*Antarctic Science* (2025), **37**, 104–116
doi: 10.1017/S0954102024000555



## Physical Sciences

# Microplastics in Antarctic air: revealing current findings

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### Abstract

This work provides a comprehensive examination of microplastic air pollution in Antarctica. Due to atmospheric microplastics' emerging importance, analytical procedures and health effects are discussed. Microplastic pollution poses an increasing threat to the unique and delicate Antarctic ecosystem, potentially triggering harmful consequences not only for the local ecosystem and fauna, but also for human health and well-being, given the severe implications of microplastic pollution for global scenarios such as imminent worldwide warming and the melting of polar ice. Numerous investigations have now exposed the extent of microplastic pollution in the Antarctic and the prevalence of both nano- and microplastics in this region, a significant storehouse of the planet's freshwater. This work also highlights the challenges of assessing the hazards that microplastics, particularly the nanoscale variants, may pose to human health and life maintenance. The results of this work suggest that global mechanisms of microplastic pollution mitigation are critical to microplastic transportation to the Antarctic reaches. This overview provides a better understanding of microplastic pollution in Antarctica while highlighting the urgency of more comprehensive research in this area to elucidate more precisely the short-, medium- and long-term effects of the arrival of these emerging contaminants in the Antarctic.

**Keywords:** Air pollution; Antarctica; human health risks; microplastics; nanoplastics

(Received 11 June 2024; revised 10 November 2024; accepted 12 December 2024)

## Introduction

In the southernmost part of the planet, specifically below the 60°S parallel, lies the Antarctic continent (Fig. 1), a frozen desert formed by a territorial extension of ~14.2 million $km^2$ and 30 million $km^3$ of ice (British Antarctic Survey 2024), bathed by the Atlantic, Pacific and Indian oceans. Antarctica is not only the most remote and uninhabited region on the planet, but also the driest, windiest and coldest region in the world, with the lowest temperature record ever measured on Earth at -89.2°C (British Antarctic Survey 2024).

Despite its climatic conditions, Antarctica is an area of extraordinary scientific interest not only because of its dense ice sheets averaging 4.8 km thick, which constitute 60% of all fresh water on Earth and 90% of all fresh water on the surface of the planet, and which give the area the highest average altitude of all the continents (British Antarctic Survey 2024), but also because of the unpolluted nature of its territory due to its remote geographical position and the almost absolute absence of human activity. These unique characteristics, incomparable to other regions of the globe, make Antarctica a suitable site for studying all sections of the atmosphere, observing exceptional natural phenomena and even monitoring and investigating space, among other scientific endeavours (British Antarctic Survey 2024). Nevertheless, over the years, pollutants associated with anthropogenic activity from different latitudes of the globe have emerged in this remote frozen zone, especially in its atmosphere, posing an imminent risk to the maintenance of the delicate Antarctic ecosystem and introducing unprecedented serious polluting threats to the area.

Specialized research into the occurrence of plastic microparticles in Antarctic ecosystem matrices such as water (Waller *et al.* 2017, Zhang *et al.* 2022a, Gurumoorthi & Luis 2023), snow (Lim 2021, Aves *et al.* 2022), soil (Munari *et al.* 2017, Perfetti-Bolaño *et al.* 2022) and into the Antarctic flora (Botterell *et al.* 2019) and fauna (Auman *et al.* 2004, Bessa *et al.* 2019, Fragão *et al.* 2021, Bergami *et al.* 2023) has developed significantly over the past decade. Nevertheless, it is only recently that their presence in the Antarctic atmosphere has been identified for the first time, as evidenced in a particular study aimed at characterizing Antarctic aerosols (Marina-Montes *et al.* 2022). In addition to demonstrating the presence of exotic minerals, fertilizers and different types of black carbon, this work revealed the presence of microplastics (MPs) in aerosols from this area, specifically polystyrene fibres smaller than 5 $\mu$m in size, exposing serious concerns about the large-scale impact of anthropogenic activities and the pollution related to it, even in the remotest part of the globe, and

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**Cite this article:** Deylami, S., Cárdenas-Escudero, J., López Ochoa, M., Ayuso-Haro, J., Galán-Madruga, D., Urraca Ruiz, J. L., & Cáceres, J. 2025. Microplastics in Antarctic air: revealing current findings. *Antarctic Science*, 104–116. https://doi.org/10.1017/S0954102024000555

