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Microplastics in glaciers of the Tibetan Plateau: Evidence for the long-range transport of microplastics

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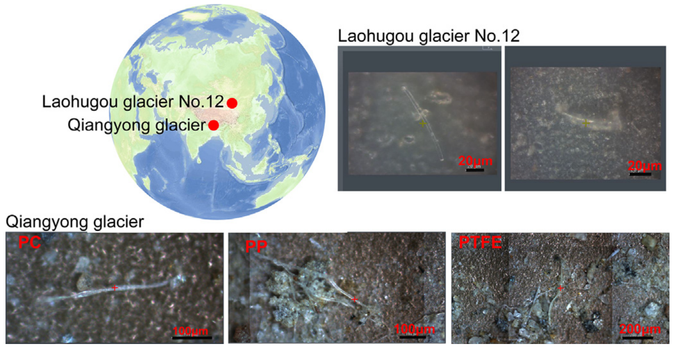
HIGHLIGHTS

- Tibetan Plateau pristine environment has been affected by atmospheric pollutants through long range transport.
- Microplastics have been detected from glacier surface snow in Tibetan Plateau.
- Atmospheric transport played an important role on microplastics into the plateau.
- Ice core may provide an opportunity to study history variations of microplastics.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics are globally prevalent on a large scale in various marine and terrestrial environments, including Arctic snow and precipitation in protected areas of the United Sates. However, reports of microplastics from glaciers are rare, especially for the Tibetan Plateau (TP), which is widely known as the world's Third Pole and Asian Water Tower. Adjacent to human settlements in South Asia, East China, and Central Asia, the TP features regular cross-border air pollution (e.g., black carbon and mercury), which can affect its vulnerable and pristine environments. In previous studies, abundant microplastics have been reported from Tibetan rivers/lakes water and sediments, and surface soils. We detected microplastics in glacier surface snow on the TP, which were isolated from the impact of human activities, indicating that microplastics can be transported over long distances. This evidence is expected to be significant for understanding the atmospheric transport of microplastics to the TP, and provides a global perspective on the microplastic cycle.

Microplastics (MPs) have been acknowledged internationally as pollutants and a significant environmental hazard since the 1960s (Kenyon and Kridler, 1969; Revel et al., 2018; Zeng, 2018; Zhang Q. et al., 2020). To date, studies on MPs from atmospheric deposition and glaciers remain limited, and the magnitude of their environmental effects is yet to be assessed (Hale et al., 2020; Wright et al., 2020; Zhang Y. et al., 2020). Recently, abundant MPs have been detected from the

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supraglacial debris of the Forni Glacier (Italian Alps) (Ambrosini et al., 2019), European and Arctic snow (Bergmann et al., 2019), and precipitation in the protected areas of the United States (Brahney et al., 2020). These results suggest that atmospheric long-range transport (or airborne pathways) and deposition can be a significant and non-negligible pathway for MPs in the environment (Evangeliou et al., 2020; Hale et al., 2020; Wright et al., 2020).

The Tibetan Plateau (TP), known as the world's Third Pole with limited anthropogenic activities, is extremely sensitive to global environmental changes because of its unique topography (Yao et al., 2012). It is surrounded by regions dominated by the production of plastics (China and other Asian countries) and the dismantling of commercial ships (South Asia, India, Bangladesh, and Pakistan) (PlasticEurope, 2019). The recognition of MP pollution in the remote area of the TP might be an important scientific issue and a relevant topic in addressing the global plastic cycle (Allen et al., 2019; Evangeliou et al., 2020; Bank and Hansson, 2019). However, studies on MPs in high-altitude glaciers of this remote area have not been reported yet.

