8

POLLUTION IN ANTARCTICA

Stephen J. Roberts, Kevin A. Hughes, Chuxian Li, Rebecca H. Peel, Krystyna M. Saunders, Larissa Schneider, and Catherine L. Waller

8.1 Introduction

Antarctica's isolation from lower latitude pollutants due to natural barriers like circumpolar atmospheric and oceanic currents means it is undoubtedly less polluted than other parts of the world (Barker and Thomas, 2004). However, less than 32% of its landmass is considered 'pristine' and non-impacted by human activities (Pertierra et al., 2017; Leihy et al., 2020). In this chapter, we examine well-known currently well-regulated pollutants primarily associated with tourism, research stations, growing risks of oil, fuel spills from accidents within Antarctica and increased shipping in the Southern Ocean (SO) (e.g., Ruoppolo et al., 2013; Brooks et al., 2024; Stark, 2022). We then assess some 'novel' pollutants associated with mid-late 20th century anthropogenic activities outside of Antarctica whose impacts and ecological threats are not yet fully established (e.g., Bergami et al., 2023).

8.2 Pollutants Sources Associated with Human Activities in Antarctica

Despite the vast size of Antarctica (14,000,000 km^2) (Figure 0.1), ice-free ground where most terrestrial biodiversity is found is scarce and represents less than 0.3% of the continent's area (c. 42,000 km^2) (Terauds et al., 2012). Most Antarctic terrestrial biological communities, bird colonies and seal haul-out sites are found on ice-free ground within 5 km of the coast, an area of c. 6,000 km^2 (Hull and Bergstrom, 2006). Human activities have been focussed largely within this small area since people arrived ~ 200 years ago.

Antarctic nearshore environments contain some of the richest marine habitats yet are extremely vulnerable to human impacts from shipping and tourism (Aronson et al., 2011). At locations subject to prolonged human presence and/or the activities

DOI: 10.4324/9781003406471-8

This chapter has been made available under a CC-BY 4.0 license.

of multiple national Antarctic programmes, cumulative impacts can be substantial, resulting in environmental degradation (Braun et al., 2014). The main impacts from habitat destruction, disturbance of wildlife, introduction of non-native species and pollution (Tin et al., 2009), and expansion of the human footprint across ice-free regions of Antarctica puts human needs in direct competition with those of nature (Pertierra et al., 2017; Brooks et al., 2019; Hawes et al., 2023). We examine the key pollution sources in Antarctica (tourism, research stations, sewage, wastewater, fuel spills, and local emissions) in the following section.

Tourism: Antarctic tourism facilitated over 104,000 visitors, predominantly to the Antarctic Peninsula, during the 2022/2023 season (International Association of Antarctica Tour Operators, 2023). The construction of permanent infrastructure to support this is not currently permitted, yet some national Antarctic programmes have permanent or semi-permanent infrastructure for tourism and non-governmental activities (Netherlands, 2023). Antarctic tourism numbers have dramatically rebounded following the COVID-19 pandemic, and ship-based tour operators continue to identify new sites for tourist visits while diversifying the range of activities available (Bender et al., 2016; Hughes and Convey, 2020) (Figure 8.1).

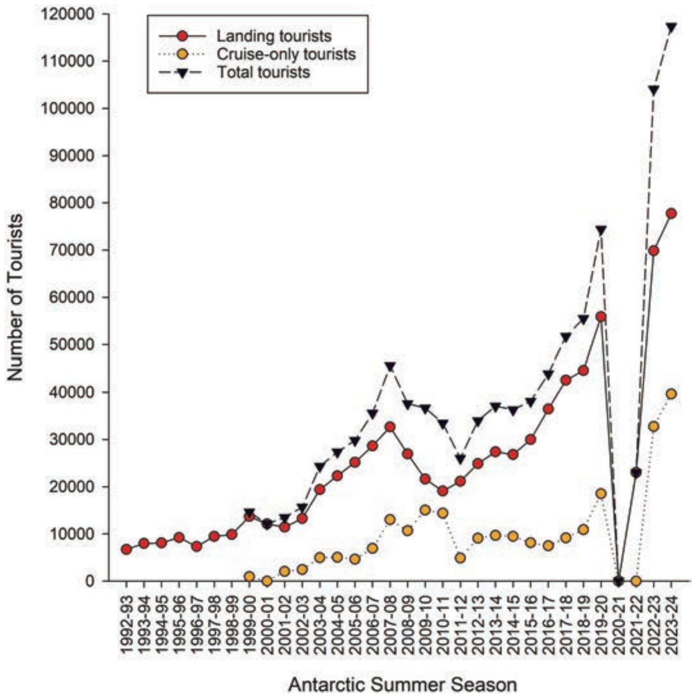

FIGURE 8.1 Number of tourists visiting the Antarctic Treaty area facilitated by members of the International Association of Antarctica Tour Operators (IAATO, 2023). Data for 2023/2024 are estimated by IAATO. Fewer tourist numbers during the 2020/2021 and 2021/2022 seasons were due to the COVID-19 pandemic.

Research stations: Research stations have negative impacts on local geomorphology, biological communities, and aesthetic and wilderness values (Klein et al, 2008; Kennicutt et al., 2010; Brooks et al., 2019; Palmer et al., 2022). Since the International Geophysical Year (1957/58), scientific activities have expanded significantly. There are now 75 research stations with an estimated 5000 national operator staff working in Antarctica annually (COMNAP, 2022, Chu et al., 2019). Substantial, but often uncharacterised, levels of impact have resulted from the construction and operation of facilities (including research stations, ports, and airstrips) by governmental Antarctic programmes, and seasonal and deep field camps (COMNAP, 2017).

Nations with a longer presence on the continent are currently investing heavily in redeveloping their Antarctic infrastructure (e.g., Argentina, Australia, New Zealand, UK, USA), or constructing additional stations in new locations (e.g., China). Stations provide nations with a mechanism to demonstrate substantial scientific research activity and participate in the governance of the Antarctic Treaty area by becoming a Consultative Party to the Antarctic Treaty Consultative Meeting (Gray and Hughes, 2016; Karatekin et al., 2023). Abandoned stations and historical waste dumps generated before the 1998 Environmental Protection to the Antarctic Treaty Protocol, which prohibits the dumping of waste, are found across the continent, creating substantial local pollution and associated impacts (e.g., Fryirs et al., 2013; Stark et al., 2023). Notably, several abandoned stations built on ice shelves between 1950 and 1990, such as the UK Halley I–IV on the Brunt Ice Shelf and the South African SANAE I–III stations on the Fimbul Ice Shelf, have calved into the ocean (Aronson et al., 2011).

There are many examples of quarrying and construction activities destroying breeding habitats for birds and terrestrial biological communities (Ewing et al., 1989; Wilson et al, 1990; Hughes et al., 2016; 2023), although some attempts have been made at relocating vegetation (Câmara et al., 2021). Trampling and compression of Antarctic soils by pedestrian traffic and vehicle movement affect soil properties and biodiversity, with visual impacts remaining decades after the original event (Tejedo et al., 2014). Human visits and wildlife disturbance from aircraft and, more recently, remotely operated vehicles, can lead to reduced reproductive success and displacement of biota (Chwedorzewska and Korczak, 2010; Coetzee and Chown, 2016; Mustafa et al., 2018).

Sewage and wastewater: Release of sewage and wastewater is the only waste disposal into the Antarctic environment permitted under the Protocol (Annex III), and only when environmental conditions provide initial dilutions and rapid dispersal. Treatment is not mandatory, but at a minimum, sewage maceration should be undertaken at research stations with more than 30 personnel. For stations located on floating ice shelves or inland areas of permanent ice, disposal of sewage and wastewater in deep ice pits is allowed as it is the only practicable option.

Sewage disposal standards date back to 1991 when the Protocol was agreed but are now considered inadequate (ATS, 1998 a, b). Treatment of sewage is increasingly undertaken at research stations, but more than 50% lack sewage treatment and large seasonal fluxes in sewage are prevalent (Gröndahl et al., 2009; COMNAP, 2022). Some research stations, such as the Belgian Princess Elizabeth base in Dronning Maud Land, East Antarctica (Figure 0.1), have invested heavily in sustainable microbial treatment and greywater recycling facilities that can recycle up to 75% of wastewater (Alvarez et al., 2015). Elsewhere, outdated practices have led to the release of sewage into local terrestrial and freshwater environments, or microbial and chemical contamination of streams and lakes (Peter et al., 2009; Tort et al., 2017; Hawes et al., 2023).

Sewage release has many negative consequences for the nearshore marine environment several kilometres from the outfall (Stark et al., 2016). Released chemicals include metals and metalloids (hereafter referred to collectively as metals), persistent organic pollutants (POPs), surfactants, and nutrients that change aquatic community structures (Wild et al., 2015; Webb et al., 2020; Szopińska et al., 2021; Stark et al., 2023). Effective sewage treatment prevents ongoing impacts (Conlan et al., 2010), but remedial treatment is needed to remove persistent pharmaceutical chemicals (e.g., analgesics, anti-inflammatories, antibiotics, estrogens, fungicides, preservatives, UV filters, and surfactants) whose negative impacts are well-established (Emnet et al., 2015; Perfetti-Bolaño et al., 2022). Wastewater disposal into the Antarctic environment releases sewage-derived microbial strains, which are used as markers for tracing the extent of sewage contamination, but have negative impacts on local biota by, for example, spreading antimicrobial-resistant genes (Hughes, 2003; Power et al., 2016; Hernández, et al., 2019; Hwengwere et al., 2022; Corti et al., 2023).