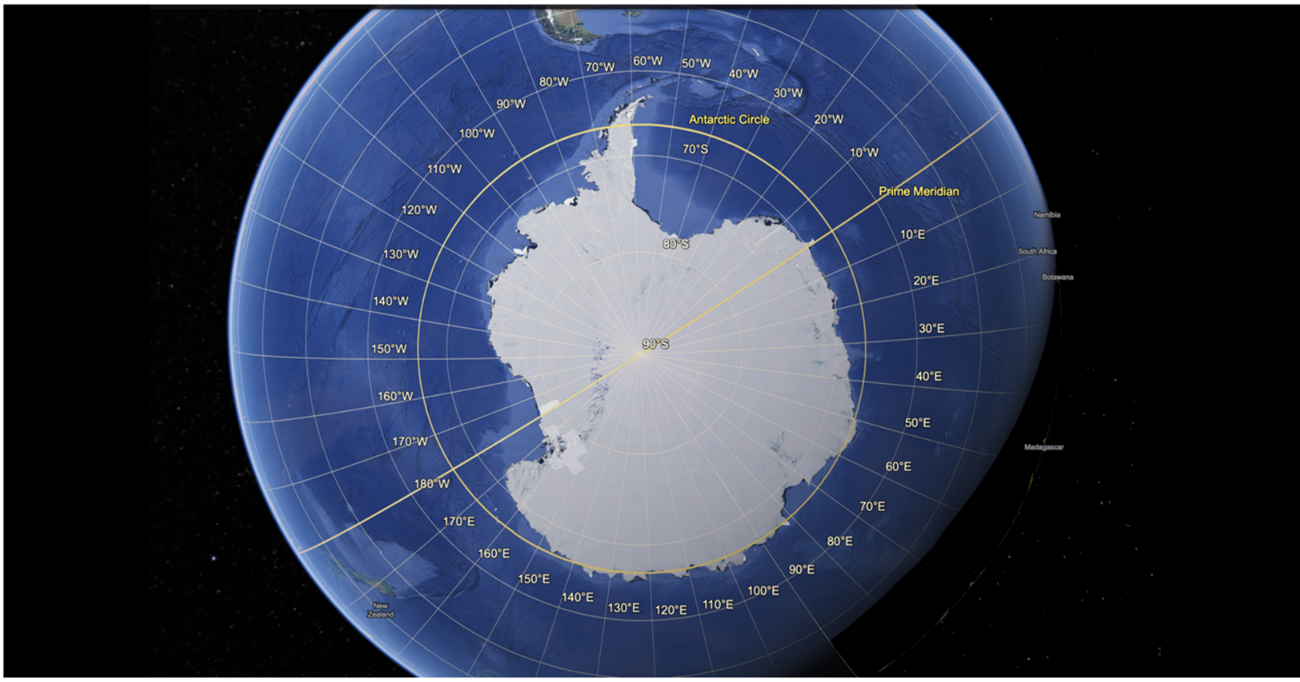



**Figure 1.** Antarctica's geolocalization satellite picture. The closest land region to the Antarctic continent is the southern coast of Cape Horn, Argentina, the southernmost region of the American continent. The Weddell Sea separates the two areas, where waters from the south Pacific, south Atlantic and Antarctic oceans mix. Image taken from Google Earth. Image data credit: SIO, NOAA, US Navy, NGA, GEBCOPGC/NASAU.S. Geological Survey Landsat/Copernicus.

representing a historic turning point in the modern study of atmospheric pollution, especially in Antarctica.

In this sense, this review article aims to offer a detailed and context-specific overview of the causes of MP occurrence in Antarctic air, with a perspective orientated towards the elucidation of the mechanisms involved in their transport, whether long term, regional or local, by exploring the evidence produced to date, not only from a point of view strictly associated with the air matrix, but also from its integration with the other matrices that constitute the Antarctic environment and the processes that these involve in participating in the dynamics of MP contamination. Moreover, for the first time ever, this review article focuses on understanding the link between MP pollution in the Antarctic region and its influence on climate change, an emerging field of environmental study that has been underexplored at present and is extremely necessary for the establishment of objective and efficient measures to combat the consequences of these pollutants in the environment of the Antarctic region.

## Historical background to the study of atmospheric pollutants in Antarctica

Research associated with pollution in the Antarctic region, according to the SciFinder® Discovery Platform, consists of a relatively limited number of publications compared to in the other areas of the globe. Specifically, publications concerning studies of environmental pollutants (Fig. 2a) make the most significant contribution to Antarctic pollution research. However, publications specific to MPs and air pollutants are relatively minimal. Using the term 'microplastics in Antarctica' as a search criterion from 2010 onwards, an increase in publications on this topic is evidenced (Fig. 2b), indicative of the youth and slow growth of this relevant and specialized line of research.

Studying atmospheric pollution in the Antarctic region and concerns about its effects on this unique and delicate ecosystem, such as global warming, are not new (Table I). In 1896, more than 100 years ago, research led by Arrhenius demonstrated the ability of water vapour and carbon dioxide gases to significantly influence the Earth's temperature (Arrhenius 1896). This study ended the debate on the cause of the glacial and interglacial climate change that occurred during the Pleistocene and provided substantial evidence that emissions of these gases would contribute to increasing the Earth's temperature in the future (Tolman 1899).

These studies initiated the era of global warming research and produced countless publications supporting the importance of monitoring air pollutants and their impacts on the delicate Antarctic environment. Years later, given the installation of multiple military and research bases in the Antarctic region, questions arose regarding the impacts of such anthropological activity on atmospheric pollution, mainly associated with gaseous and particulate matter emissions from fossil fuel-fired power generators. This led to the detection of new Antarctic air pollutants, such as $NO_x$, CO, inhalable particulate matter with a diameter of ≤ 10 μm ($PM_{10}$), as well as $CO_2$ (Sergey 2020) and $SO_2$ (Kakareka & Salivonchyk 2022). Similar studies on the impacts of anthropological activity in this region led to the detection of metallic contaminant species in the Antarctic atmosphere, such as Cd, Cu and Zn, as well as significant contributions of Pb and S (Boutron & Wolff 1989). More recent studies (Marina-Montes *et al.* 2020) aimed at studying the transport of heavy metals and the evolution of aerosols in Antarctica have demonstrated the presence of Hf, Zr, As, Cu, Sn, Zn and Pb in Antarctic aerosols, which has provided significant evidence of the imminent contamination faced by the Antarctic region and, in turn, the severity of air pollution caused by anthropological activities.

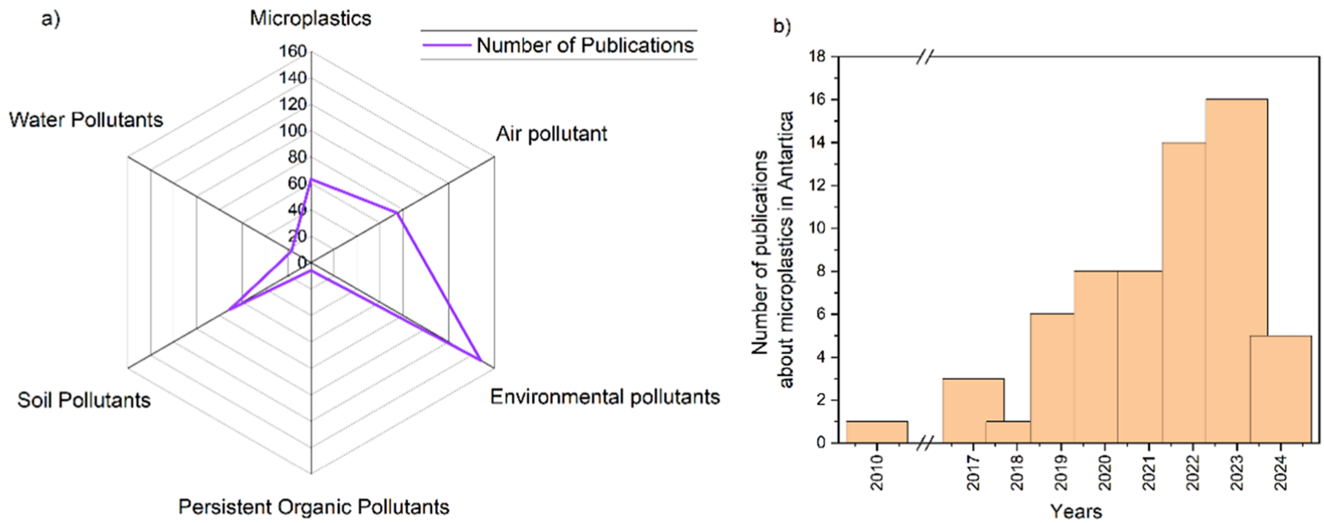



**Figure 2.** Research into Antarctica's atmospheric microplastic pollution through the years, according to SciFinder® Discovery Platform. **a.** Number of publications concerning environmental pollutants. **b.** Number of publications about 'microplastics in Antarctica'.

