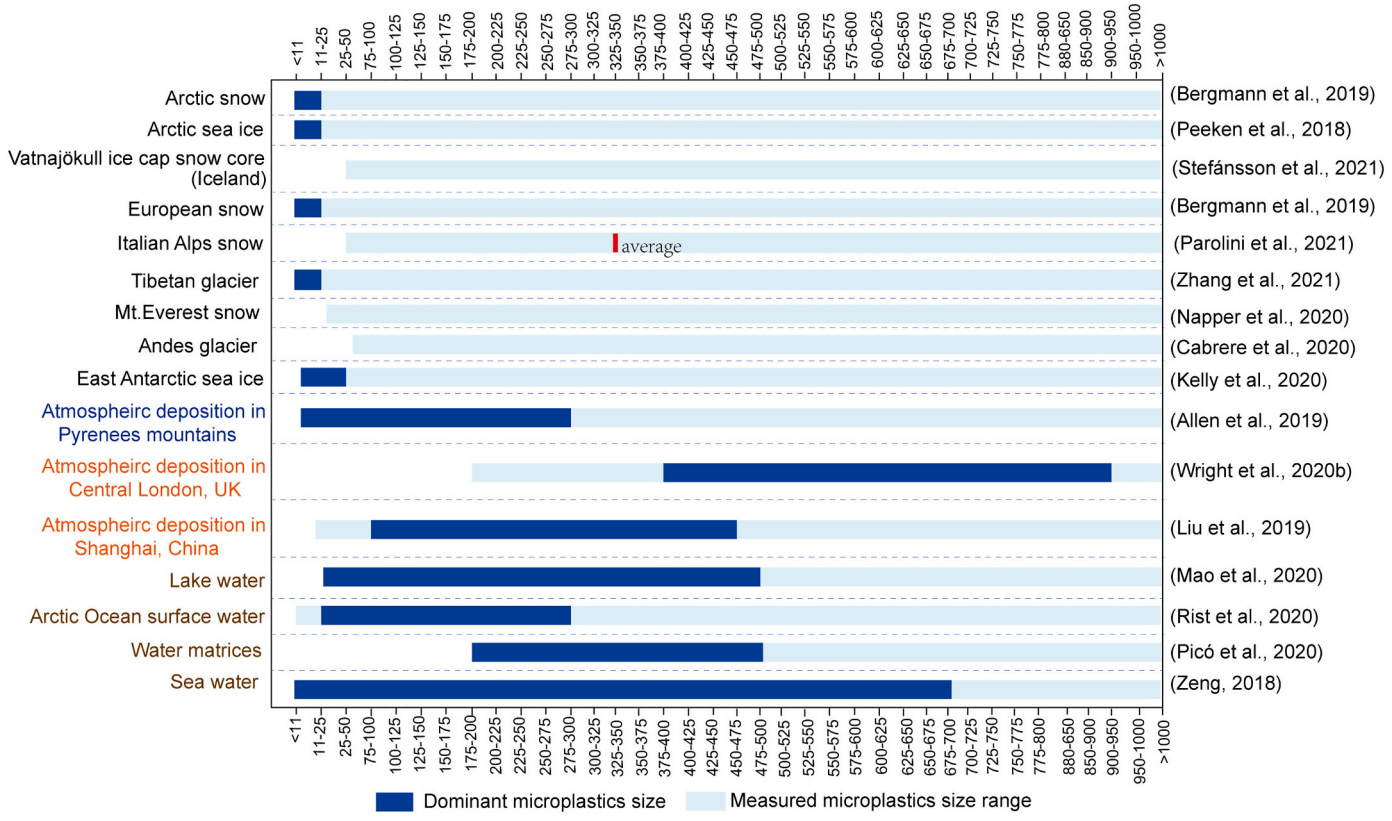

Fig. 2. Summary of the size distribution of microplastics (μm) found in snow and ice in the typical cryospheric regions, atmospheric deposition in remote and urban areas, and other representative results from the aquatic environment.

studied for microplastics, and no temporal and spatial associated variations have therefore been reported as yet in this type of sample (Cabrera et al., 2020).