In this work, snow samples from two glaciers are studied. Laohugou glacier No.12 is located in the Qilian Mountains of the northern Tibetan Plateau. It is a large valley glacier with an area of 21.9 km^2. Qiangyong glacier is located between the Himalayan ranges and the Yarlung Zangbo River in the southern Tibetan Plateau, with a length of 4.6 km and a total area of 7.7 km^2. In snow samples collected from the Qiangyong glacier (QY) in the southern TP and Laohugou glacier No. 12 (LHG) in the northern TP (Text S1, Table S1, and Fig. S1 in the supplementary information (SI)), three shapes of MPs were detected (fiber, fragment, and film) using FTIR and Raman spectroscopy (Fig. 1a). For the measured MPs in snow, most fibers were black, similar to those detected from urban atmospheric deposition (Zhang Q. et al., 2020), whereas the films were of different colors (red, green, and blue). The polymers identified from the glacier snow samples included polyamide (PA), rubber, polypropylene (PP), polyethylene terephthalate (PET), polycarbonate (PC), polytetrafluoroethylene (PTFE), and polyethylene (PE) (Fig. 2a and Table S2 in SI). To date, fibers are the most common shape of MPs found in Tibetan glaciers. The latest studies on atmospheric MP indicate that the main shape of suspected MPs in urban areas was fiber (Liu K. et al., 2019; Liu C. et al., 2019). In rural and remote areas of Europe, fragment was the dominant shape from wet and dry deposition (Klein and Fischer, 2019; Allen et al., 2019). No spherical or pellet-shaped MPs, which are commonly found in seawater or freshwater, were found from the TP glaciers (Lambert and Wagner, 2017). From Alps glacier snow samples, it's reported that fibers represented 65.2% and fragments 34.8% of items in all samples pooled; both microplastic fragments and fibers were of diverse colour (Ambrosini et al., 2019). As to the snow samples from Andes glacier, transparent, blue, white and red mcroplastics were the morest abundant colors (Cabrera et al., 2020).