## Origins of microplastics and their transport to Antarctica

The limited evidence gathered in studies associated with delimiting the sources or origins of MPs in Antarctica and other remote regions points to the importance of certain factors of a physical, chemical and climatological-meteorological nature that strongly influence the way MPs are generated, incorporated and transported into the atmosphere (Horton & Dixon 2018), eventually reaching the Antarctic continent (Obbard 2018, Mishra *et al.* 2021, Citterich *et al.* 2023). These studies suggest that MP origins and transport to the polar regions are not fully elucidated (Obbard 2018, González-Pleiter *et al.* 2020). Nevertheless, recent studies have pointed in important directions regarding resolving this uncertainty.

Depending on how they originate, MPs are classified into two main groups: primary and secondary MPs (Laskar & Kumar 2019, An *et al.* 2020, Mathew *et al.* 2024). Primary MPs originate from the direct use of products, as is the case of microbeads in personal care products, plastic pellets (or nurdles) used in industrial manufacturing and plastic fibres used in synthetic fabrics such as Nylon, Lycra and polyester (An *et al.* 2020). Secondary MPs are formed from the degradation of larger plastics, especially plastic waste that accumulates on the Earth's surface and is subsequently subjected to inclement weather over long periods (An *et al.* 2020, Mathew *et al.* 2024), undergoing physical processes such as wind erosion (Waldschläger & Schüttrumpf 2019), wave action or mechanical abrasion (Song *et al.* 2017) and chemical processes such as degradation by the action of ultraviolet radiation from sunlight (Bergmann *et al.* 2015). Additionally, in aquatic environments, plastic wastes can undergo further degradation due to wave action (Bergmann *et al.* 2015), digestive fragmentation by marine fauna (Dawson *et al.* 2018) and freeze degradation (Peeken *et al.* 2018), generating smaller MPs - even nanoplastics - that can be incorporated into the atmosphere, as has recently become evident (Liu *et al.* 2019a). Irrespective of their type, MPs can enter directly and very quickly into the environment by various means, such as subsequent discharge into wastewater systems, as in the case of personal care products; involuntary loss through spills during manufacturing or transportation; or by abrasion during laundering, as in the specific case of synthetic textiles. Due to their direct interaction with the environment, secondary MPs are incorporated faster into the ecosystem (Akdogan & Guven 2019, An *et al.* 2020).

Although MPs were first qualitatively determined in Antarctic air in 2021, specifically in aerosol samples collected on quartz filters with the aid of active collectors (Marina-Montes *et al.* 2022), to date only two recently published studies have reported quantitative results. Specifically, the first study showed a daily deposition (average ± standard deviation) of 1.7 ± 1.1 MPs $m^{-2}$ $day^{-1}$ from passive-collected bulk atmospheric deposition samples ($n$ = 7) at 1.5 m above sea level in the Victoria Land, with values ranging from 0.76 ± 0.05 MPs $m^{-2}$ $day^{-1}$ at Edmonson Point to 3.44 ± 0.25 MPs $m^{-2}$ $day^{-1}$ at Larsen Glacier (Illuminati *et al.* 2024). The other study, aimed at establishing PM concentrations in Antarctic air, reported an occurrence of 0.035 PMs $m^{-3}$ in samples collected at ~25 m above sea level using a high-volume air sampler (Chen *et al.* 2023). In semi-quantitative terms, another previous study, aimed at identifying the nature of MPs present in Antarctic air, indicated the presence of 58 different types of MPs in atmospheric aerosol samples actively collected on fibreglass filters by collectors using a high-volume air sampler ~20 m above sea level (Cunningham *et al.* 2022).

According to the evidence collected to date, the specific incorporation of MPs into the atmosphere depends mainly on the morphology and physical characteristics of the particle, with smaller and less dense particles being more easily incorporated into the air (Obbard 2018, Chen *et al.* 2023). In comparison, larger and heavier particles are typically incorporated into aquatic systems (Jambeck *et al.* 2015, Van Sebille *et al.* 2016). Even during their transport in air, which is facilitated due to their lightweight nature, MPs can undergo fragmentation, leading to the formation of smaller MPs and nanoplastics (Napper & Thompson 2019), which, in turn, can deposit as heteroaggregates with organic matter and black carbon (Dubaish & Liebezeit 2013, Oriekhova & Stoll 2018) or can also form dynamically from aged MPs that are deposited after air transport (Materić *et al.* 2021). In addition, recent evidence has shown the relevance of the contribution of MPs to the atmosphere from ice cores originating from water contaminated with MPs, which, in turn, serve as huge vectors and reservoirs for these tiny pollutants (Peeken *et al.* 2018).