Microplastics have also been reported at considerable concentrations in sea ice, with a noticeably higher microplastic load found in Arctic sea ice as compared to Antarctic sea ice (Kelly et al., 2020; Peeken et al., 2018). Microplastics recorded in sea ice from the Arctic were two orders of magnitude higher than those previously reported for highly contaminated surface waters such as the Pacific gyre (Peeken et al., 2018; Lusher et al., 2015). However, even in the Arctic sea ice, microplastic concentrations varied significantly from several items to hundreds or thousands of particles per liter (2–3 orders of magnitude) (Table 3) (Cabrera et al., 2020; Geilfus et al., 2019; Kanhai et al., 2020; Obbard et al., 2014; Peeken et al., 2018; Von Friesen et al., 2020). A previous study reported that microplastic concentrations decreased rapidly below the upper layer (top 1 cm) of the sea ice, suggesting a rapid and efficient concentration of microplastics during the initial formation (Geilfus et al., 2019). It has also been reported that microplastic abundance in the ice floes that underlie surface waters (0–18 × 10^{-3} items L^{-1}) was orders of magnitude lower than that in sea ice cores (Kanhai et al., 2020). The mean concentrations of microplastics in sea ice cores from the western and eastern Fram Strait were 6 × 10^2 items L^{-1} in land-locked ice and 2 × 10^3 items L^{-1} in drifting sea ice (Bergmann et al., 2017). The growth region, melting, and drifting paths of the ice potentially influenced the characteristics and concentrations of microplastics in the sea ice (Geilfus et al., 2019; Peeken et al., 2018). Recently, on the surface of the Collis glacier in King George Island, Antarctica, polystyrene (EPS) was found ranging between 0.17 and 0.33 items m^{-2} (González-Pleiter et al., 2020). Although direct comparisons between these observational data should be made with caution, these findings indicated that microplastics were widespread all over the world, even the remote cryosphere. In particular, simulation of the microplastics produced by road traffic suggested that a typical cryospheric region, the Artic, may be a particularly sensitive receptor region for atmospheric microplastics (Evangeliou et al., 2020). Constraining the link of microplastics with distinct atmospheric, terrestrial, and cryospheric residue times to global biogeochemical cycles by observation and simulation is therefore an urgent issue (Brahney et al., 2020; Bank and Hansson, 2019; Stubbins et al., 2021).

3.3. *Shapes and polymer compositions*

The dominant form of atmospheric microplastics within the larger particle size range (e.g., >20 μm) were usually fibers (Brahney et al., 2020; Dirs, 2016; Liu et al., 2019; Wright et al., 2020b; Zhang et al., 2020a), which often contributed more than half of the relatively larger microplastic particles identified in field studies. Fibers reaching lengths >100 μm have been detected in Tibetan glacier snow and Mt. Everest snow (Napper et al., 2020; Zhang et al., 2021), along with fragments, films, and granules (Fig. S2). Fibers were the most common shape of microplastic particles collected from river surface water in Tibet (69–92%) (Feng et al., 2020; Jiang et al., 2019), and represented 65.2% of the plastic items found in subglacial debris from the Alps, with fragments comprising the other 34.8% (Ambrosini et al., 2019). The microfibers in Arctic snow ranged from 65 to 14,300 μm, approximately 31% are smaller than 500 μm, and European snow fibers were significantly longer than those found in Arctic snow (Bergmann et al., 2019). Plastic fragments and fibers in the snow cores of the Vatnajökull Ice Cap were found to range from ~30–1300 μm and 1300–3000 μm, respectively (Stefánsson et al., 2021).

The polymer composition of microplastics in snow and ice varied considerably (Table 3 and Fig. 4). In the first report on microplastics in sea ice, rayon was the most prevalent synthetic microplastic found (54%), followed by PET (21%), PA (16%), and PP (3%) (Obbard et al., 2014). Of the 17 different polymer types in Arctic sea ice, polyethylene (PE), polyamide (PA), ethylene vinyl acetate (EVA), polyester (PES), and