Fuel spills: The most significant large-scale fuel spill in Antarctic marine or terrestrial environments was the sinking of the Argentine naval supply vessel, *Bahai Paraiso* in 1989, at Arthur Harbour, near Palmer Station, Anvers Island (Figure 0.1), which resulted in the loss of ~600,000 litres of fuel and subsequent impacts upon bird and marine invertebrate populations (Kennicutt et al., 1992). Many areas around stations have been subject to chronic fuel and other POPs contamination, primarily due to oil spills and poor infrastructure maintenance, but also as a result of the long-distance transport of industrial by-products (Peter et al., 2009; Golubev, 2021).

Away from stations, leaking oil drums left in (abandoned) station dumps have resulted in substantial quantities of contaminated ground with one estimate suggesting between 1 and 10,000,000 m^3 of contaminated soil being present in Antarctica (Snape et al., 2001). For example, lead and zinc in soil in the immediate vicinity of Marambio Station, Seymour Island, Antarctic Peninsula (Figure 0.1) exceeded baseline values by up to five times (Chaparro et al., 2007). Fuel spills can have long-term impacts on soil properties (i.e., moisture, hydrophobicity, soil temperature) and biological communities including microbial activity (Aislabie et al., 2004; Hughes et al., 2007; Vázquez et al., 2017). More positively, some indigenous microorganisms have proven capable of degrading hydrocarbons, including polyaromatic hydrocarbons (PAHs), which has resulted in attempts to remediate contaminated soils *in situ* at some Antarctic locations (McWatters et al., 2016).

Local atmospheric emissions: Atmospheric pollution is an almost inevitable result of fossil fuel combustion to power research stations, ships, aircraft, and overland vehicles. Local levels of atmospheric pollution are generally low compared to other areas of the planet (e.g., nitrogen oxides; Helmig et al., 2020; Marina-Montes et al., 2020), and many emissions originate outside of Antarctica (Wolff, 1992; Leal et al., 2008). Recent examination of snow in the vicinity of research stations and coastal tourist sites found black carbon from fossil fuel combustion to be above background levels measured elsewhere on the continent (Khan et al, 2019; Cordero et al., 2022). This is of particular concern as it can darken the snow, which lowers its albedo and increases melt rates (Cereceda-Balic et al., 2020).

8.3 Novel Pollutants

Many of the pollutants that end up in or around Antarctica and sub-Antarctic Islands have been dispersed globally by atmospheric (Bargagli et al., 2008; Li et al., 2020; Aves et al., 2022), oceanic (Jiskra et al., 2021; Cunningham et al., 2020, 2022), and migration (Wild et al., 2022) processes.

The most common airborne and gaseous pollutants hazardous to health are particulate matter with diameters less than or between 2.5 ($PM_{2.5}$) and 10 (PM_{10}) microns, black and elemental carbon, nitrogen oxides, ozone, sulphur dioxide, POPs, volatile organic compounds, PAHs, per- and polyfluoroalkyl substances, and carbon monoxide associated with industrial, agricultural, and automotive industries (WHO, 2021). Even though the Northern Hemisphere is thought to have a much lower hydroxyl-radical pollution self-cleaning capacity, some of these pollutants have similar concentrations in the Southern Hemisphere to the Arctic (Patra et al., 2014). POPs have been extensively studied in Antarctica since the 1960s, and their negative impact on human, wildlife, and ecosystem health is well-established and regulated by the Stockholm Convention (Goerke al., 2004; Cabrerizo et al., 2013; Marrone et al., 2021; Alfaro Garcia et al., 2022; Garnett et al., 2022; Corsolini et al., 2022; Kuepper et al., 2022). Recent reviews of POPs in Antarctica include: ImPACT Action Group (2021); Cordero et al. (2022); da Silva et al. (2023); Luarte et al. (2023); Kessenich et al. (2023).

Pollution levels in Antarctica can also be assessed by comparison with baseline (pre-industrial) levels at pristine sites (Angulo, 1996) and by using natural archives such as ice cores, lake/marine sediments, and peatland records (Li et al., 2020). For example, evidence of anthropogenic greenhouse gas emissions, including carbon dioxide and black carbon from incomplete combustion of biomass dating back centuries, are preserved in Antarctic ice cores and have been linked to large-scale forest clearance, and changes in settlement patterns and land use on surrounding continents (e.g., McConnell et al., 2021; Thomas et al., 2023; King et al., 2024). Most pollutants have substantially lower concentrations in Antarctica and the SO

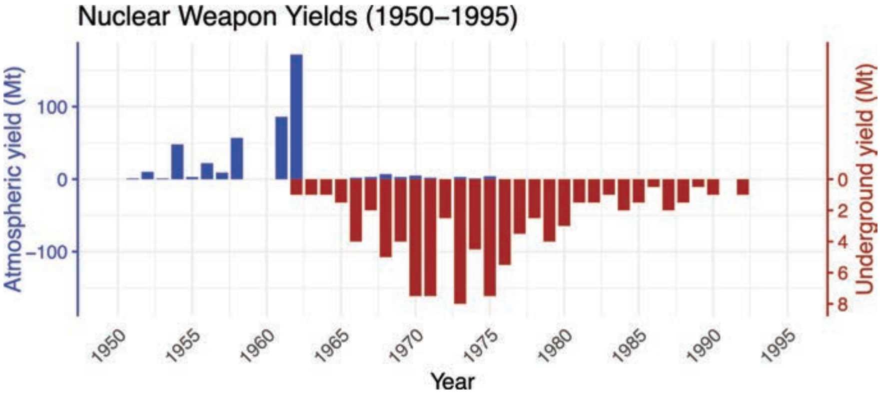

FIGURE 8.2 The shift from atmospheric to underground testing following the ratification of the Partial Test Bay Treaty (PTBT) in 1963 (see Prăvălie, 2014). The Threshold Test Ban Treaty in 1974 banned underground tests greater than 150 kilotons. The Comprehensive Test Ban Treaty banning all nuclear test explosions was adopted in 1996 by the United Nations but has not been ratified by all countries (Giovannini, 2021).

than in populated areas of the Northern Hemisphere due to their remoteness, low population density, and comparative lack of landmass (Bargagli et al., 2008).

In the following section, we highlight some novel (far-travelled) pollutants, such as anthropogenic radionuclides, metals and plastics, that have been found extensively across Antarctica and the SO but remain largely unregulated.

Anthropogenic radionuclides: Perhaps the most dramatic example of a globally dispersed pollutant is radioactive fallout from atmospheric nuclear weapons testing (Figure 8.2). Comparatively little is known about the distribution of anthropogenic radionuclides from atmospheric fallout across the Southern Hemisphere, principally because there are only a few landmasses in the SO, concentrations of these radionuclides are low, and, until recently, analytically challenging to measure (Child et al., 2008, 2013; Arienzo et al., 2016). While the concentrations and impacts of radionuclide pollution are much lower, they can bioaccumulate through the food chain, and, unlike other pollutants, remain radioactive for centuries to millennia (Saunders and Meredith, 2023).

Atmospheric nuclear weapons testing injected anthropogenic radionuclides, principally Radium-226 (^{226}Ra), Caesium-137 (^{137}Cs), and Strontium-90 (^{90}Sr), but also Americium-241 (^{241}Am), Plutonium-239 and -240 (^{239}Pu,^{240}Pu), Uranium-236 (^{236}U), and Iodine-131 (^{131}I) into the stratosphere, which were mixed latitudinally by atmospheric circulation processes, and distributed globally as fallout (United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000). Of the 2053 nuclear weapons tests conducted between 1945 and 2006, more than a quarter (530) were tested in the atmosphere before the Partial Test Ban Treaty, which restricted atmospheric testing, came into effect in 1963 (Figure 8.2).

Approximately 83% of the 530 Mt total explosive yield detonated between 1951 and 1992 (440 Mt) was due to atmospheric tests conducted between 1951 and 1980, with the Former USSR and the USA the largest contributors, followed by China, France, and the UK (Prăvălie, 2014) (Figure 8.2). Although only 10% of tests were conducted in the Southern Hemisphere, between 1945 and 1980 the fallout inventory in the Southern Hemisphere was approximately one-third of that in the Northern Hemisphere (UNSCEAR, 2000; Hancock et al., 2011).

Anthropogenic radionuclides, such as ^{137}Cs, ^{241}Am, and ^{239}Pu, have been found in soil, lichens, mosses, cryoconite, peat deposits, ice core records and lake/marine sediments (Li et al., 2017; Szufa et al., 2018). Caesium-137 fallout, which peaked in 1963, is widely used as a chronological marker in lake, marine, and peat records globally (Foucher et al., 2021) (Figure 8.3). While the concentration of ^{137}Cs in records from the Southern Hemisphere high latitudes is often very low or below detection limits (Li et al., 2017) (Figure 8.3), the timing of the ^{137}Cs peak varies between 1963 and 1965, likely due to the time taken for atmospheric mixing between the Northern and Southern Hemispheres (Foucher et al., 2021).

Similarly, plutonium isotope peaks linked to radioactive fallout have increasingly been found in ice cores from the Arctic and Antarctica (Arienzo et al., 2016) (Figure 8.3). Recent analytical improvements mean it is possible to measure fallout radionuclides, such as ^{239}Pu at peta-m concentrations. This advance led to the recent discovery of ^{239}Pu and ^{240}Pu in soils, peat deposits and lake sediments from sub-Antarctic Islands and Tasmania, significantly widening their known spatial coverage (Harrison et al., 2021).