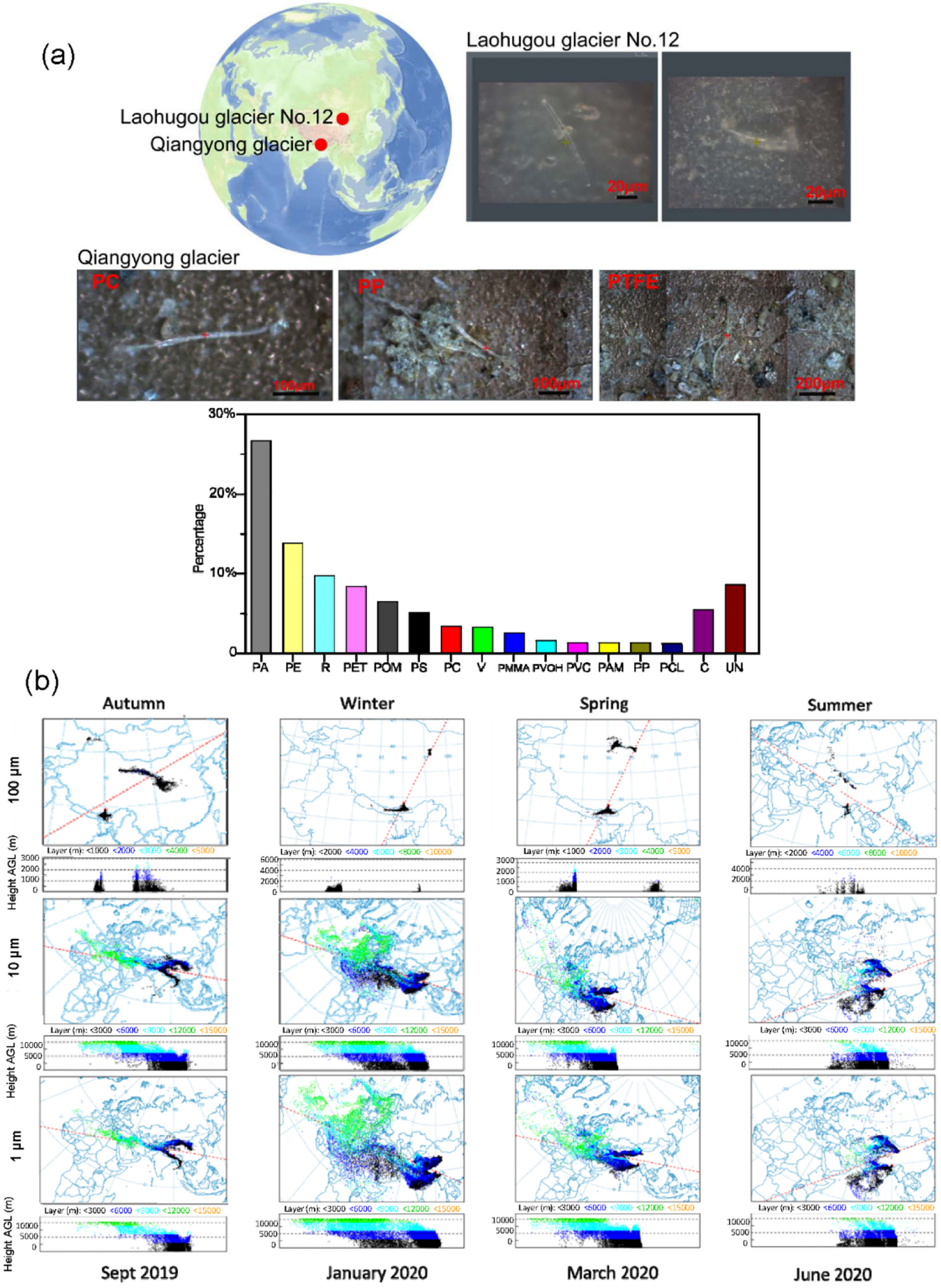
MPs in the environment vary in shape, size, and polymer composition depending on the sources, degradation and erosion processes, and residence time. For example, atmospheric MPs from different regions (urban, suburban, and remote locations) show large differences in size distributions and chemical compositions (Allen et al., 2019; Cai et al., 2017; Zhang Y. et al., 2020). Most fragment particles were usually less than 50 μm in size, but fibers were predominantly 100–300 μm in length (Hale et al., 2020). In this study, MP sizes less than 100 μm were predominant in the TP snow (Fig. S2 in SI). It was expected that the MP abundance increased as the fragment size decreased (Hale et al., 2020). This would correspond with the results of studies in the remote areas of Europe, where MP fibers were found to be larger than 2600 μm, whereas MPs with sizes of 50–150 μm contributed to more than 50% of the total detected MPs (Allen et al., 2019). Approximately 60% of the MP particles in sea ice samples were approximately 11 μm in size, with approximately 30% of MP particles in the range of 11–25 μm (Peeken et al., 2018). The size distribution of MPs in European and Arctic snow (11–500 μm, with 60% in the range of 11 μm) was unexpectedly similar to that found in Arctic sea ice and deep-sea sediments (Bergmann et al., 2017, 2019; Peeken et al., 2018), indicating the presence of numerous particles below the detection limit of 11 μm. For Alps glacier snow, about 39% of plastic items could not be characterized because their size was below the limit of detectability (~100 mm) due to the limitation od measurements (Ambrosini et al., 2019). In the TP, the smallest MPs in glacier snow were less than 10 μm in diameter, although MPs up to 500 μm long were also detected (Fig. 1a). As the MP particles found in European and Arctic snow were quite small (60% were ~11 μm) (Bergmann et al., 2019), MPs in Tibetan glaciers may be similar due to the snow deposition of MPs onto glacier surfaces. Due to the limited data in this study, we cannot provide comprehensive MP size distributions.