**Table I.** Background and key events in research on Antarctic aerosols and microplastic occurrence.

| | Year | Event description | Reference(s) |
|---|---|---|---|
| **Early studies about Antarctic atmospheric aerosols** | 1965 | Voskresenskiy (1968) conducted the first direct experiments with Antarctic aerosols at Mirny Station related to the total concentration of condensation nuclei quantitation in Antarctica's coastal zone with an expansion-type cloud chamber instrument. In this study, it was found that the number of condensation nuclei near the Antarctic coast was extremely low and was closely linked to wind direction. | Voskresenskii (1968) |
| | 1966 | Cradle *et al.* (1968) studied the chemical composition of Antarctic atmospheric particulate matter collected by impaction for the first time. The analysis showed that the Antarctic samples were enriched in sulphur species ($SO_4^{2-}$ and $S_2O_8^{2-}$) compared to samples from other locations around the globe. | Cadle *et al.* (1968) |
| | | Fischer (1967) published the results of an atmospheric turbidity study in Antarctica at McMurdo Station. | Fischer (1967) |
| | 1967 | For the first time in the Antarctic region, trace atmospheric chemistry was studied by determining gaseous species (aldehydes, $NO_2$ and $SO_2$) at trace levels by Fischer *et al.* (1968) | Fischer *et al.* (1968) |
| | 1969 | Preliminary explorations of Antarctic atmospheric chemistry were presented through a comparative study of the content of particulate matter and trace gases in this polar region with those of other areas of the globe by Fischer *et al.* (1969). | Fischer *et al.* (1969) |
| | 1979 | The first evidence on the study of aerosols in the Antarctic region was consolidated by Shaw (1979) in a literature review. | Shaw (1979) |
| | 1984 | *Science News* reported on the first international collaboration to study the transport of atmospheric pollutants to the Antarctic region. | Science News (1984) |
| | 1989 | Tomoyuki (1989) summarized the findings on the phenomenological behaviour of submicron aerosols observed in the Antarctic troposphere and highlighted that most Antarctic submicron particles are of tropospheric not stratospheric or anthropogenic origin. | Tomoyuki (1989) |
| **Early studies about Antarctic microplastic occurrence** | 2010 | Barnes *et al.* (2010) warned about the presence of microplastics around Antarctica and their imminent arrival in this far, delicate ecosystem. | Barnes *et al.* (2010) |
| | 2013 | Gheorghe *et al.* (2013) identified Antarctic scientific-based wastewaters as an important source of microplastic in the Antarctic region. | Gheorghe *et al.* (2013), Caruso *et al.* (2022) |
| | 2017 | For the first time, Munari *et al.* (2017) detected microplastics in Antarctic sediments. | Munari *et al.* (2017) |
| | 2020 | May - Kelly *et al.* (2020) reported microplastic contamination (11.71 particles/l) in east Antarctic Sea ice. | Kelly *et al.* (2020) |
| | | December - the first detection of microplastics (0.95 elements/1000 $m^3$) in freshwater in an Antarctic Specially Protected Area was reported by González-Pleiter *et al.* (2020). | González-Pleiter *et al.* (2020) |
| | 2021 | The first detection of microplastics in Antarctic glaciers was reported by González-Pleiter *et al.* (2021). The study indicated that the detected microplastics were deposited on the glaciers by local currents and past activities, probably by air transport. | González-Pleiter *et al.* (2021) |
| | | Mishra *et al.* (2021) reported that microplastic studies in the Antarctic are limited compared to those in the Arctic. | Mishra *et al.* (2021) |
| | | For the first time, microplastics were detected in Antarctic aerosols by Marina-Montes *et al.* (2022). | Marina-Montes *et al.* (2022) |
| | 2022 | The first detection of nanoplastics (52.3 ng/ml), principally constituted from polyethylene, in Antarctic Sea ice samples by Materić *et al.* (2022). | Materić *et al.* (2022) |
| | | Aves *et al.* (2022) reported the first detection of microplastics (29 particles/l) in Antarctic snow samples. | Aves *et al.* (2022) |
| | | The results of the first multiple media assessment of microplastics study in Antarctica were published by Cunningham *et al.* (2022). | Cunningham *et al.* (2022) |

Regarding MP transportation to Antarctica, one study has suggested that microparticle transportation is caused by a long-range transport pathway from the mainland; however, plastic debris entering the sea is another major contributor to the problem of MPs in the Antarctic environment (Obbard 2018). Another study estimated that out of 275 million metric tons of plastic waste produced that year by 192 countries during 2010, between 4.8 and 12.7 million metric tons of plastic waste entered the sea (Obbard 2018). In contrast to the transport dynamics of larger plastic debris, which can float on the sea surface and be subject to wind stress,

https://doi.org/10.1017/S0954102024000555 Published online by Cambridge University Press

MP particles are completely submerged, which slows down their transport (Lebreton & Borrero 2013). In more detail, MPs present in the ocean matrix can take many months or even years to cross the Pacific Ocean (Desforges *et al.* 2014). Even marine sediments in which the presence of MPs has been found constitute vectors that play a role in the transport of MPs (Browne *et al.* 2011, Munari *et al.* 2017); however, these transport mechanisms are not completely understood (Ballent *et al.* 2013), such as the case of MP transport in sea ice, which deposits MPs in the sea during the spring-summer period as well as the pollutants that accumulate during their formation in autumn and winter (Pfirman *et al.* 2004). Considering, however, the significant amounts of MPs detected in air in urban (Dris *et al.* 2016, Yuan *et al.* 2023,Chen *et al.* 2024, Leitão *et al.* 2024) and remote (Aves *et al.* 2024, Niu *et al.* 2024, Wei *et al.* 2024) areas, as well as the majority occurrence of plastic fibres in the detected PMs, it is considered that the transport of PMs in air is more significant than in water (Obbard 2018). From a quantitative perspective, the overall atmospheric contribution of land- and aquatic-based sources is very different, as is evidenced by the fact that 80% of MPs are produced on land, whereas the rest come from oceanic sources (Van Sebille *et al.* 2016). According to the evidence available to date, vectors actively involved in the long-term transport of MPs to the Antarctic region include ocean currents from the Atlantic to the Pacific and rivers, into which solid plastic debris is incorporated from the surface, and wind, which carries contaminants from urban sites or over long distances (Obbard 2018). All of this is significantly influenced by the vertical heterogeneity of the medium in which MPs are transported (Hardesty *et al.* 2017) and their typical morphology (fibres; Dris *et al.* 2016, Carr 2017, Obbard 2018), causing the vertical mixing of these pollutants and their distribution in the environment according to their physical characteristics (Ballent *et al.* 2012, Kukulka *et al.* 2012, Isobe *et al.* 2014). Observational and modelling studies have provided very important evidence specifically associated with the vertical mixing of MPs caused by wind-driven turbulence, which causes the distribution of MPs in the water column according to their size, explaining the proportion of smaller MPs increasing with depth (Cózar *et al.* 2014, Eriksen *et al.* 2014, Obbard 2018).

This evidence is congruent with a more recent study focused on modelling the transport of MPs to the Antarctic that, in addition to confirming the mechanism of long-range transport of MPs, provided evidence about the Southern Hemisphere MP contribution, which is similar to the long-range transport of non-plastic particles (Chen *et al.* 2023).

Recently, a very specific and specialized study on the sources and modelling of the airborne transport of MPs collected at a remote Southern Hemisphere site has reported the first remote deposition fluxes of airborne MPs in New Zealand, providing very interesting evidence on the transport of MPs to the Antarctic aerial matrix (Aves *et al.* 2024). The results of this study indicate the significant contribution of MPs from sea spray to the atmosphere. Additionally, this study has pointed out the relevance of resuspension processes and the reincorporation into the atmosphere of already deposited MPs due to two aerodynamic processes: 1) the atmospheric resuspension of previously transported and deposited MPs in remote parts from populated areas and 2) atmospheric resuspension from the ocean due to the breaking of waves and the bursting of bubbles.