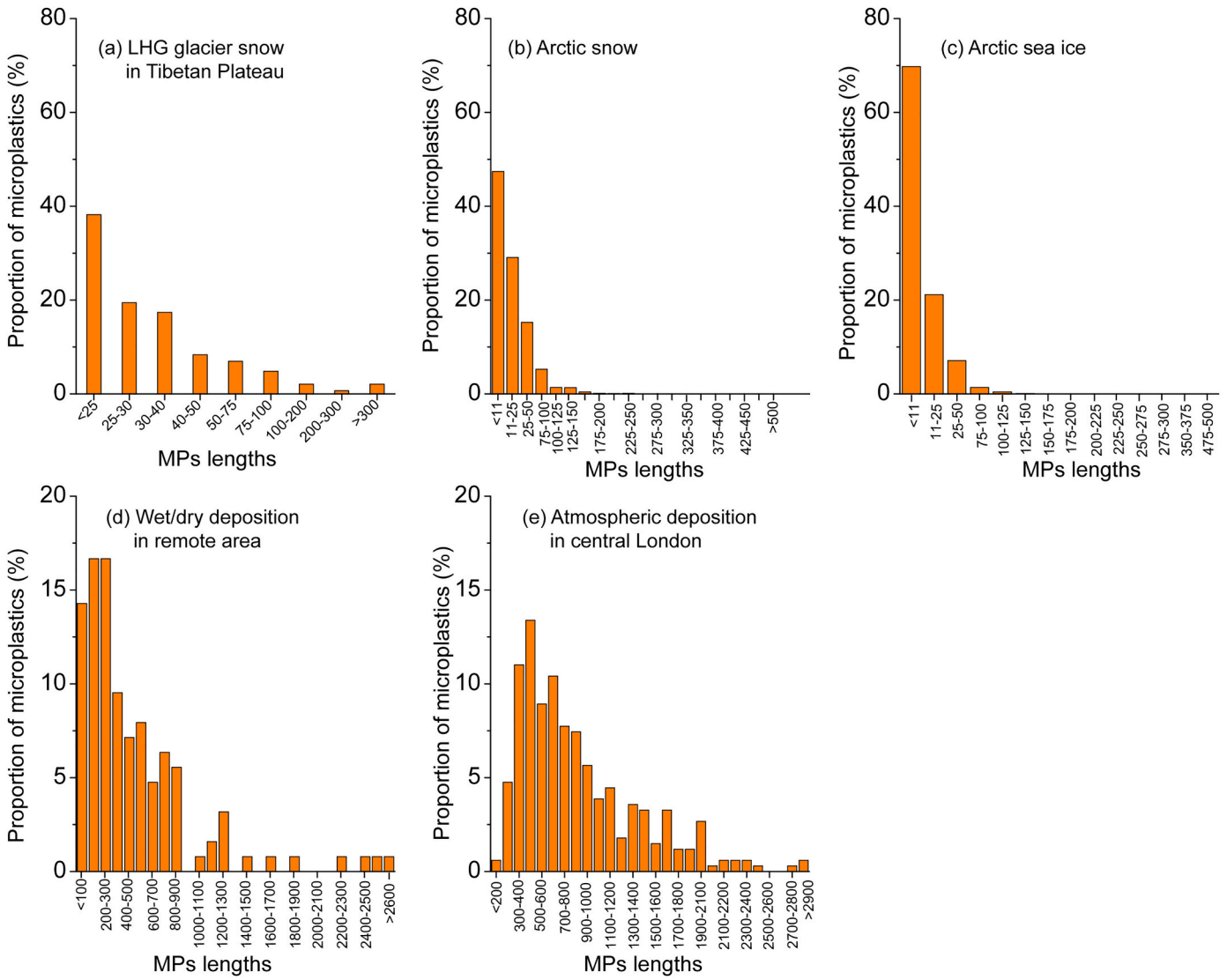

Fig. 3. Size distributions of microplastic particles (μm) in snow and ice and atmospheric deposition from the published literature. Data (a) cited from (Zhang et al., 2021) for all microplastic particles; (b) cited from (Bergmann et al., 2019) for all microplastic particles; (c) cited from (Peeken et al., 2018) for observed microplastic particles; (d) cited from (Allen et al., 2019), showing the length of fibers from atmospheric deposition; (e) cited from (Wright et al., 2020b), showing the size distribution of fibrous particle lengths. Fragment data are not shown here.

PP contribute more than half of the plastic debris measured (Fig. 4) (Peeken et al., 2018), and of the 19 polymers measured, acrylates/polyurethanes/varnish/lacquer were found to occur most frequently in Arctic snow, with PA/varnish/rubber/EVA and PE dominating European snow (Bergmann et al., 2019). Acrylonitrile butadiene styrene (ABS) has also been found in the snow cores of the Vatnajökull Ice Cap (Stefánsson et al., 2021).

The alpine snowpit study showed the presence of PET, propylene carbonate (PC), and polyvinyl chloride (PVC), with PET dominating (Materić et al., 2020). PET was also noted to dominate the polymer compositions in Alpine winter surface snow and subglacial debris (Ambrosini et al., 2019; Pastorino et al., 2020). Most of the microplastics found in the snow from Mt. Everest were also polyester fibers (Napper et al., 2020). Polymer compositions from Tibetan glacier snow indicated that PET (12%), rubber (10%), PA (10%), PP (8%), and polyurethane (PU 8%) are dominant. In comparison, the major microplastic polymers found in the surface water and soil samples from the Tibetan Plateau mainly comprise PP and PE (Jiang et al., 2019); with PET, PA, polystyrene (PS), PE and many other polymers identified in wet/dry depositions from remote areas (Allen et al., 2019; Brahney et al., 2020). PET is most commonly used in the construction of synthetic fibers and plastic bottles. Owing to its crystalline transparency, relatively light weight (1.3–1.4 g cm^{-3}), high resistance, and long life, PET is a commercially important synthetic material (PlasticsEurope, 2019). The predominance of PET as compared to the other polymers was consistent with previous studies investigating the microplastic pollution in urban air, which found that the composition of urban microplastics predominantly comprises fibers (Materić et al., 2020). Microplastic fibers found in cryosphere regions, such as snow from Mt. Everest (PET > acrylic > nylon > PP), were suggested to have primarily come from clothing and equipment (local sources) (Napper et al., 2020). The different polymer compositions of microplastics can be used to tentatively identify organic additives, which varied between the polymer leachates in the environment (Capolupo et al., 2021; Macleod et al., 2021). However, the potential impacts in cryospheric regions have been poorly studied.