The relatively large amounts of ^{239}Pu, ^{240}Pu, and ^{236}U released during atmospheric weapons testing and different isotopic signatures used by different countries in weapons manufacturing can be used to track changing fallout patterns (Figure 8.3c) (Hotchkis et al., 2000). The impact of USA testing in the Southern Hemisphere and Former USSR testing in the Arctic up to 1970, and the post-1970 shift to Chinese testing in the Northern Hemisphere and French testing in the Southern Hemisphere is shown in Figure 8.3. Consequently, $^{240}Pu/^{239}Pu$ atom ratios found in some records from sub-Antarctic latitudes are towards the lower end of the global range of 0.16–0.19 (Kelley et al., 1999) and have been attributed to tropospheric fallout from French nuclear tests in the Pacific during the 1960s and 1970s (Chamizo et al., 2011; Kelley et al., 1999).

Metals: The occurrence and accumulation of metals have been recorded in Antarctica in soils, marine sediments, and biota (Bargagli, 2008; Koppel et al., 2021). Research stations are the main source of locally derived metal contaminants, originating from waste dumps and contaminated sites but also local geology (Regoli et al., 2005; Aronson et al., 2011; Padeiro et al., 2016; Webb et al., 2020). Impact assessments highlight arsenic, cadmium, copper, lead, mercury, and zinc as elements of most concern (Tin et al., 2009).

Some metals are emitted by industrial processes in gaseous form, while others become associated with fine particles or remain as by-products and confined to

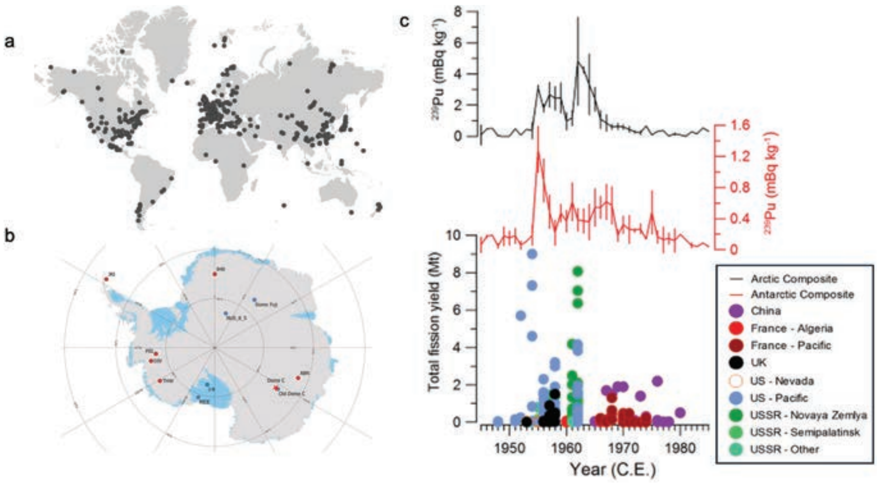

FIGURE 8.3 (a) Global distribution of sediment core records containing ^{137}Cs, highlighting the comparative lack of records from the Southern Ocean region (modified from Foucher et al., 2021; https://creativecommons.org/licenses/by/4.0/). Caesium-137 peaks have also been found in lake sediments from the Falkland Islands, Signy Island (Appleby et al., 1995), and South Africa (Rose et al., 2021) (not shown on maps). (b) Location of ice cores and snow pits where ^{239}Pu has been detected in Antarctica (from Severi et al., 2023). (c) Arctic (black line) and Antarctic (red line) composite ice core records of ^{239}Pu activities (with standard error bars) and a summary of total fission yields by country and testing locations (reprinted from Arienzo et al., 2016, copyright 2023 American Chemical Society).

industrial facilities (Hopke et al., 2020). Metals in gaseous form, such as mercury, can travel long distances within the atmosphere before being deposited in remote areas like Antarctica (Bargagli, 2008; Whiteside and Herndon, 2022; Marina-Montes et al., 2020). Consequently, elevated concentrations of metals above natural background levels have been observed in the atmosphere, snow, soil, and aquatic ecosystems of Antarctica far from research stations (e.g., Szopinska et al., 2021).

Although only 10% of the world's population resides in the Southern Hemisphere, major economies, such as Argentina, Australia, Brazil, Chile and South Africa, are significant consumers of coal and key producers in the mining sector (Figure 8.4). These nations have high industrial emissions rates, and their geographical proximity to Antarctica facilitates the transport of metals to the region (EIA, 2023; World Mining Data, 2023).

Studies from Australia have shown that pollutants from mining activities travel long distances, with the potential to affect the SO and sub-Antarctic Islands, such

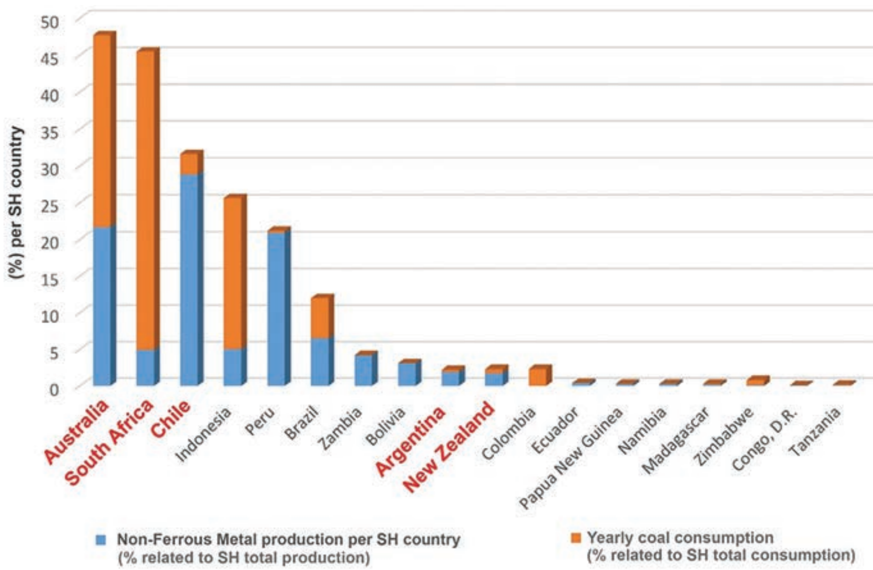

FIGURE 8.4 Antarctic gateway states, including Argentina, Australia, Chile, New Zealand, and South Africa (bold), are among the top consumers of coal and leading non-ferrous metal producers in the Southern Hemisphere (World Mining Data, 2023).

as Macquarie Island (Figure 0.1) (Schneider et al., 2019). Both Southern South America and Africa also contribute significant amounts of metals to the sub-Antarctic (Li et al., 2020) and Antarctic (Planchon et al., 2002; Tuohy et al., 2015; Schwanck et al., 2017, 2022; Fan et al., 2021; Liu et al., 2021), and most regulatory frameworks governing pollution in these countries are weaker (Sinclair and Schneider, 2019; Fisher et al., 2023).

Long-term studies examining archives of metal deposition indicate an increase in metals across Antarctica from pre-industrial to post-industrial periods. Ice core records from Dome A and the Antarctica Peninsula (Figure 0.1) indicated that enrichment factors of antimony, arsenic, cadmium, copper, and lead were significantly larger than 10, which is predominantly due to mining production and burning of coal in Australia and South America (Liu et al., 2021). Other ice core studies show consistent, albeit varying, increases in metals since the end of 19th century, including lead (Schwanck et al., 2022; McConnell et al., 2014; Hong et al., 1998; Vallelonga et al., 2002; 2004; Görlach and Boutron, 1992), cadmium (Hong et al., 1998; Schwanck et al., 2022), copper (Hong et al., 1998; Vallelonga et al., 2004), and arsenic (Schwanck et al., 2016). A compilation of available peat and lake sediment records, alongside independent estimates of global mercury emissions, has shown that mercury deposition in the Southern Hemisphere has been enriched fourfold since the C15th (Li et al., 2020).

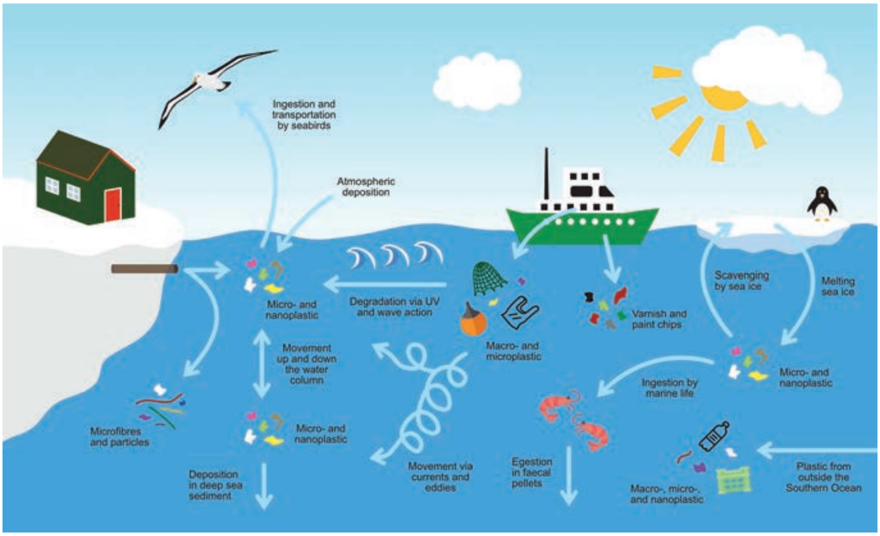

FIGURE 8.5 Summary of major sources and contamination pathways of plastics on and around Antarctica.