For this reason, interesting research has been developed on MP inputs from local and nearby sources, especially military bases, as the evidence highlights their role in Antarctic MP pollution (Citterich *et al.* 2023). In 2009, it was established that of the 71 military bases existing in Antarctica at that time, 52% lacked a waste treatment plant and 37% were permanent, implying a persistent anthropological polluting activity in the region (Mishra *et al.* 2021). Further studies evidenced the incorporation of MPs into the environment from the wastewater produced by scientific bases (Gheorghe *et al.* 2013, Caruso *et al.* 2022). On the other hand, studies have also suggested that the transport of MPs, especially fibres present in Antarctic freshwater, potentially results from the waterproof clothing used by the bases' personnel, which is mainly constituted of polytetrafluorethylene (PTFE) and fibres such as acrylic and polyester fibres, the same kind of fibres found in the freshwater of an Antarctic Specially Protected Area (González-Pleiter *et al.* 2020). This is also consistent with a further study that highlighted microfibres from textiles as a significant source of MPs in the Antarctic environment (Acharya *et al.* 2021). All of these MPs from local sources play a role in Antarctic air MP pollution, and some studies suggest that the occurrence of MPs in Antarctic air also stems from an important local origin (da Silva *et al.* 2023, Riboni *et al.* 2024).

Given the controversy surrounding the concrete delimitation of the sources of MPs in Antarctic air, some researchers consider that this situation is due to diffuse origins and multiple global processes (Cunningham *et al.* 2022). Despite the astonishing evidence of MP pollution in the Antarctic region and its atmosphere, from the evidence provided in this paper it is clear that this line of research on the origins and transportation of MPs to the Antarctic region is as yet understudied (Obbard 2018, González-Pleiter *et al.* 2020, Aves *et al.* 2022).

## Antarctica's microplastics menace

MPs are defined as plastic particles smaller than 5 mm in diameter or length, whose chemical composition is given by long polymeric chains, mainly constituted by carbon and hydrogen atoms bonded together (Materić *et al.* 2022). Several plastic polymers, such as polyamide, polyethylene and polyethylene terephthalate, are common constituents of these plastic microparticles (Kılıç *et al.* 2023). Although they did not detect the presence of MPs, the first studies warning about the emerging situation of plastic pollution in remote and uninhabited regions of the planet, such as Antarctica, date back to 2010 (Barnes *et al.* 2010). Perhaps the first observation of MPs in the Antarctic atmosphere, dating from 2021 (Marina-Montes *et al.* 2022), can be considered relatively late compared to studies of MPs in other matrices in the Antarctic environment. Nevertheless, it was not until 2016 that a specialized study on the detection of MPs in the non-Antarctic atmosphere was carried out for the first time, specifically in the city of Paris (Dris *et al.* 2016); therefore, the line of research on MPs in the atmosphere, in general, could be considered relatively young and, in the specific case of the Antarctic region, bibliographically scarce. Despite this situation, unprecedented research was published in 2022 in which the simultaneous study of multiple media of the Antarctic environment, including air, was carried out (Cunningham *et al.* 2022). In addition to presenting a thorough characterization of MPs in the air (Fig. 3), this study demonstrated their presence in other Antarctic matrices analysed, making it the first integrated study of MP contamination on the Antarctic continent.

Specifically, a total of 82 MP particles were detected, with a distribution in the matrices analysed of 53 (65%) in air, 18 (22%) in seawater and 11 (13%) in sediment samples. Interestingly, of the 53 MPs observed in air samples, four were simultaneously detected

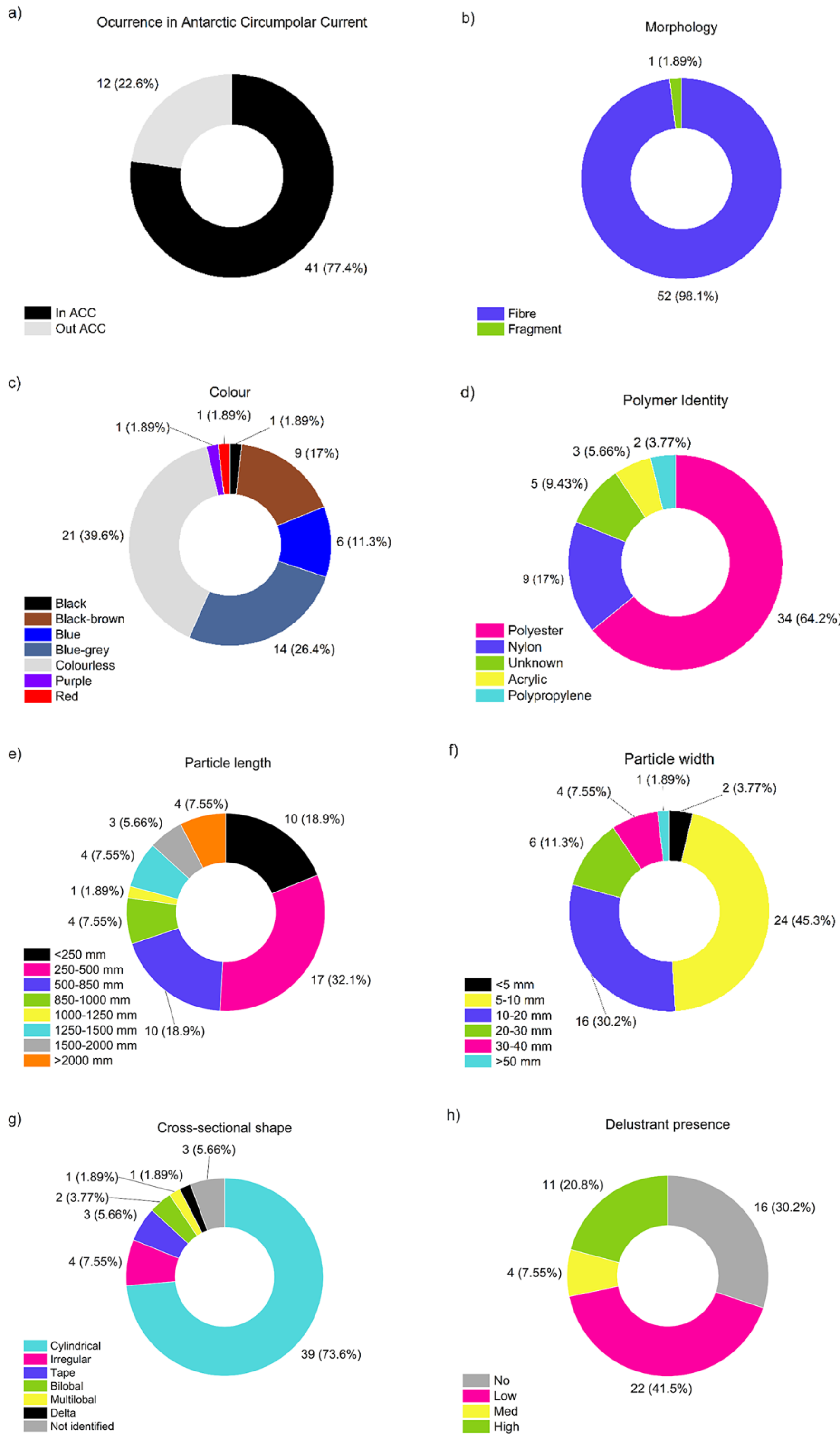
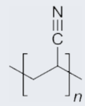
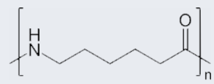
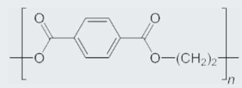
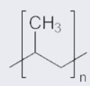
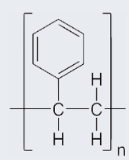