According to data released from PlasticsEurope (2019), plastic production reached 359 million metric tons in 2018 with an annual increase of 3%. Plastic production in Asia accounts for approximately 51% of global production (PlasticsEurope, 2019). Once these plastics have been released into the environment, the transportation of MPs through air and water flow is practically impossible to mitigate through regulatory measures. It has been estimated that long-range transport accounted for more than 1000 metric tons of plastic deposition on protected areas in the Western United States annually (Brahney et al., 2020). Wind transfer could deposit 7–34% of primary or waste MPs into the oceans (Boucher and Friot, 2017; Evangeliou et al., 2020), and a proportion of oceanic MPs can also be transported as atmospheric MPs (Allen et al., 2020). These findings further highlight the importance of atmospheric transport for MP deposition (Zhang et al., 2019). Atmospheric transport of MPs was also considered to be a major pathway into remote regions (Brahney et al., 2020; Evangeliou et al., 2020).

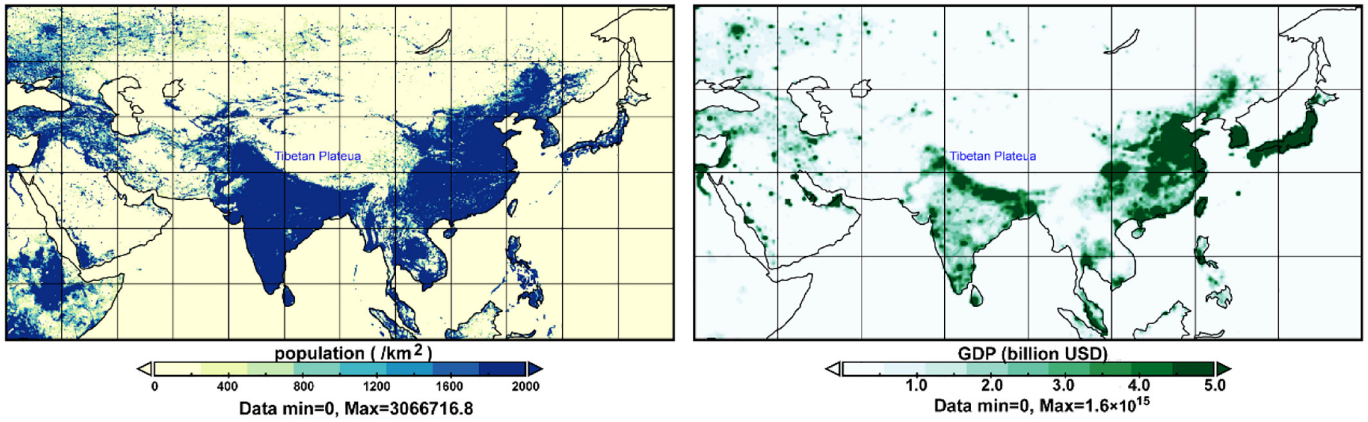
The potential sources and routes by which engineered MPs entered the TP have been discussed in previous studies (Zhang et al., 2019). In the northeast part of the TP, MPs in water bodies mainly came from tourism. Activities such as agriculture and previous secondary industries were also found to be the major contributors to soil MPs (Feng et al., 2020; Xiong et al., 2018). Studies in river water and lakeshore sediments in the TP indicated the impact of human activities (e.g., solid waste and wastewater) (Jiang et al., 2019; Zhang et al., 2016). Atmospheric MP deposition should also be considered in remote areas (Hale et al., 2020). In this study, tentative atmospheric particle modeling for 100 μm MP particles suggested local input of MPs in the studied areas (Fig. 1b). However, particle dispersion modeling, undertaken to consider 10 and 1 μm MP particles, suggested that the atmospheric transportation of MPs deposited on the studied glaciers mainly originated from Central Asia, Northern Africa (autumn), across Central Europe and as far as the Atlantic Ocean (winter and spring), down over the northern Indian Ocean and up toward Russia (summer) (Fig. 1b). The simulation results may indicate that MPs arriving at the TP could have been transported from both, short- and long-range distances, because human activities at higher elevations of the plateau is minimal.