Plastics: Plastic pollution in the SO is being increasingly recorded, with sources, including local pollution from fishing vessels and research stations, and debris transported on currents from elsewhere (Waller et al., 2017). Plastic release from research stations is likely to be minimal on a continental scale, but substantial amounts of plastic debris, including fishing equipment, have been found on beaches at various locations in the Antarctic region (Munari et al., 2017; Reed et al., 2018; Waluda et al., 2020) (Figure 8.5).

Depending upon the properties of the plastic, it may float or sink, thereby accessing different benthic and pelagic habitats, and can persist in the environment for decades or longer (Cuningham et al., 2020; Rowland et al., 2021a; Rota et al., 2022). Large plastic items can be hazardous to wildlife, through ingestion or entanglement, and may act as vectors for the transfer of non-native species (Arnould and Croxall, 1995; Barnes, 2002). Microplastics (particles or fibres <5 mm) can be released in wastewater, produced, for example, by clothes washing, but a more substantial source may be the degradation of larger fragments of marine plastic debris due to exposure to solar UV radiation, chemicals, biological processes, and physical damage. The impact of microplastics on Antarctic biodiversity remains unknown but may include reduced feeding efficiency and reproductive success in Antarctic krill (*Euphausia superba*) (Dawson et al., 2018; Rowlands et al., 2021b). Plastic pollution has the potential to substantially impact key Antarctic species, particularly when combined with other environmental and anthropogenic stressors (Rowlands et al., 2021b). Horton and Barnes (2020) also highlighted that Antarctic organisms face a number of stressors in the SO and that the impact of plastics should not be studied in isolation.

While the definition of nanoplastics is still debated, the consensus is that any plastic particle smaller than 1 μm is classified as a nanoplastic (Hartmann et al., 2019). Like microplastics, nanoplastics are largely formed via the breakdown of larger plastic items, although some primary sources exist (Piccardo et al., 2020). Initially, in terms of transport mechanisms and impact, nanoplastics were thought of as an extension of microplastics (Moore, 2008), however recent studies have shown that the behaviour of these particles is often quite different (Gigault et al., 2018; Gigault et al., 2021; Pradel et al., 2023).

The study of nanoplastics in the environment is a relatively new field (Ter Halle et al., 2017; Piccardo et al., 2020), presenting unique size-related analytical challenges. Although the sources, transport, ecological impacts, and fates are not well understood, much work has been undertaken in the related field of hydrocarbon and POP 'chemical' pollutants since the 1960s in Antarctica (de Silva et al., 2023 for review). To date, there has only been one study of nanoplastics in Antarctica, reporting values of 37.7–60.0 ng mL^{-1} in a sea ice core (Materić et al., 2022). Reports of microplastic concentrations in the SO are more numerous, with values ranging from zero (Kuklinski et al., 2019) to over 500 particles L^{-1} (Garza et al., 2023).

Despite a lack of data, nanoplastics are predicted to be as pervasive as microplastics (Alimi et al., 2018), and perhaps more so, since nanoplastics can be transported extremely long distances in the atmosphere (Materić et al., 2022). Moreover, the length of time it takes for the long-range transport of oceanic plastic pollution to reach Antarctica gives ample time for fragmentation into smaller size fractions (Obbard, 2018) and there are many potential sources of plastic pollution within the SO (Rowlands et al., 2021b). As an emerging field, there is limited literature on the impact of nanoplastic on Antarctic organisms (Alice et al., 2021), but nano-sized polystyrene spheres have been found to affect the immune response, swimming abilities, and gut epithelium of Antarctic marine organisms (Bergami et al., 2019; Bergami et al., 2020; Bergami et al., 2022). Rowlands et al. (2021a) observed impaired embryonic development of Antarctic krill when exposed to polystyrene nanoplastic particles. Furthermore, the impacts of nanoplastic on krill (Rowlands et al., 2021a) and the sub-Antarctic pteropod *Limacina retroversa* (Manno et al., 2022) were found to be worse when subjected to a multi-stressor environment.

Policies related to plastic pollution have been implemented within the SO; the International Convention for the Prevention of Pollution from Ships (MARPOL, Annex V) legislates against the disposal of plastic overboard (International Maritime Organisation (IMO), 1988), while the Antarctic Treaty prohibits the release of macroplastic waste into the Antarctic environment (Secretariat to the Antarctic Treaty, 1998). While guidelines are in place for plastic use on research stations (SCAR, 2024) and in the tourism industry (IAATO, 2019, 2020), no regulations exist. Collaborative governance under the Antarctic Treaty presents an opportunity to put research findings into policy and create international action (Secretariat to the Antarctic Treaty, 1961).

8.4 Impact of Climate Change on Pollution in Antarctica

Shifts in atmospheric circulation and global warming may further enhance the transport and deposition of pollutants to Antarctica (Convey et al., 2009; Turner et al., 2014). For example, increases in pollutant deposition in Antarctic ice cores have been attributed to increased cyclonic activity associated with more poleward-focused and stronger Southern Hemisphere westerly winds (Schwanck et al., 2022). This is driving sea ice poleward, increasing the advection of warm and moisture-laden air across the Antarctic and sub-Antarctic (Marshall et al., 2017; Oliva et al., 2017; Heredia Barion et al., 2023), likely enabling increased wet deposition of contaminants. Melting ice sheets and thawing permafrost and snowpack can also release previously trapped substances into surrounding environments (Pérez-Rodríguez et al., 2019).

8.5 Summary

- Since the International Geophysical Year, scientific activities and tourism in Antarctica have expanded significantly, with more than ~100,000 people visiting the continent annually. Most visits are made to the Antarctic Peninsula where numerous pollution-related incidents have been reported.
- Research stations are the main source of locally derived contamination and human activities have led to substantial increases in the long-range deposition of pollutants to Antarctic and sub-Antarctic regions.
- Greater focus on the evaluation of impacts that largely unregulated pollutants could have on Antarctic and SO environments and ecosystem health in the future is required.
- Future changes in climate, including increased rainfall and melting ice from Antarctica, will lead to increased concentrations of pollutants across Antarctic terrestrial and marine environments.
- Global distribution mechanisms may have a more substantial influence, requiring local versus global sources to be established and disentangled prior to the establishment of effective policy and mitigation strategies.

Acknowledgements

This chapter is a contribution to the ‘Human Impacts and Sustainability’ research theme of the SCAR Scientific Research Programme: ‘Integrated Science to Inform Antarctic and Southern Ocean Conservation’ (Ant-ICON). We thank Ilari Corsi and Simon Turner for their constructive reviews.

References

Aislabie, J.M. et al., 2004. Hydrocarbon spills on Antarctic soils: Effects and management. *Environmental Science and Technology* 38, 1265–1274. https://doi.org/10.1021/es0305149

Alfaro Garcia, L.A. et al., 2022. Bioaccumulation of per and polyfluoroalkyl substances in antarctic breeding south polar skuas (Catharacta maccormicki) and their prey. *Frontiers in Marine Science* 9. https://doi.org/10.3389/fmars.2022.819525

Alice, P. et al., 2021. Micro- and nanoplastic transfer in freezing saltwater: Implications for their fate in polar waters. *Environmental Science: Processes Impacts* 23, 1759–1770. https://doi.org/10.1039/D1EM00280E

Alimi, O.S. et al., 2018. Microplastics and nanoplastics in aquatic environments: Aggregation, deposition, and enhanced contaminant transport. *Environmental Science and Technology* 52, 1704–1724. https://doi.org/10.1021/acs.est.7b05559

Alvarez, C.E.D. et al., 2015. *Antarctica's New Buildings: Wastewater and Energy Systems*. INCT-APA Annual Activity Report 128–133. https://doi.org/10.4322/apa.2015.025

Angulo, E., 1996. The Tomlinson Pollution Load Index applied to heavy metal, 'Mussel-Watch' Data: A useful index to assess coastal pollution. *Science of the Total Environment* 187, 19–56. https://doi.org/10.1016/0048-9697(96)05128-5

Appleby, P.G., et al., 1995. Radiometric dating of Lake Sediments from Signy Island (Maritime Antarctic): Evidence of recent climatic change. *Journal of Paleolimnology* 13, 179–191. https://doi.org/10.1007/BF00678106

Arienzo, M.M. et al., 2016. A method for continuous 239Pu determinations in Arctic and Antarctic ice cores. *Environmental Science and Technology* 50, 7066–7073. https://doi.org/10.1021/acs.est.6b01108

Arnould, J.P.Y., and Croxall, J.P., 1995. Trends in entanglement of Antarctic fur Seals (Arctocephalus Gazella) in man-made debris at South Georgia. *Marine Pollution Bulletin* 30, 707–712. https://doi.org/10.1016/0025-326X(95)00054-Q

Aronson, R.B. et al., 2011. Anthropogenic impacts on marine ecosystems in Antarctica. *Annals of the New York Academy of Sciences* 1223, 82–107. https://doi.org/10.1111/J.1749-6632.2010.05926.X

Aves, A.R. et al., 2022. First evidence of microplastics in Antarctic snow. *The Cryosphere* 16, 2127–2145. https://doi.org/10.5194/tc-16-2127-2022