**Figure 3.** Characterization of microplastics detected in Antarctica's atmosphere, specifically at various locations in the Weddell Sea, inside and outside the Antarctic Circumpolar Current (ACC). Thirty-one samples and two airfield blanks were collected at ~20 m above sea level using a high-volume air sampler with an average flow rate of 0.82 $m^3$/min through a five-stage cascade impactor loaded with pre-combusted glass fibre filters. The characterization of microplastic was based on several criteria: **a.** occurrence in ACC, **b.** morphology, **c.** colour, **d.** polymer identity, **e.** particle length, **f.** particle width, **g.** cross-sectional shape and **h.** delustrant presence. This figure is adapted from Cunningham *et al.* (2022), an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0; https://creativecommons.org/licenses/by/4.0/) Copyright © 2022 Cunningham, Rico Seijo, Altieri, Audh, Burger, Bornman, Fawcett, Gwinnett, Osborne and Woodall.

in seawater samples and one in sediment samples, providing information on the potential relationship between these three different matrices in the dynamics of MP occurrence in Antarctica. One of the most interesting results of this study is the evidence for the occurrence of MPs inside and outside the Antarctic Circumpolar Current (ACC; Fig. 3a), which was observed in 41 (77%) and 12 (23%) MPs, respectively, demonstrating the influence of local sources on these pollutants' atmospheric occurrence. Other

https://doi.org/10.1017/S0954102024000555 Published online by Cambridge University Press

**Table II.** Chemical compounds that can be released from polymers detected in Antarctic air.

| Formula | Name | Chemical structure | Toxic chemicals released | Reference(s) |
|---|---|---|---|---|
| $(C_3H_3N)_n$ | Polyacrylonitrile (PAN) |  | Bisphenol A (BPA), bisphenols (BPs), benzophenones (BzPs) | Sait *et al.* (2021) |
| $(C_6H_{11}NO)_n$ | Nylon 6 (PA6) |  | Arsenic (As), chromium (Cr), fluoranthene, phenanthrene, endocrine disrupters such as 17$\alpha$-ethynylestradiol, 17$\beta$-estradiol and estriol | Lara *et al.* (2021), Cao *et al.* (2022), Li *et al.* (2024) |
| $(C_{10}H_8O_4)_n$ | Polyethylene terephthalate (PET) |  | Hexachlorobenzene, dichlorodiphenyl trichloroethane (DDT), polychlorinated biphenyls (PCBs), tetradecane, 2,4-di-tert-butylphenol, p-benzoyl-toluene, octadecane, phthalate esters | Cao *et al.* (2022), Li *et al.* (2024) |
| $(C_3H_6)_n$ | Polypropylene (PP) |  | Arsenic (As), chromium (Cr), fluoranthene, phenanthrene | Cao *et al.* (2022), Li *et al.* (2024) |
| $(C_8H_8)_n$ | Polystyrene (PS) |  | Cadmium (Cd), copper (Cu), polycyclic aromatic hydrocarbons (PAHs), phthalates, trihalomethane | Gulizia *et al.* (2023), Li *et al.* (2024) |

characteristics of the MPs observed in the Antarctic air samples collected in this study, such as their morphology (Fig. 3b), colour (Fig. 3c), identity (Fig. 3d), length (Fig. 3e), width (Fig. 3f), cross-sectional shape (Fig. 3g) and delustrant presence (Fig. 3h), provide evidence of their local origin and anthropogenic provenance, specifically through their association with the clothing used by people carrying out activities in the region. These results are very different from those obtained in another previous study characterizing airborne MPs in samples taken along the cruise trajectory from the mid-Northern Hemisphere (~30°N, close to Changjiang Estuary) to Antarctica (~74°S), in which the occurrence of MPs in Antarctic air was attributed to long-range transport (Chen *et al.* 2023).

Regardless of their origin, source and type, MPs pose an imminent environmental threat because they are not biodegradable, which results in their indiscriminate distribution and accumulation in the environment, disturbing the equilibrium of ecosystems. Moreover, recent studies have proven that chemicals with high human and environmental toxic impact commonly used as functional additives in plastics, such as phthalates, polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol A (TBBPA), can leach out from plastics after entering the environment or the human body (Biale *et al.* 2022, Do *et al.* 2022, Sun & Zeng 2022, Gulizia *et al.* 2023, Novotna *et al.* 2023, Prabhu *et al.* 2024, Tang *et al.* 2024), particularly from the smaller MPs (Gulizia *et al.* 2023). Table II shows the main polymers that constitute the MPs detected in Antarctic air and the toxic compounds they are capable of transferring into the environment.

Other studies (Biale *et al.* 2022, Gulizia *et al.* 2023, Novotna *et al.* 2023, Li *et al.* 2024) present more in-depth information regarding this MPs leaching mechanism. In addition to this situation, MP surfaces are able to adsorb toxic chemical compounds and undergo chemical modifications that produce other pollutants that can be released thereafter (Liu *et al.* 2019b). This evidence supports the capacity of MPs to absorb, transport and release dangerous chemical substances (Thompson *et al.* 2004, Fred-Ahmadu *et al.* 2020, Dissanayake *et al.* 2022).