The TP has ensured a permanent flow to Asia's major rivers, significantly influencing the socio-economic development of surrounding countries, which account for a fifth of the global population (Yao et al., 2012; Immerzeel et al., 2019). The population density and gross domestic product were intensively distributed around the TP (Fig. 2a and b), suggesting that more plastic production, use, waste, and leakage

Fig. 1. Microplastics measured from glacier snow in the Tibetan Plateau (a), and (b) atmospheric particle dispersion modeling of 100, 10, and 1 μm MP particles arriving at the Laohugou Glacier and Qiangyong Glacier. In part (a), the abbreviations for the measured polymers can be referred from Table S2 in SI. In part (b), MP particles were modeled as spherical with a density of 1 g/cm^3, and settling velocities were calculated using the Stokes law (0.3, 0.003, and 0.00003 m/s, respectively). Modeling was completed using HYSPLIT version 5 using the GDAS 1 degree archived global meteorology and run in the backward mode with a continuous tracer plume emission for 168 h at 50, 100, and 500 m above ground level.


(a)
Laohugou glacier No.12
Qiangyong glacier
Laohugou glacier No.12
20μm
20μm
Qiangyong glacier
PC
100μm
PP
100μm
PTFE
200μm
Percentage
30%
20%
10%
0
PA
PE
R
PET
POM
PS
PC
V
PMMA
PVOH
PVC
PAM
PP
PCL
C
UN
(b)
Autumn
Winter
Spring
Summer
100 μm
10 μm
1 μm
Height AGL (m)
Layer (m): <1000 <2000 <3000 <4000 <5000
Layer (m): <2000 <4000 <6000 <8000 <10000
Layer (m): <3000 <6000 <9000 <12000 <15000
Sept 2019
January 2020
March 2020
June 2020

(a) Population (b) Gross Domestic Product (GDP)



(c) Annual wind (d) Spring wind

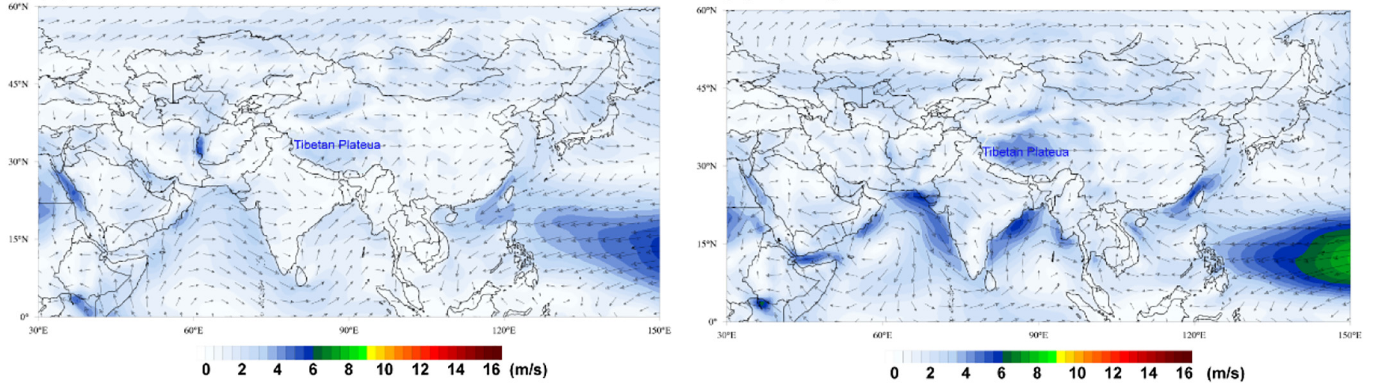


Fig. 2. Distributions of (a) population and (b) gross domestic product around the Tibetan Plateau, and simulated ERA-Interim annual wind (c) and spring wind (d) in the Tibetan Plateau and its surroundings. Population and GDP data shown in (a) and (b) were downloaded from Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, https://esg.pik-potsdam.de/projects/isimip/) (Murakami and Yamagata, 2016). These data were then obtained using PANOPLY (a Java application that allows users to make plots of data from netCDF, HDF, and GRIB dataset). ERA-Interim data of wind for (c) and (d) were prepared on the lines of https://climatereanalyzer.org/.