Bargagli, R., 2008. Environmental contamination in Antarctic ecosystems. *Science of the Total Environment* 400, 212–226. https://doi.org/10.1016/j.scitotenv.2008.06.062

Barker, P.F., and Thomas, E., 2004. Origin, signature and palaeoclimatic influence of the Antarctic circumpolar current. *Earth-Science Reviews* 66, 143–162. https://doi.org/10.1016/j.earscirev.2003.10.003

Barnes, D.K.A., 2002. Invasions by marine life on plastic debris. *Nature* 416, 808–809. https://doi.org/10.1038/416808a

Bender, N.A. et al., 2016. Patterns of tourism in the Antarctic Peninsula region: A 20-year analysis. *Antarctic Science* 28, 194–203. https://doi.org/10.1017/S0954102016000031

Bergami, E. et al., 2019. Polystyrene nanoparticles affect the innate immune system of the Antarctic sea urchin *Sterechinus neumayeri*. *Polar Biology* 42, 743–757. https://doi.org/10.1007/s00300-019-02468-6

Bergami, E. et al., 2020. Nanoplastics affect moulting and faecal pellet sinking in Antarctic krill (*Euphausia superba*) juveniles. *Environment International* 143, 105999. https://doi.org/10.1016/j.envint.2020.105999

Bergami, E. et al., 2022. Behavioural, physiological and molecular responses of the Antarctic fairy shrimp *Branchinecta gaini* (Daday, 1910) to polystyrene nanoplastics. *NanoImpact* 28, 100437. https://doi.org/10.1016/j.impact.2022.100437

Bergami, E. et al., 2023. Textile microfibers in wild Antarctic whelk *Neobuccinum eatoni* (Smith, 1875) from Terra Nova Bay (Ross Sea, Antarctica). *Environmental Research* 216, 114487. https://doi.org/10.1016/j.envres.2022.114487

Braun, C. et al., 2014. Environmental assessment and management challenges of the fildes Peninsula region. In Tin, T. et al. (Eds.), *Antarctic Futures: Human Engagement with* *the Antarctic Environment*. Netherlands, Dordrecht: Springer, pp. 169–191. https://doi.org/10.1007/978-94-007-6582-5_7

Brooks, S.T. et al., 2019. Our footprint on Antarctica competes with nature for rare ice-free land. *Nature Sustainability* 2, 185–190. https://doi.org/10.1038/s41893-019-0237-y

Brooks, S.T. et al., 2024. Systematic conservation planning for Antarctic research stations. *Journal of Environmental Management* 351, 119711. https://doi.org/10.1016/j.jenvman.2023.119711

Cabrerizo, A., Dachs, J., Barceló, D., Jones, K.C., 2013. Climatic and Biogeochemical Controls on the Remobilization and Reservoirs of Persistent Organic Pollutants in Antarctica. Environ. Sci. Technol. 47, 4299–4306. https://doi.org/10.1021/es400471c

Câmara, P.E.A.S. et al., 2021. The largest moss carpet transplant in Antarctica and its bryosphere cryptic biodiversity. *Extremophiles* 25, 369–384. https://doi.org/10.1007/s00792-021-01235-y

Cereceda-Balic, F., Vidal, V., Ruggeri, M.F., and González, H.E., 2020. Black carbon pollution in snow and its impact on albedo near the Chilean stations on the Antarctic Peninsula: First results. *Science of the Total Environment* 743, 140801. https://doi.org/10.1016/j.scitotenv.2020.140801

Chamizo, E. et al., 2011. Presence of plutonium isotopes, 239Pu and 240Pu, in soils from Chile. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Proceedings of the 10th ECAART10 European Conference*, 269, 3163–3166. https://doi.org/10.1016/j.nimb.2011.04.021

Chaparro, M.A.E. et al., 2007. Magnetic screening and heavy metal pollution studies in soils from Marambio Station, Antarctica. *Antarctic Science* 19, 379–393. https://doi.org/10.1017/S0954102007000454

Child, D.P. et al., 2008. High sensitivity analysis of plutonium isotopes in environmental samples using accelerator mass spectrometry (AMS). *Journal of Analytical Atomic Spectrometry* 23, 765–768. https://doi.org/10.1039/B715788F

Child, D.P., and Hotchkis, M.A.C., 2013. Plutonium and uranium contamination in soils from former nuclear weapon test sites in Australia. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Proceedings of the Twelfth International Conference on Accelerator Mass Spectrometry,* Wellington, New Zealand, 20–25 March 2011 294, 642–646. https://doi.org/10.1016/j.nimb.2012.05.018

Chu, W.-L. et al., 2019. Heavy metal pollution in Antarctica and its potential impacts on algae. *Polar Science, Joint volume of Special Issue MISA7 and Regular Issue* 20, 75–83.

Chwedorzewska, K.J., and Korczak, M., 2010. Human impact upon the environment in the vicinity of Arctowski Station, King George Island, Antarctica. *Polish Polar Research* 1, 45–60.

Coetzee, B.W.T., and Chown, S.L., 2016. A meta-analysis of human disturbance impacts on Antarctic wildlife. *Biological Reviews* 91, 578–596. https://doi.org/10.1111/brv.12184

COMNAP, 2017. *Antarctic Station Catalogue. COMNAP Secretariat*. https://www.comnap.aq/s/COMNAP_Antarctic_Station_Catalogue.pdf

COMNAP, 2022. *Wastewater Management Practices at Antarctic Stations: Preliminary Survey Results*. Information Paper 76. Berlin, Germany: ATCM-XLIV, 23 May–2 June 2022.

Conlan, K.E. et al., 2010. Benthic changes at McMurdo Station, Antarctica following local sewage treatment and regional iceberg-mediated productivity decline. *Marine Pollution Bulletin* 60, 419–432. https://doi.org/10.1016/j.marpolbul.2009.10.009

Convey, P. et al., 2009. Antarctic climate change and the environment. *Antarctic Science* 21, 541–563. https://doi.org/10.1017/S0954102009990642

Cordero, R.R. et al., 2022. Black carbon footprint of human presence in Antarctica. *Nature Communications* 13, 984. https://doi.org/10.1038/s41467-022-28560-w

Corsolini, S., and Ademollo, N., 2022. POPs in Antarctic ecosystems: Is climate change affecting their temporal trends? *Environmental Science: Processes & Impacts* 24, 1631–1642. https://doi.org/10.1039/D2EM00273F

Corti, A. et al., 2023. Marine sponges as bioindicators of pollution by synthetic microfibers in Antarctica. *Science of the Total Environment* 902, 166043. https://doi.org/10.1016/j.scitotenv.2023.166043

Cunningham, E.M., et al., 2020. High abundances of microplastic pollution in deep-sea sediments: Evidence from Antarctica and the Southern Ocean. *Environmental Science and Technology* 54, 13661–13671. https://doi.org/10.1021/acs.est.0c03441

Cunningham, E.M. et al., 2022. The transport and fate of microplastic fibres in the Antarctic: The role of multiple global processes. *Frontiers in Marine Science* 9. https://doi.org/10.3389/fmars.2022.1056081

da Silva, J.R.M.C. et al., 2023. Occurrence and distribution of legacy and emerging pollutants including plastic debris in Antarctica: Sources, distribution and impact on marine biodiversity. *Marine Pollution Bulletin* 186, 114353. https://doi.org/10.1016/j.marpolbul.2022.114353

Dawson, A.L. et al., 2018. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. *Nature Communications* 9, 1001. https://doi.org/10.1038/s41467-018-03465-9

Emnet, P. et al., 2015. Personal care products and steroid hormones in the Antarctic coastal environment associated with two Antarctic research stations, McMurdo Station and Scott Base. *Environmental Research Journal* 136, 331–342. https://doi.org/10.1016/j.envres.2014.10.019

Energy Information Administration (EIA), 2023. U.S. energy facts - data and statistics - U.S. *Energy Information Administration (EIA)* (Accessed 3.19.24). https://www.eia.gov/energyexplained/us-energy-facts/data-and-statistics.php

Ewing, T., 1989. Greenpeace's running battle with France now in Antarctica. *Nature* 337, 106–106. https://doi.org/10.1038/337106b0

Fan, S. et al., 2021. Concentrations, particle-size distributions, and dry deposition fluxes of aerosol trace elements over the Antarctic Peninsula in Austral summer. *Atmospheric Chemistry and Physics* 21, 2105–2124. https://doi.org/10.5194/acp-21-2105-2021

Fisher, J.A. et al., 2023. A synthesis of mercury research in the Southern Hemisphere, part 2: Anthropogenic perturbations. *Ambio* 52, 918–937. https://doi.org/10.1007/s13280-023-01840-5

Foucher, A. et al., 2021. A worldwide meta-analysis (1977–2020) of sediment core dating using fallout radionuclides including ^{137}Cs and ^{210}Pb$_{xs}$. *Earth System Science Data* 13, 4951–4966. https://doi.org/10.5194/essd-13-4951-2021

Fryirs, K. et al., 2013. The type and spatial distribution of past waste at the abandoned Wilkes Station, East Antarctica. *Polar Record* 49, 328–347. https://doi.org/10.1017/S0032247412000721

Garnett, J. et al., 2022. Increasing accumulation of perfluorocarboxylate contaminants revealed in an Antarctic Firn Core (1958–2017). *Environmental Science and Technology* 56, 11246–11255. https://doi.org/10.1021/acs.est.2c02592