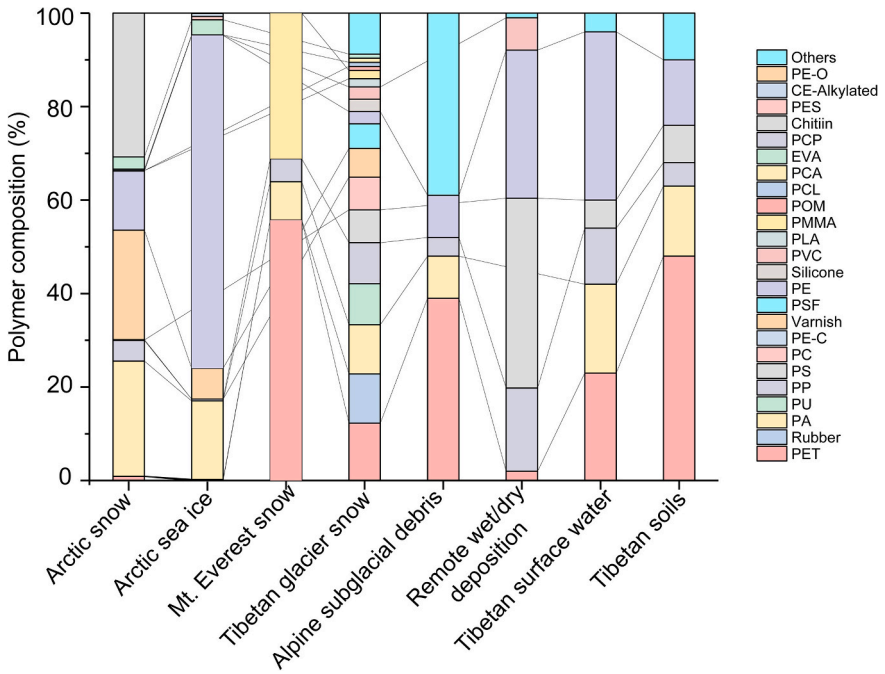

Fig. 4. Relative compositions of polymers identified in snow and ice and wet/dry deposition in remote areas. Detailed data can be found in Supplementary Table S1. Arctic snow (Bergmann et al., 2019); Arctic sea ice (Peeken et al., 2018); Mt. Everest snow (Napper et al., 2020); Tibetan glacier snow (Zhang et al., 2021); Alpine subglacial debris (Ambrosini et al., 2019); Remote wet/dry locations (Allen et al., 2019); Tibetan surface water and soil (Jiang et al., 2019).

4. Transport pathways of microplastics in typical cryospheric regions

4.1. Microplastics in sea ice

Ocean currents are important drivers in the distribution of floating microplastic particles in the marine environment (Onink et al., 2019). The amount of pelagic microplastics around the Pacific Ocean subtropical convergence zone was predicted to double by 2030 and quadruple by 2060 (Isobe et al., 2019). Seawater from the North Pacific Ocean has been found to contain higher MPs than other oceans, which may also affect the loading of microplastics in the western Arctic Ocean (Kim et al., 2021). This increasing burden of microplastics in the ocean is likely to lead to high loading of microplastics in the surface oceanic waters of the Arctic because of the potential impact of ocean surface circulation (Lebreton et al., 2012; Tošić et al., 2020). Additionally, the warm branch of the thermohaline circulation plays an important role in transporting floating microplastics from the northern Atlantic to the Arctic Sea (Lima et al., 2021). The Arctic Ocean has been hypothesized to be an important sink for plastic debris and is considered to be the end point for floating plastics in the North Atlantic branch of the thermohaline circulation (Bergmann et al., 2017; Cózar et al., 2017). Meanwhile, more recent research has suggested that ocean sea floors may be temporary sinks and that continued oceanic transport may occur (Kane et al., 2020). Considering the growth region and drift paths of Arctic Sea ice, microplastics within the sea ice may be transported along with the relatively highly microplastic contamination in the offshore North Atlantic waters into the Arctic Ocean and eventually carried to the Fram Strait (Peeken et al., 2018; Renner et al., 2014). Additionally, the transpolar drift stream may also transport microplastics from the western Arctic Ocean into the Arctic Central and Eurasia Basins (Kim et al., 2021).