## Environmental and climate implications of microplastic air pollution in Antarctica

The main problem stemming from MPs in Antarctica's atmosphere is associated with MP deposition on Antarctic glaciers, the most important reservoirs of fresh water worldwide (Stefánsson *et al.* 2021). These iced masses play an important role in Earth's thermal equilibrium, which includes the water cycle (Huntington 2006, Yao *et al.* 2019), carbon cycle (Anesio *et al.* 2009, Torres *et al.* 2017, Li *et al.* 2018) and ecological equilibrium of ecosystems (Lydersen *et al.* 2014, Hotaling *et al.* 2017, Ficetola *et al.* 2021). Specifically in the context of glacier melting, contamination by deposited airborne MPs constitutes a challenge through two main pathways. The first pathway concerns the release of MPs contained in glaciers, contaminating the surrounding water bodies (Fuentes *et al.* 2016, Ambrosini *et al.* 2019, Dong *et al.* 2021, González-Pleiter *et al.* 2021), which in turn may participate in the incorporation of MPs into the atmosphere. The second pathway relates to the involvement of MPs in accelerating glacier melting (Stefánsson *et al.* 2021, Zhang *et al.* 2022a,b). Given their chemical differences from the composition of glaciers, MPs are considered to be second-phase materials inside them, making it

https://doi.org/10.1017/S0954102024000555 Published online by Cambridge University Press

easier for them to potentially influence the physical properties of glaciers, such as their light absorption and other rheological properties associated with their melting (Hunter *et al.* 2019, Stefánsson *et al.* 2021), thus exacerbating the effects of climate change on the melting of Antarctic ice masses and their important role in the global thermal equilibrium. According to some specialized studies, dark impurities that absorb solar radiation in the ice can decrease the albedo of the glacier surface (Zhang *et al.* 2017a,b, 2020, Skiles *et al.* 2018, Kang *et al.* 2020). In other words, by absorbing more radiation, these impurities cause a decrease in the percentage of radiation that any surface reflects of the radiation that falls on it, casting shadows on the snow or ice layer, therefore leading to the intensification of the melting process of the frozen material. Given the diversity of MP colours that can be found in glaciers (Ambrosini *et al.* 2019, Rochman *et al.* 2019, González-Pleiter *et al.* 2021, Stefánsson *et al.* 2021, Zhang *et al.* 2022b) and their ability to absorb radiation similar to dark impurities (Zhang *et al.* 2020, Revell *et al.* 2021), these emerging contaminants could increase ice melting by significantly reducing albedo (Zhang *et al.* 2022a,b). Further studies of this phenomenon have provided evidence that MPs have a more pronounced influence on the reflective capacity of glaciers when the albedo of a glacier is relatively low (Geilfus *et al.* 2019, Revell *et al.* 2021). Therefore, glaciers are most susceptible to melting at the same time that they are most susceptible to this effect.

Other critical issues associated with MP Antarctic air pollution are directly related to the effects of global warming, which highlights a very intricate and challenging scenario for the health of the Antarctic atmosphere in the short-, medium- and long-term future. The increase in global temperatures experienced as a consequence of climate change has the potential to accelerate the decomposition of macroplastics and MPs, resulting in the increased fragmentation and distribution, and thus increased occurrence, of these emerging pollutants (Zhang *et al.* 2021, Chang *et al.* 2022, Haque & Fan 2023, Hasan *et al.* 2023, Sharma *et al.* 2023), both globally and locally on the Antarctic continent. This has been shown by demonstrating that rising temperatures increase the physical degradation of plastics by thermal breakdown, making them more sensitive to the various degradation processes that give rise to these plastic microparticles (Kamweru *et al.* 2011). Furthermore, climate change may lead to highly destructive natural disasters , such as storms, hurricanes and floods, which are also important sources, vectors and means of massive and extensive dissemination of MPs, thus increasing their distribution in the environment (Cooper & Corcoran 2010), facilitating and amplifying the probability of their occurrence in previously unaffected areas (Obbard *et al.* 2014), such as the Antarctic atmosphere before MP air detection. All of this evidence underlines the urgent need for a global response to the growing crisis of MP pollution, its integration with measures to mitigate the effects of climate change and the incorporation of effective policies specifically aimed at protecting the Antarctic continent and its ecosystem, especially its atmosphere.

## Microplastics in the Antarctic atmosphere: insights, opportunities and challenges

Since the 1980s, when the earliest studies on aerosols in Antarctica were carried out, the meteorological connection between the Antarctic region and the rest of the globe has been taken into consideration (Shaw 1988). Thus, the possible effects of anthropogenic activities on Antarctica have been clearly discerned. Since then, the development of scientific and other anthropogenic activities, such as tourism and fishing, has steadily increased over time, constituting an imminent threat to the preservation of the Antarctic atmosphere, disregarding the potential effects of human activities in the area. A specific illustration of this situation is evidenced by studies carried out over the past decade, which show that the estimated contribution of MPs per person per day has increased significantly by 2.4 mg (Gouin *et al.* 2011) to 7.5 mg (Gouin *et al.* 2015) from 2011 to 2015, with a possible maximum contribution per person per day of 27.5 mg of MPs (Gouin *et al.* 2015). While it is true that these estimates have been taken as references for polar marine pollution, it is important to consider that plastic particles present in the sea can easily enter the atmosphere and remain in it for long periods of time, which is the basis for these MPs' long-term transport, as discussed previously. Although the environmental impact assessments of the activities carried out in the Antarctic region are regulated through the Environmental Protocol of the Committee for the Protection of the Environment, a body created to advise Antarctic Treaty Parties on environmental issues, to date no specific procedures or policies have been developed to study, control and mitigate the impacts of MP emissions on marine, terrestrial and aerial ecosystems, essentially because there is considered to be a lack of scientific evidence on the existence and impact of this type of emerging pollutant (Waller *et al.* 2017).

In general, the occurrence of MPs on the Antarctic continent has been an underdeveloped line of research. Scientific research in this area has mainly been orientated towards studying these emerging pollutants in marine environments, which has meant a significant limitation in the evidence associated with plastic microparticles in the air specifically being found. The compartmentalized study of the Antarctic ecosystem has been a significant disadvantage in terms of obtaining evidence demonstrating MPs' dynamic and integrated nature in this remote region of planet Earth.