Garza, T.N. et al., 2023. Quantifying microplastics in fjords along the Western Antarctic Peninsula. *Marine Pollution Bulletin* 193, 115144. https://doi.org/10.1016/j.marpolbul.2023.115144

Gigault, J. et al., 2018. Current opinion: What is a nanoplastic? *Environmental Pollution* 235, 1030–1034. https://doi.org/10.1016/j.envpol.2018.01.024

Gigault, J. et al., 2021. Nanoplastics are neither microplastics nor engineered nanoparticles. *Nature Nanotechnology* 16, 501–507. https://doi.org/10.1038/s41565-021-00886-4

Giovannini, F., 2021. The CTBT at 25 and beyond. *Arms Control Today* 51, 6–12. https://www.jstor.org/stable/27067296

Goerke, H. et al., 2004. Increasing levels and biomagnification of persistent organic pollutants (POPs) in Antarctic biota. *Marine Pollution Bulletin* 48, 295–302. https://doi.org/10.1016/j.marpolbul.2003.08.004

Görlach, U., Boutron, C.F., 1992. Variations in heavy metals concentrations in Antarctic snows from 1940 to 1980. Journal of Atmospheric Chemistry 14, 205–222. https://doi.org/10.1007/BF00115234

Golubev, S., 2021. Seabirds in conditions of local chronic oil pollution, Davis Sea, Antarctica. *Birds* 2, 275–284. https://doi.org/10.3390/birds2030020

Gray, A.D., Hughes, K.A., 2016. Demonstration of "substantial research activity" to acquire consultative status under the Antarctic Treaty. *Polar Research* 35, 34061. https://doi.org/10.3402/polar.v35.34061

Gröndahl, F. et al., 2009. Survey of wastewater disposal practices at Antarctic research stations. *Polar Research* 28, 298–306. https://doi.org/10.3402/polar.v28i2.6109

Hancock, G.J. et al., 2011. Plutonium as a chronomarker in Australian and New Zealand sediments: A comparison with 137Cs. *Journal of Environmental Radioactivity, South Pacific Environmental Radioactivity Association: 2008 Conference* 102, 919–929. https://doi.org/10.1016/j.jenvrad.2009.09.008

Harrison, J.J. et al., 2021. A record of fallout 239Pu and 240Pu at world Heritage Bathurst Harbour, Tasmania, Australia. *Journal of Environmental Radioactivity* 237, 106679. https://doi.org/10.1016/j.jenvrad.2021.106679

Hartmann, N.B. et al., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. *Environmental Science and Technology* 53, 1039–1047. https://doi.org/10.1021/acs.est.8b05297

Hawes, I. et al., 2023. The need for increased protection of Antarctica's inland waters. *Antarctic Science* 35, 64–88. https://doi.org/10.1017/S0954102022000463

Helmig, D. et al., 2020. Impact of exhaust emissions on chemical snowpack composition at Concordia Station, Antarctica. *The Cryosphere* 14, 199–209. https://doi.org/10.5194/tc-14-199-2020

Heredia Barión, P.A. et al., 2023. The impact of Holocene deglaciation and glacial dynamics on the landscapes and geomorphology of Potter Peninsula, King George Island (Isla 25 Mayo), NW Antarctic Peninsula. *Frontiers of Earth Science* 10. https://doi.org/10.3389/feart.2022.1073075

Hernández, F. et al., 2019. Occurrence of antibiotics and bacterial resistance in wastewater and sea water from the Antarctic. *Journal of Hazardous Materials* 363, 447–456. https://doi.org/10.1016/j.jhazmat.2018.07.027

Hong, S. et al., 1998. Heavy metals in Antarctic Ice from Law Dome: Initial results. *Environmental Research* 78, 94–103. https://doi.org/10.1006/enrs.1998.3849

Hopke, P.K. et al., 2020. Global review of recent source apportionments for airborne particulate matter. *Science of the Total Environment* 740, 140091. https://doi.org/10.1016/j.scitotenv.2020.140091

Horton, A.A., and Barnes, D.K.A., 2020. Microplastic pollution in a rapidly changing world: Implications for remote and vulnerable marine ecosystems. *Science of the Total Environment* 738, 140349. https://doi.org/10.1016/j.scitotenv.2020.140349

Hotchkis, M.A.C. et al., 2000. Measurement of ^{236}U in environmental media. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and*

Atoms, 8th International Conference on Accelerator Mass Spectrometry 172, 659–665. https://doi.org/10.1016/S0168-583X(00)00146-4

Hughes, K.A., 2003. Aerial dispersal and survival of sewage-derived faecal coliforms in Antarctica. *Atmospheric Environment* 37, 3147–3155. https://doi.org/10.1016/S1352-2310(03)00207-3

Hughes, K.A. et al., 2007. Tolerance of Antarctic soil fungi to hydrocarbons. *Science of the Total Environment* 372, 539–548. https://doi.org/10.1016/j.scitotenv.2006.09.016

Hughes, K.A. et al., 2016. Antarctic geoconservation: A review of current systems and practices. *Environmental Conservation* 43, 97–108. https://doi.org/10.1017/S0376892915000387

Hughes, K.A. et al., 2023. Loss of research and operational equipment in Antarctica: Balancing scientific advances with environmental impact. *Journal of Environmental Management* 348, 119200. https://doi.org/10.1016/j.jenvman.2023.119200

Hughes, K.A., and Convey, P., 2020. Implications of the COVID-19 pandemic for Antarctica. *Antarctic Science* 32, 426–439. https://doi.org/10.1017/S095410202000053X

Hull, B.B., and Bergstrom, D.M., 2006. Antarctic terrestrial and limnetic ecosystem conservation and management. In Bergstrom, D. M. et al. (Eds.), *Trends in Antarctic Terrestrial and Limnetic Ecosystems: Antarctica as a Global Indicator*. Netherlands, Dordrecht: Springer, pp. 317–340. https://doi.org/10.1007/1-4020-5277-4_15

Hwengwere, K. et al., 2022. Antimicrobial resistance in Antarctica: Is it still a pristine environment? *Microbiome* 10, 71. https://doi.org/10.1186/s40168-022-01250-x

ImPACT (Input Pathways of Persistent Organic Pollutants in Antarctica) Action Group, 2021. *IP137: Persistent Organic Chemicals in Antarctica: A Horizon Scan of Priority Challenges*. Report to ATCM43. Paris. https://scar.org/~documents/policy/antarctic-treaty/atcm-xliii-and-cep-xxiii-2021-paris-france/atcm43-ip137?layout=default

International Association of Antarctica Tour Operators (IAATO), 2023. *A Five-Year Overview and 2022–23 Season Report on IAATO Operator Use of Antarctic Peninsula Landing Sites and ATCM Visitor Site Guidelines*. Information Paper 53. Helsinki, Finland: ATCM-XLV.

International Association of Antarctica Tour Operators (IAATO), 2019. *Reducing Single-Use Plastic and Waste Generated by Polar Tourism*. IAATO, Providence, Rhode Island

International Association of Antarctica Tour Operators (IAATO), 2020. *Reducing Waste – Guidelines for Visitors to Antarctica*. IAATO, Providence, Rhode Island

International Maritime Organisation (IMO), 1988. *International Convention for the Prevention of Pollution from Ships (MARPOL)* [WWW Document]. https://www.imo.org/en/about/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx (Accessed 3.19.24).

Jiskra, M. et al., 2021. Mercury stable isotopes constrain atmospheric sources to the ocean. *Nature* 597, 678–682. https://doi.org/10.1038/s41586-021-03859-8

Karatekin, F. et al., 2023. The emerging contribution of Türkiye to Antarctic science and policy. *Antarctic Science* 35, 299–315. https://doi.org/10.1017/S0954102023000172

Kelley, J.M. et al., 1999. Global distribution of Pu isotopes and 237Np. *The Science of the Total Environment* 237–238, 483–500. https://doi.org/10.1016/S0048-9697(99)00160-6

Kennicutt, M.C., Sweet, S.T., 1992. Hydrocarbon contamination on the Antarctic peninsula: III. The *Bahia Paraiso*—Two years after the spill. *Marine Pollution Bulletin, Environmental Awareness in Antarctica: History, Problems, and Future Solutions* 25, 303–306. https://doi.org/10.1016/0025-326X(92)90686-Z

Kennicutt, M.C., Klein, A., Montagna, P., Sweet, S., Wade, T., Palmer, T., Sericano, J., Denoux, G., 2010. Temporal and spatial patterns of anthropogenic disturbance at McMurdo Station, Antarctica. Environmental Research Letters 5, 034010. https://doi.org/10.1088/1748-9326/5/3/034010

Kessenich, H.E. et al., 2023. Potential drivers of the recent large Antarctic ozone holes. *Nature Communications* 14, 7259. https://doi.org/10.1038/s41467-023-42637-0

Khan, A.L. et al., 2019. Local emissions and regional Wildfires influence refractory black carbon observations Near Palmer Station, Antarctica. *Frontiers of Earth Science* 7. https://doi.org/10.3389/feart.2019.00049

King, A.C.F. et al., 2024. Reconciling ice core CO2 and land-use change following New World-Old World contact. *Nature Communications* 15, 1735. https://doi.org/10.1038/s41467-024-45894-9

Klein, A.G. et al., 2008. The historical development of McMurdo station, Antarctica, an environmental perspective. *Polar Geography* 31, 119–144. https://doi.org/10.1080/10889370802579856