In the Arctic Ocean, sea ice is considered to be a temporal sink of microplastics, where particles are retained within the ice and released into the ocean when the ice melts (Obbard et al., 2014; Peeken et al., 2018). Microplastics in sea ice were concentrated by 1–2 orders of magnitude compared with ambient seawater (Bergmann et al., 2017; Von Friesen et al., 2020). Although microplastics did not appear to affect the growth of sea ice (Geilfus et al., 2019), there is a gap in the knowledge in terms of the processes and rates at which microplastics are incorporated into sea ice, and the resulting impact on sea ice properties. The recent increase in shipping, fishing, and tourism in the Arctic region is expected to increase the amount of microplastics that are directly released into the Arctic Ocean, which may lead to variation in the concentrations of microplastics in sea ice as it grows (Halsband and Herzke, 2019; Geilfus et al., 2019). This indicates that sea ice may also be a local source of anthropogenic microplastics. The important implication of sea ice melting as a result of Arctic warming is the associated release of microplastics from the sea ice into Arctic seawater. These findings further suggest that the accelerated melting of Arctic sea ice due to climate change will have a major impact on the transport of microplastics within, but also into and out of the Arctic. Assessing the potential storage and release of microplastics from sea ice is an important issue.

Abundant microplastics have also been detected in the seawater of the Southern Ocean recently (Isobe et al., 2017; Suaria et al., 2020). The significant concentrations of microplastics in this ocean indicate that marine plastic pollution has spread across the world (Isobe et al., 2017; Zeng, 2018). The concentration of microplastics in the sea ice from the eastern Antarctic has been reported as reaching 11.7 items L^{-1} (Kelly et al., 2020), which is much lower than that found in a recent study investigating Arctic sea ice (Peeken et al., 2018). These results suggest that sea ice in the Southern Ocean also has the potential to serve as a reservoir for microplastics. Dispersal modeling of plastic particles suggests that plastics in the surface waters around the Antarctic Peninsula could have originated from any point on the Antarctic continent or throughout the Southern Ocean (Isobe et al., 2019) and that the surface water that is transferred from lower latitudes may have contributed to the plastic in the Southern Ocean (Waller et al., 2017). In addition, fishing activities occurring around Antarctica is likely a source of plastics in the local environment (Do Sul et al., 2011; Lacerda et al., 2019).

4.2. Microplastics in mountain glaciers and Arctic land snow cover

Mountain glaciers or Arctic land snow in remote cryospheric regions are usually far away from anthropogenic sources of microplastics. After being released from the primary or secondary sources, microplastics can be transported into wetlands, lakes, rivers, oceans, and the atmosphere (Allen et al., 2019; Evangeliou et al., 2020; Hale et al., 2020). In particular, air currents and wind can transport microplastics far from the point of emission (Allen et al., 2019; Brahney et al., 2020; González-Pleiter et al., 2021; Stefánsson et al., 2021). Weather events (e.g., storms) will also facilitate the transport of plastic particles into terrestrial and aquatic ecosystems (Dris et al., 2016; Hitchcock, 2020). As in the first discovered microplastics in snow from the Vatnajökull Ice Cap, the atmospheric transport of microplastic particles may be one of the important pathways for microplastic pollution (Stefánsson et al., 2021).

Air mass trajectory analysis of the remote areas in the Pyrenees mountains and the western US has indicated that atmospheric microplastics can be transported through the atmosphere over long distances, suggesting long-range or global transport (Allen et al., 2019; Brahney et al., 2020). In the Himalayas, the alternative interactions of valley wind and glacier wind act as efficient channels for south-to-north airflow, transporting atmospheric pollutants (Cong et al., 2015). The aerosol vertical distribution achieved by the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIPSO) retrievals (Fig. S3a-c) and WRF/COSMO simulations (Fig. S4 and Fig. S5) have been used to demonstrate that smoke plumes containing pollutants originating from South Asia could reach altitudes above 6 km and are therefore able to cross the Himalayas (Chen et al., 2019b; Lüthi et al., 2015). Under these mechanisms, pollutants such as the microplastics that are emitted from South Asian (source) regions can be transported to the inland Tibetan Plateau and eventually become deposited and accumulate on glacier surfaces (sinks). Furthermore, in the northern Tibetan Plateau, air masses from central Asia and northwest/north China may contribute to the deposition of atmospheric microplastic on the surface of the glaciers in the Qilian Mountains through long-range and high-altitude atmospheric transport (Zhang et al., 2021), which is also evidenced by the CALIPSO images illustrating that polluted smoke that is elevated from the surrounding regions can reach the Qilian Mountains (Fig. S3d-f). These results demonstrate that in remote cryospheric areas, atmospheric long-range transport is the main pathway for air pollutant transport and deposition, including microplastics (Bergmann et al., 2019; Evangeliou et al., 2020).