The evidence available to date suggests that the MP transport mechanism is a complex process in general, in which multiple factors are implicated, not only those associated with the morphological, chemical and physical characteristics of these plastic microparticles, but also being strongly influenced by meteorological parameters. Specifically, with respect to the transport of MPs to the Antarctic region, although it is true that the multiple processes that may be involved in this transport have been described and are believed to consolidate into a long-range transport route to the continent, there is no clear evidence to indicate, for example, the degree of influence, hierarchy and impact of each of these processes on the transport of plastic microparticles to Antarctica. The studies currently available only identify the transport of MPs as a consequence of a multifaceted and diffuse process. This situation implies important limitations in terms of the delimitation of concrete alternatives for the control and/or mitigation of MP transport to this region of interest. Although it has been generally established that surface and oceanic sources contribute 80% and 20%, respectively, of MPs globally, this type of information is not known concretely with respect to the specific context of the air in Antarctic, whose particular geographical characteristics could cause variations in the ways in which sources and long-term transport processes interact. This situation represents an important scientific challenge to the study of Antarctic air pollution with MPs, and this is even more the case when the study of these pollutants is carried out in a compartmentalized manner; that is, without an integrated and clear consideration of how the different sources are interrelated with the

https://doi.org/10.1017/S0954102024000555 Published online by Cambridge University Press

transport processes specifically. This state of affairs is also evident when we explore the recent evidence on the potential contributions of MPs from the research stations installed in Antarctica, and the significant occurrence (77.4%) of these pollutants within the ACC, mainly fibres (98.1%), whose source is directly related to the use of textiles made from plastic fibres. This evidence in particular is a key finding, as it suggests that in the case of the Antarctic region, the processes involved in the incorporation of MPs in the air could be mainly due to phenomena primarily associated with local sources, in addition to the contributions due to long-term transport from other regions of the globe, which could be influenced by the geographical characteristics of the region, specifically by the activity of the ACC.

In this sense, it is vital that studies on this issue are carried out in an environmentally integrated manner so that all of the elements involved in MPs at both regional and local levels can be accurately and precisely addressed. Due to all of this, and as a consequence of the characteristics of the region of interest, conducting aerial sampling and analysis campaigns in Antarctica constitutes a technological challenge that requires the use of state-of-the-art methodologies, which translates into significant economic costs and the need for specialized personnel. This situation represents an ideal opportunity for the improvement and optimization of existing technologies or the development of new ones to meet the technical and scientific demands of Antarctic research. For its part, the use of artificial intelligence (AI) provides new and interesting possibilities in the context of the integrated study of MP transport models, as has been done successfully in terms of forecasting air pollution in other regions (Subramaniam *et al.* 2022). This AI-based approach could allow more in-depth study of Antarctic air pollution with MPs, considering both the mechanisms of incorporation from local and remote sources and their links with contributions from the marine, glacial and terrestrial environments, as well as their roles in the MP resuspension phenomenon addressed in this work.

Beyond the consequences that directly affect the Antarctic environment, pollution by MPs in this remote region constitutes a particular emerging situation specifically associated with the interference of MPs in the melting process of Antarctic glaciers. This fact is not only relevant from the perspective of the persistence of these pollutants in the most important freshwater reservoirs on the planet, but also represents the introduction of a new variable that contributes to the problems of global warming and climate change. This represents a field of study of utmost importance for the delimitation of concrete interventions against this global phenomenon and again justifies the development of collaborative efforts that translate into interdisciplinary and multisectoral studies that can address specifically 1) the limitations of studies carried out using compartmentalized approaches and 2) the emerging opportunities for the production of in-depth insights that could be key to both the control and mitigation of the climate change crisis and MP pollution on a global scale.

## Conclusions

This work demonstrates in a clear and concrete way that the presence of MPs in the pristine, clean air of Antarctica is a frightening reality of the contemporary world, and that besides being a local problem in the region, it is also a major component of global warming and climate change, as well as being an incontrovertible threat to the world's most important freshwater reservoirs. While the origins and sources of MPs represent a widely explored line of research to date, the investigation of the phenomenon of MP transport to the Antarctic continent is a complex and intricate scientific issue involving an aerodynamic process that cannot be controlled, and in which multiple factors simultaneously interact through a variety of mechanisms that have not yet been conclusively elucidated. This is due to the lack of specialized, integrated research into the compartments that make up this environment, whether at the local or regional level. This scenario is further complicated by new studies that highlight a significant problem associated with the ability of plastic microparticles to re-enter the atmosphere once deposited in marine or terrestrial environments, to be re-transported to other latitudes, where they experience new climatic and meteorological conditions that not only favour their physical and chemical degradation, but also increase their capacity to release toxic chemical compounds, thus increasing both the polluting potential of MPs and the difficulty of implementing mitigation and control measures for these pollutants.

In addition, this work also provides evidence that the occurrence of MPs in the Antarctic atmosphere is not an environmental concern with only local impacts. Considering the potential of these pollutants to intervene in the processes associated with global warming and climate change on the Antarctic continent, which are directly related to glacier melting, the presence of MPs in the air of this region represents a global threat with a direct impact on the planet's climate. Furthermore, we must not overlook the significant threat posed by the persistence of these plastic microparticles in Antarctic glaciers, not only from the point of view of their role as an active vector of these pollutants in local and regional terms, but also from the perspective of compromising the world's most important freshwater reservoirs. Therefore, the reviewed evidence reveals the importance of addressing the impacts of the presence of MPs in the Antarctic atmosphere, not only from the point of view of these MPs' contributions associated with long-term transport from distant regions of the globe, but also 1) from the perspective of the impact of local sources of MPs in the region that have been overlooked, 2) from the angle of the integrated, non-compartmentalized study of MP abundance in environmental matrices and MP dynamics with other environments and 3) the delimitation of the impacts of MPs on the already compromised health of the global environment and climate. All of this represents an underexplored scientific challenge as well as an opportunity, with the possibility of developing a specialized line of research with great impact both in the specialized field of environmental studies in Antarctica and in the scientific community in general, and with the potential to enable the exploration and assessment of the benefits of AI-based technologies in this area.

**Financial support.** The authors gratefully acknowledge the research projects PID2021-125723NB-I00 (Spanish Ministry of Economy and Competitiveness) and PR27/21-015 (Complutense University and Madrid Government). The authors also thank the public-private research project CPP2022-009754 (Spanish Ministry of Science and Innovation), in collaboration with J. Aguirre S.L. company, for the financial support to develop this study. The authors gratefully acknowledge the facilities, materials and resources of the Complutense University of Madrid. JC-E especially thanks Universidad de Panamá and Instituto para la Formación y Aprovechamiento de los Recursos Humanos de Panamá (IFARHU) for the financial support for his doctoral studies.

**Competing interests.** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Author contributions.** SD: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft/review & editing, Data curation, Visualization. JC-E: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft/review & editing, Data curation, Visualization. MLO: Methodology, Formal analysis, Writing - original draft/review & editing. JA-H: Methodology, Formal analysis, Writing - original draft/review & editing. DG-M: Methodology, Formal analysis, Writing - original draft/review & editing. JLUR: Methodology, Formal analysis, Writing - original draft/review & editing. JOC: Conceptualization, Formal analysis, Writing - original draft/review & editing, Data curation, Project administration, Funding acquisition, Supervision.

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