Koppel, D.J. et al., 2021. Assessing metal contaminants in Antarctic soils using diffusive gradients in thin-films. *Chemosphere* 269, 128675. https://doi.org/10.1016/j.chemosphere.2020.128675

Kuepper, N.D. et al., 2022. Persistent organic pollutants and mercury in a colony of Antarctic seabirds: Higher concentrations in 1998, 2001, and 2003 compared to 2014 to 2016. *Polar Biology* 45, 1229–1245. https://doi.org/10.1007/s00300-022-03065-w

Kuklinski, P. et al., 2019. Offshore surface waters of Antarctica are free of microplastics, as revealed by a circum-Antarctic study. *Marine Pollution Bulletin* 149. https://doi.org/10.1016/J.MARPOLBUL.2019.110573

Leal, M.A. et al., 2008. Atmospheric impacts due to anthropogenic activities in remote areas: The case study of Admiralty Bay/King George Island/Antarctic Peninsula. *Water, Air, & Soil Pollution* 188, 67–80. https://doi.org/10.1007/s11270-007-9525-7

Leihy, R.I. et al., 2020. Antarctica's wilderness fails to capture continent's biodiversity. *Nature* 583, 567–571. https://doi.org/10.1038/s41586-020-2506-3

Li, C. et al., 2020. Unequal anthropogenic enrichment of mercury in Earth's Northern and Southern Hemispheres. *ACS Earth Space Chemistry* 4, 2073–2081. https://doi.org/10.1021/acsearthspacechem.0c00220

Li, C. et al., 2017. Recent ^{210}Pb,^{137}Cs and^{241}Am accumulation in an ombrotrophic peatland from Amsterdam Island (Southern Indian Ocean). *Journal of Environmental Radioactivity* 175–176, 164–169. https://doi.org/10.1016/j.jenvrad.2017.05.004

Liu, K. et al., 2021. Assessment of heavy metal contamination in the atmospheric deposition during 1950–2016 A.D. from a snow pit at Dome a, East Antarctica. *Environmental Pollution* 268, 115848. https://doi.org/10.1016/j.envpol.2020.115848

Luarte, T., et al., 2023. Levels of persistent organic pollutants (POPs) in the Antarctic atmosphere over time (1980 to 2021) and estimation of their atmospheric half-lives. *Atmospheric Chemistry and Physics* 23, 8103–8118. https://doi.org/10.5194/acp-23-8103-2023

Manno, C. et al., 2022. Under pressure: Nanoplastics as a further stressor for sub-Antarctic pteropods already tackling ocean acidification. *Marine Pollution Bulletin* 174, 113176. https://doi.org/10.1016/j.marpolbul.2021.113176

Marina-Montes, C. et al., 2020. Heavy metal transport and evolution of atmospheric aerosols in the Antarctic region. *Science of the Total Environment* 721, 137702. https://doi.org/10.1016/j.scitotenv.2020.137702

Marrone, A. et al., 2021. Antarctic fish as a global pollution sensor: Metals biomonitoring in a twelve-year period. *Frontiers in Molecular Biosciences* 8. https://doi.org/10.3389/fmolb.2021.794946

Marshall, G.J. et al., 2017. The signature of Southern Hemisphere atmospheric circulation patterns in Antarctic precipitation. *Geophysical Research Letters* 44(11), 580–511, 589. https://doi.org/10.1002/2017GL075998

Materić, D. et al., 2022. Nanoplastics measurements in Northern and Southern polar ice. *Environmental Research* 208, 112741. https://doi.org/10.1016/j.envres.2022.112741

McConnell, J.R. et al., 2014. Antarctic-wide array of high-resolution ice core records reveals pervasive lead pollution began in 1889 and persists today. *Scientific Reports* 4, 5848. https://doi.org/10.1038/srep05848

McConnell, J.R. et al., 2021. Hemispheric black carbon increase after the 13th-century Māori arrival in New Zealand. *Nature* 598, 82–85. https://doi.org/10.1038/s41586-021-03858-9

McWatters, R.S. et al., 2016. On site remediation of a fuel spill and soil reuse in Antarctica. *Science of the Total Environment* 571, 963–973. https://doi.org/10.1016/j.scitotenv.2016.07.084

Moore, C.J., 2008. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. *Environmental Research, the Plastic World* 108, 131–139. https://doi.org/10.1016/j.envres.2008.07.025

Munari, C. et al., 2017. Microplastics in the sediments of Terra Nova Bay (Ross Sea, Antarctica). *Marine Pollution Bulletin* 122, 161–165. https://doi.org/10.1016/j.marpolbul.2017.06.039

Mustafa, O. et al., 2018. State of knowledge: Antarctic wildlife response to unmanned aerial systems. *Polar Biology* 41, 2387–2398. https://doi.org/10.1007/s00300-018-2363-9

Netherlands, 2023. *Infrastructure Supporting Tourism and other Non-Governmental Activities in Antarctica*. Working Paper 4. Helsinki, Finland: Antarctic Treaty Consultative Meeting XLV, 29 May–8 June 2023.

Obbard, R.W., 2018. Microplastics in Polar Regions: The role of long-range transport. *Current Opinion in Environmental Science & Health, Micro and Nanoplastics* 1, 24–29. https://doi.org/10.1016/j.coesh.2017.10.004

Oliva, M. et al., 2017. Recent regional climate cooling on the Antarctic Peninsula and associated impacts on the cryosphere. *Science of the Total Environment* 580, 210–223. https://doi.org/10.1016/j.scitotenv.2016.12.030

Padeiro, A. et al., 2016. Trace element contamination and availability in the Fildes Peninsula, King George Island, Antarctica. *Environmental Science: Processes Impacts* 18, 648–657. https://doi.org/10.1039/C6EM00052E

Palmer, T.A. et al., 2022. Anthropogenic effects on the marine environment adjacent to Palmer Station, Antarctica. *Antarctic Science* 34, 79–96. https://doi.org/10.1017/S0954102021000535

Patra, P.K. et al., 2014. Observational evidence for interhemispheric hydroxyl-radical parity. *Nature* 513, 219–223. https://doi.org/10.1038/nature13721

Pérez-Rodríguez, M. et al., 2019. Thawing of snow and ice caused extraordinary high and fast mercury fluxes to lake sediments in Antarctica. *Geochimica et Cosmochimica Acta* 248, 109–122. https://doi.org/10.1016/j.gca.2019.01.009

Perfetti-Bolaño, A. et al., 2022. Analysis of the contribution of locally derived wastewater to the occurrence of pharmaceuticals and personal care products in Antarctic coastal waters. *Science of the Total Environment* 851, 158116. https://doi.org/10.1016/j.scitotenv.2022.158116

Pertierra, L.R. et al., 2017. High resolution spatial mapping of human footprint across Antarctica and its implications for the strategic conservation of Avifauna. *PLOS ONE* 12, e0168280. https://doi.org/10.1371/journal.pone.0168280

Peter, M.L. et al., 2009. Risk assessment for the Fildes Peninsula and Ardley Island, and development of management plans for their designation as specially protected or specially managed areas. *German Federal Environment Agency: https://www.umweltbundesamt.de/en/publikationen/risk-assessment-for-fildes-peninsula-ardley-island*

Piccardo, M. et al., 2020. Nanoplastics in the oceans: Theory, experimental evidence and real world. *Marine Pollution Bulletin* 157, 111317. https://doi.org/10.1016/j.marpolbul.2020.111317

Planchon, F.A.M. et al., 2002. Changes in heavy metals in Antarctic snow from Coats Land since the mid-19th to the late-20th century. *Earth and Planetary Science Letters* 200, 207–222. https://doi.org/10.1016/S0012-821X(02)00612-X

Power, M.L. et al., 2016. *Escherichia coli* out in the cold: Dissemination of human-derived bacteria into the Antarctic microbiome. *Environmental Pollution* 215, 58–65. https://doi.org/10.1016/j.envpol.2016.04.013

Pradel, A. et al., 2023. The environmental fate of nanoplastics: What we know and what we need to know about aggregation. *NanoImpact* 29, 100453. https://doi.org/10.1016/j.impact.2023.100453

Prăvălie, R., 2014. Nuclear weapons tests and environmental consequences: A global perspective. *Ambio* 43, 729–744. https://doi.org/10.1007/s13280-014-0491-1

Reed, S. et al., 2018. Microplastics in marine sediments near Rothera Research Station, Antarctica. *Marine Pollution Bulletin* 133, 460–463. https://doi.org/10.1016/j.marpolbul.2018.05.068

Regoli, F. et al., 2005. Interactions between metabolism of trace metals and xenobiotic agonists of the aryl hydrocarbon receptor in the antarctic fish *Trematomus bernacchii*: Evironmental perspectives. *Environmental Toxicology and Chemistry* 24, 1475–1482. https://doi.org/10.1897/04-514r.1

Rose, N.L., Turner, S.D., Unger, L.E., Curtis, C.J., 2021. The chronostratigraphy of the Anthropocene in southern Africa: Current status and potential. South African Journal of Geology 124, 1093–1106. https://doi.org/10.25131/sajg.124.0053

Rota, E. et al., 2022. Macro- and microplastics in the Antarctic environment: Ongoing assessment and perspectives. *Environments* 9, 93. https://doi.org/10.3390/environments9070093

Rowlands, E. et al., 2021a. The effects of combined ocean acidification and nanoplastic exposures on the embryonic development of Antarctic Krill. *Frontiers in Marine Science* 8. https://doi.org/10.3389/fmars.2021.709763