5. Perspectives

5.1. Historical variation in microplastics retrieved from mountain glacier ice cores

As an important climatic and environmental archive, chemicals that reach glaciers are deposited and accumulated from the atmosphere via both dry and wet deposition. Due to the low temperature and lack of disturbance from human activities, air pollutants (including microplastics) that stored in glaciers are rarely disturbed, especially at the high elevations in which glaciers form (usually above the altitude of the equilibrium line). As shown in the sketch map in the Supplementary Information (Fig. S6), ice cores are usually drilled from ice that is formed through the compaction of accumulated snow, the composition of which can be used to reconstruct past climates and monitor environmental changes (environmental archives) (Gabrieli and Barbante, 2014; Jouzel, 2013; Kang et al., 2019). Ice cores are typically retrieved from high mountain glaciers (e.g., Tibetan Plateau, Andes, or Alps) and can be used as temporal records of atmospheric microplastic deposition, providing valuable information on historical contamination (Cabrera et al., 2020; Kaspari et al., 2011). The loss of mass from the accumulation zones of glaciers under climate warming may disturb the records (Kang et al., 2015; Kehrwald et al., 2008), rendering ice core dating inaccurate. However, ice cores from the accumulation zone of most glaciers are still effectively to preserve and provide information about the climate and the environment in the past.

Ice cores that are drilled from selected benchmark glaciers on the Tibetan Plateau (the East Rongbuk and Geladaindong glaciers) can provide a high-resolution reconstruction of the history of greenhouse gases, climate change, and the environmental evolution over the past several decades to hundreds of years (e.g., BC records) (Jenkins et al., 2016; Kang et al., 2020). During the past 60 years, carbon emissions have shown an increasing trend because of the large consumption of fossil fuels and biomass fuels; however, the rate of plastic production surpassed that of carbon emissions after 1997, when the Tokyo Protocol was signed (Borrelle et al., 2017; PlasticsEurope, 2019) (Fig. S7a). Even after 2015, when the Paris Agreement and Clean Seas agreements were signed, the increase in plastic production continued (PlasticsEurope, 2019). The marine continuous plankton recorder and lake sediments historic plastic pollution trends confirmed a significant increase in the amount of plastic debris reaching oceanic and freshwater environments (Fig. S7b). Macroplastics have been accumulating in the open ocean from 1957 to 2016, agreeing with the increase in plastic production worldwide (Ostle et al., 2019). Especially since the 1900s, a period with a rapid increase in both carbon emissions and plastic production, a significant increase in plastic in the ocean has been observed (Cózar et al., 2014). Microplastics identified in lake sediments show a relatively low number of particles in older sediments (Turner et al., 2019), corresponding to the relatively low plastic production at the time.

Future scenarios of global plastic waste generation and disposal continue to be disproportionately high in the African and Asian continents (Lebreton and Andrady, 2019). This plastic waste is expected to enhance the microplastic burden in the environment through a combination of solar UV radiation, chemical degradation, and the diverse weathering fragmentation of plastic waste in the waters into micro-sized particles (Adelhafidia et al., 2015). Three ice cores from the East Rongbuk glacier on Mt. Everest, Ganglongjiama glacier in the Tanggulha Mountains, and Laohugou glacier No.12 in the Qilian Mountains (Fig. S8) have been drilled over the past few years to investigate the temporal variations in the microplastics reaching the Tibetan plateau. The two sites in the Himalayas and the northern Tibetan Plateau are controlled or significantly influenced by Indian monsoons and westerlies, respectively, while the site in the central area is located in the transition zone of the Indian monsoon and westerlies (Yao et al., 2013). These studies are designed to help reveal one hundred years of variation in microplastics, and may provide an important perspective on the temporal behavior of microplastics in the cryosphere.

5.2. Possible impact on the carbon cycle

Microplastics are composed of variable polymers that are mainly composed of different monomers. These monomers mostly contain C and H. Owing to weathering by mechanical friction, chemical oxidation, or biological erosion in the environment, microplastic surfaces can act as new niches for aquatic microorganisms, and the constantly increasing microplastic pollution has the potential to globally impact the carbon dynamics of pelagic environments by altering heterotrophic activities (Arias-Andres et al., 2018; Fernández-González et al., 2020). The effects of microplastics on greenhouse gas emissions from fertilized soil indicate that microplastics have a selective effect on microbes and can potentially have a serious impact on terrestrial biogeochemical cycles (Ren et al., 2019). Marine microplastics may affect carbon stocks through their impact on phytoplankton photosynthesis and growth and can cause changes in the marine biological pump (Shen et al., 2019). Glaciers store large amounts of organic carbon from local or distant sources, which are released downstream and affect the terrestrial and aquatic carbon fluxes during ice and snow melt (Hood et al., 2015; Li et al., 2018). The sorption of organic pollutants onto microplastics may cause the redistribution of organic carbon in snow owing to the different contributions

of hydrogen bonding. Furthermore, microplastics may affect the evaluation of total organic carbon analysis of water or sediments due to absorbed pollutants (Hu et al., 2019). Recent research has indicated that microplastics can inhibit organic matter degradation, which can influence greenhouse gas (e.g., CO_2, CH_4 and NH_3) emissions from soil (Sun et al., 2020). The results revealed that PE and PHA aggravated CH_4 and NH_3 emissions by 7.9–9.1% and 20.9–33.9%, respectively; however, PVC decreased CH_4 and NH_3 emissions by 6.6% and 30.4%, respectively (Sun et al., 2020). In the context of straw incorporation, although microplastics were enriched in carbon, they were relatively stable and difficult to be used by microorganisms, lead to reducing the mineralization and decomposition of soil organic carbon but increasing the mineral-associated soil organic carbon content (Yu et al., 2021). Until now, few studies have been conducted detailing the effects that microplastics have on the carbon cycle in the cryosphere. The potential effect of microplastics on the transport of carbonaceous substances (Zheng and Suh, 2019) therefore requires further study, as it is a cause of significant concern in the Earth's carbon cycle as shown in Fig. 5.