occurred in these regions due to extensive human activities. Simulations of annual ERA-Interim mean wind indicated that one branch of the westerly was forced from a high terrain into a northwesterly path (along the Himalayas) (Fig. 2c). Particularly in the spring season, when atmospheric brown clouds occur over South Asia (Ramanathan et al., 2005), the polluted air masses could reach the southern Himalayas and are further carried by the mountain-valley breeze circulation into the TP (Fig. 2d). Glaciers and lakes in the TP are usually distant from major sources of pollutants. Previous studies also indicated that air pollutants from South Asia could be transported into the complex topography of the Himalayan-TP by local meteorological conditions and regional atmospheric flows (Kang et al., 2019). For instance, a majority of anthropogenic black carbon over the TP was transported from South Asia, which contributed to 40–80% of surface BC in the monsoon season (Yang et al., 2018; Zhang et al., 2018). Stable isotopes of mercury in sediments of Lake Gokyo at high elevations of the Himalayas suggested that transboundary mercury transport from anthropogenic emissions in South Asia was the dominant source (Huang et al., 2020). Based on this understanding and as an important air pollutant, MPs can be transported by atmospheric circulation and deposited on glaciers and lakes far from their source regions because of their buoyant and persistent properties, indicating that the long-range atmospheric transport of MPs is a significant source of their deposition on the TP. As shown in Figs. 1b and 2c, especially in the summer season, the southern TP was mainly influenced by the South Asian monsoon, which brought excess precipitation to the plateau (Yao et al., 2012). “Plastic rains” (wet deposition), as mentioned by Brahney et al. (2020), may bring a large amount of MPs to the glacier surface.

The TP contains the largest volume of glaciers outside the polar regions, most of which are undergoing rapid retreat (Yao et al., 2012). Glaciers can provide insight into the long-range (or global-scale) atmospheric transport of air pollutants (including MPs, or black carbon), owing to their extremely high elevation, meteorological (wind) conditions, and unique dry and wet (snow) deposition processes (Kang et al., 2019; Zhang Y. et al., 2020). MP deposition, accumulation in glaciers, or release from melting glaciers may provide important information that has so far been neglected, such as high-altitude MP transport dynamics (shape, size, ubiquity, and historical variations), and possible atmospheric source identification. As glaciers are currently retreating, these small particles will be released into aquatic ecosystems. The possible contamination and impacts of MPs on the ecosystems in the TP and other remote areas are increasingly concerning, and may pose a future climatic risk due to their ability to absorb solar radiation and accelerate melting (Bergmann et al., 2019; Brahney et al., 2020; Evangeliou et al., 2020). Technological developments will enhance the study of MPs in the cryospheric environment in the future, and provide inroads into nanoplastic analysis (Materic et al., 2020; Sun et al., 2020). Mitigating the emissions of polymers into the air and aquatic ecosystems should be a universal responsibility to avoid exceeding critical environmental threshold concentrations.

CRediT authorship contribution statement

In this study, Y. Zhang, T. Gao, X. Luo and S. Kang initiated and coordinated the commentary. Y. Zhang wrote the manuscript, S. Kang and D. Allen guided the whole work and gave critical comments. T. Gao, and X.

Luo carried out the field work in the TP. Y. Zhang and T. Gao did the experiment. S. Allen and D. Allen produced the figures on simulations of MPs transport. All authors commented on the submitted manuscript.

Declaration of competing interest

The authors declare that they have no conflict 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.scitotenv.2020.143634.

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