Rowlands, E. et al., 2021b. A Polar outlook: Potential interactions of micro- and nano-plastic with other anthropogenic stressors. *Science of the Total Environment* 754, 142379. https://doi.org/10.1016/j.scitotenv.2020.142379

Ruoppolo, V. et al., 2013. Wildlife and oil in the Antarctic: A recipe for cold disaster. *Polar Record* 49, 97–109. https://doi.org/10.1017/S0032247411000763

Saunders, KM, and Meredith K.T., 2023. Monitor changes to ice-bound nuclear fallout in Antarctica. *Nature* 619, 465. https://doi.org/10.1038/d41586-023-02246-9

Schwanck, F. et al., 2016. Anomalously high arsenic concentration in a West Antarctic ice core and its relationship to copper mining in Chile. *Atmospheric Environment* 125, 257–264. https://doi.org/10.1016/j.atmosenv.2015.11.027

Schwanck, F. et al., 2017. A 125-year record of climate and chemistry variability at the Pine Island Glacier ice divide, Antarctica. *The Cryosphere* 11, 1537–1552. https://doi.org/10.5194/tc-11-1537-2017

Schneider, L. et al., 2019. How significant is atmospheric metal contamination from mining activity adjacent to the Tasmanian Wilderness World Heritage Area? A spatial analysis of metal concentrations using air trajectories models. *Science of the Total Environment* 656, 250–260. https://doi.org/10.1016/j.scitotenv.2018.11.241

Schwanck, F. et al., 2022. Anthropogenic trace elements (Bi, Cd, Cr, Pb) concentrations in a West Antarctic ice core. *Anais da Academia Brasileira de Ciências* 94, e20210351. https://doi.org/10.1590/0001-3765202220210351

Scientific Committee on Antarctic Research (SCAR), 2024. *Plastic in Polar Environments (PLASTIC-AG)*. https://scar.org/science/life/plastic (accessed 3.19.24).

Secretariat of the Antarctic Treaty (ATS), 1961. *The Antarctic Treaty*. https://www.ats.aq/e/antarctictreaty.html (accessed 3.19.24).

Secretariat of the Antarctic Treaty (ATS), 1998a. ANNEX III to the Protocol on Environmental Protection to the Antarctic Treaty Waste Disposal and Waste Management. https://documents.ats.aq/recatt/Att006_e.pdf

Secretariat of the Antarctic Treaty (ATS), 1998b. *The Protocol on Environmental Protection to the Antarctic Treaty*. https://www.ats.aq/e/protocol.html (accessed 3.19.24).

Severi, M., Becagli, S., Caiazzo, L., Nardin, R., Toccafondi, A., and Traversi, R., 2023. The 239Pu nuclear fallout as recorded in an Antarctic ice core drilled at Dome C (East Antarctica). *Chemosphere* 329, 138674. https://doi.org/10.1016/j.chemosphere.2023.138674

Sinclair, D., and Schneider, L., 2019. Mercury emissions, regulation and governance of coal-fired power stations in Victoria, Australia. *Environmental and Planning Law Journal* 36, 630–641. https://doi.org/10.3316/agispt.20191121020353

Snape, I. et al., 2001. Management and remediation of contaminated sites at Casey Station, Antarctica. *Polar Record* 37, 199–214. https://doi.org/10.1017/S0032247400027236

Stark, J.S., 2022. Effects of lubricant oil and diesel on macrofaunal communities in marine sediments: A five-year field experiment in Antarctica. *Environmental Pollution* 311, 119885. https://doi.org/10.1016/j.envpol.2022.119885

Stark, J.S. et al., 2016. Dispersal and dilution of wastewater from an ocean outfall at Davis Station, Antarctica, and resulting environmental contamination. *Chemosphere* 152, 142–157. https://doi.org/10.1016/j.chemosphere.2016.02.053

Stark, J.S. et al., 2023. Contamination of the marine environment by Antarctic research stations: Monitoring marine pollution at Casey station from 1997 to 2015. *PLoS One* 18, e0288485. https://doi.org/10.1371/journal.pone.0288485

Szopińska, M. et al., 2021. First evaluation of wastewater discharge influence on marine water contamination in the vicinity of Arctowski Station. *Science of the Total Environment* 789, 147912. https://doi.org/10.1016/j.scitotenv.2021.147912

Szufa, K.M., et al., 2018. Variations of plutonium isotopic ratios in Antarctic ecosystems. *Journal of Radioanalytical and Nuclear Chemistry* 318, 1511–1518. https://doi.org/10.1007/s10967-018-6274-6

Tejedo, P. et al., 2014. Trampling the Antarctic: Consequences of pedestrian traffic on Antarctic soils. In: T. Tin et al. (Eds.), *Antarctic Futures: Human Engagement with the Antarctic Environment*. Netherlands, Dordrecht: Springer, pp. 139–161. https://doi.org/10.1007/978-94-007-6582-5_6

Ter Halle, A. et al., 2017. Nanoplastic in the North Atlantic Subtropical Gyre. *Environmental Science and Technology* 51, 13689–13697. https://doi.org/10.1021/acs.est.7b03667

Terauds, A. et al., 2012. Conservation biogeography of the Antarctic. *Diversity and Distributions* 18, 726–741. https://doi.org/10.1111/j.1472-4642.2012.00925.x

Thomas, E.R., 2023. First evidence of industrial fly-ash in an Antarctic ice core. *Scientific Reports* 13, 6529. https://doi.org/10.1038/s41598-023-33849-x

Tin, T. et al., 2009. Impacts of local human activities on the Antarctic environment. *Antarctic Science* 21, 3–33. https://doi.org/10.1017/S0954102009001722

Tort, L.F.L. et al., 2017. Wastewater contamination in Antarctic melt-water streams evidenced by virological and organic molecular markers. *Science of the Total Environment* 609, 225–231. https://doi.org/10.1016/j.scitotenv.2017.07.127

Tuohy, A. et al., 2015. Transport and deposition of heavy metals in the Ross Sea Region, Antarctica. *Journal of Geophysical Research: Atmospheres* 120, 10996–11011. https://doi.org/10.1002/2015JD023293

Turner, J. et al., 2014. Antarctic climate change and the environment: An update. *Polar Record* 50, 237–259. https://doi.org/10.1017/S0032247413000296

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000. *Annex C. Exposures to the Public from Man-Made Sources of Radiation*. https://www.unscear.org/docs/reports/annexc.pdf.
Vallelonga, P. et al., 2002. The lead pollution history of Law Dome, Antarctica, from isotopic measurements on ice cores: 1500 AD to 1989 AD. *Earth and Planetary Science Letters* 204, 291–306. https://doi.org/10.1016/S0012-821X(02)00983-4
Vallelonga, P. et al., 2004. Elemental indicators of natural and anthropogenic aerosol inputs to Law Dome, Antarctica. *Annals of Glaciology* 39, 169–174. https://doi.org/10.3189/172756404781814483
Vázquez, S. et al., 2017. Bacterial communities and chemical parameters in soils and coastal sediments in response to diesel spills at Carlini Station, Antarctica. *The Science of the Total Environment* 605–606, 26–37. https://doi.org/10.1016/J.SCITOTENV.2017.06.129
Waller, C.L. et al., 2017. Microplastics in the Antarctic marine system: An emerging area of research. *Science of the Total Environment* 598, 220–227. https://doi.org/10.1016/j.scitotenv.2017.03.283
Waluda, C.M. et al., 2020. Thirty years of marine debris in the Southern Ocean: Annual surveys of two island shores in the Scotia Sea. *Environment International* 136. 105460, https://doi.org/10.1016/J.ENVINT.2020.105460
Webb, A.L. et al., 2020. Sources of elevated heavy metal concentrations in sediments and benthic marine invertebrates of the Western Antarctic Peninsula. *Science of the Total Environment* 698, 134268. https://doi.org/10.1016/j.scitotenv.2019.134268
Whiteside, M., and Herndon, J.M., 2022. Destruction of stratospheric ozone: Role of aerosolized coal fly ash iron. *European Journal of Applied Sciences* 10, 143–153. https://doi.org/10.14738/aivp.104.12689
Wild, S. et al., 2015. An Antarctic research station as a source of brominated and perfluorinated persistent organic pollutants to the local environment. *Environmental Science & Technology* 49, 103–112. https://doi.org/10.1021/ES5048232
Wild, S. et al., 2022. South polar skua (Catharacta maccormicki) as biovectors for long-range transport of persistent organic pollutants to Antarctica. *Environmental Pollution* 292, 118358. https://doi.org/10.1016/j.envpol.2021.118358
Wilson, K.-J. et al., 1990. The impact of man on Adélie Penguins at Cape Hallett, Antarctica. In Kerry, K. R., Hempel, G. (Eds.), *Antarctic Ecosystems*. Berlin, Heidelberg: Springer, pp. 183–190. https://doi.org/10.1007/978-3-642-84074-6_19
Wolff, E., 1992. The influence of global and local atmospheric pollution on the chemistry of Antarctic snow and ice. *Marine Pollution Bulletin, Environmental Awareness in Antarctica: History, Problems, and Future Solutions* 25, 274–280. https://doi.org/10.1016/0025-326X(92)90682-V
World Health Organization, 2021. *WHO Global Air Quality Guidelines. Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. Geneva: World Health Organization.
World Mining Data, n.d. *World Mining Data - Data Section*. https://www.world-mining-data.info/?World_Mining_Data___Data_Section (Accessed 3.19.24).