5.3. *Potential climatic risk of microplastics in the cryospheric regions*

Over the past few decades, global plastic production has continued to increase (PlasticsEurope, 2019). Microplastics are diverse in size, shape, and color, and comprise a wide array of polymers with varying structural characteristics (Rochman et al., 2019), occurring as a mixture of diverse chemical compounds in the environment. Arctic sea ice can be considered a temporary sink, a source, and an important transport vector of microplastics (Peeken et al., 2018). Simulation of the Arctic snow falling on the sea ice between Northern Greenland and Europe indicates that it contains large concentrations of road microplastics, primarily from North America and Europe (Evangeliou et al., 2020), illustrating the importance of atmospheric transport on microplastic pollution in the cryosphere.

Previous studies have indicated that dark substances (such as BC particles or mineral dust, known as light-absorbing impurities) in snow and ice can reduce the surface albedo and absorb more radiation (Skiles et al., 2019; Kang et al., 2020; Warren and Wiscombe, 1980; Warren, 2019; Zhang et al., 2017, 2020c). These light-absorbing impurities can significantly darken the snow cover, sea ice, and the ablation zone of the Greenland ice sheet, where the accelerated melting of seasonal snow is already reducing the albedo by exposing darker, ponded ice earlier in the season (Bond et al., 2013; Flanner et al., 2007; Skiles et al., 2019). In mountain glaciers and snow-covered areas (Alps and Tibetan Plateau), the effect of light-absorbing impurities is expected to reduce snow cover and enhance melting (Di Mauro et al., 2019; Kang et al., 2020; Zhang et al., 2017, 2020c).

Microplastics in the atmosphere and snow/ice (or supraglacial debris) include particles of many colors (Ambrosini et al., 2019; Rochman et al., 2019; Zhang et al., 2020a). These colorful fine particles have the ability to absorb radiation (Revell et al., 2021), and can therefore subsequently enhance cryospheric melting by lowering the albedo. In a recent study, the calculated the effective radiative forcing by atmospheric microplastics was to be 0.044 ± 0.399 fW m^{-2} in the present-day atmosphere with assuming a uniform surface concentrations of 1 microplastic particle per cubic metre and a vertical distribution up to 10 km altitude, which highlighted the light-absorption of microplastics (Revell et al., 2021). Plastic particles in the marine environment can contribute to the warming or cooling of the water column by scattering and attenuating incoming solar radiation, leading to potential changes in the optical and other physicochemical properties of the water column, which may induce climate feedback cycles in the ocean surface and near-surface layers (VishnuRadhan et al., 2019). In the Arctic region, an experimental study found that the accumulation of microplastics at the surface of the sea ice created impurities, which can diffuse reflected incidental light and increase the albedo (Geilfus et al., 2019). The effect of microplastics is most pronounced early on, when the newly formed

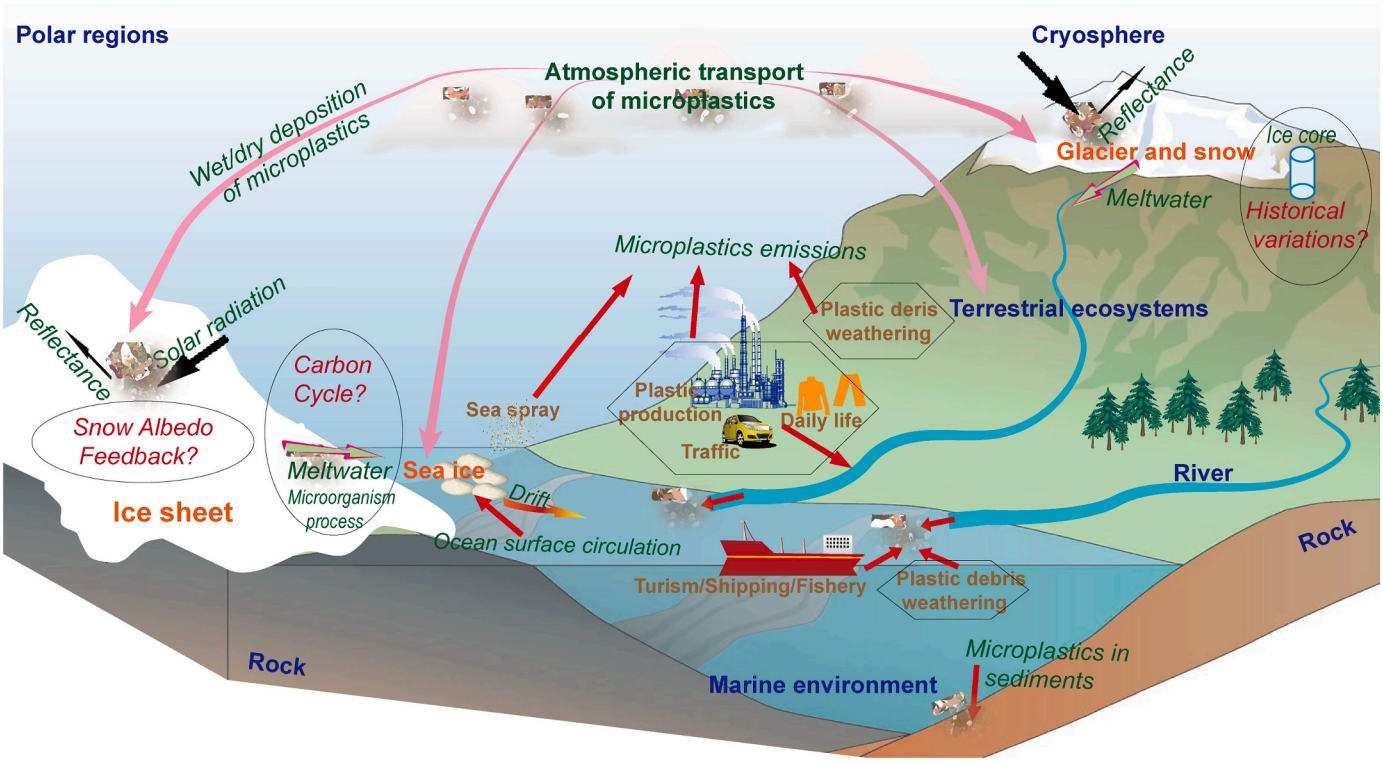

Fig. 5. A new conceptual map of microplastics in the typical cryospheric regions and their potential effect on climate change and the carbon cycle. Arrows are not to scale and are only for descriptive purposes. Concept from (Bank and Hansson, 2019; Brahney et al., 2020; Rochman et al., 2019; Zhang et al., 2019). Base map refers (Hilton and West, 2020).

ice has a relatively low albedo (Geilfus et al., 2019). Following the removal of snow during the melt season, microplastic inclusions at the sea ice surface may be subject to solar radiation loading, thereby enhancing the sea ice surface melt. At present, knowledge and understanding of the climatic effects of microplastics on snow and ice is still sparse, and several facets of this scientific issue remain poorly understood. The answers to questions such as the light absorbing and scattering properties of microplastics in snow or how we identify and quantify the potential effects of microplastics on radiation absorption and albedo reduction as compared to other particles (e.g., BC and dust) remain unanswered. Further research is needed to address these questions by continuing the study of how microplastics influence the snow and ice in cryospheric regions.

Based on the above discussion of previous studies, a novel paradigm of the plastic biogeochemical cycle has been developed to understand the fate and transport of microplastics within the cryospheric environment (Fig. 5). However, the role of the atmosphere as a dispersion pathway of microplastics, including the sources and processes from which atmospheric microplastics originate and the distance over which microplastics can travel in order to understand their presence in remote cryospheric areas requires further research and clarification.

6. Conclusions

This study presents current state-of-the-art knowledge on microplastics in snow and ice in typical cryospheric regions. Microplastics have been found in snow and ice in the Arctic, Alps, Tibetan Plateau, Andes, and the Antarctic regions, highlighting that microplastics have become ubiquitous global pollutants in the both marine and terrestrial environments. Reports detailing the presence of microplastics in snow and ice indicated that most particles were larger than 11 μm, and that the pollution was dominated by microplastics of small size (<50 μm). Most of the plastic polymers detected in the snow and ice samples were predominantly PET, PA, PE, and rubber. Because the cryospheric locations are generally at some distance from the microplastic emission sources, the snow and ice in these regions can be recognized as a temporal sink for atmospheric microplastics. Further research is needed to identify the various sources and transport routes (including primary or secondary origins) of microplastics in different cryospheric regions. To better understand the temporal fluxes under the continued increase of plastic production and waste generation, studying the microplastics that are retrieved from the ice cores of mountainous glaciers may allow us to investigate the trends of anthropogenic emerging pollutants in the Anthropocene era. Such studies are also important because microplastics comprise small sized, colorful particles that may darken the surface of snow and ice, reducing the albedo and thus posing a significant climatic risk in the cryospheric regions and altering the regional carbon cycle.

Declaration of Competing Interest

All authors of this work declare that there is NO conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2022.103924.

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