Monitoring persistent organic chemicals in Antarctica in support of global chemical policy: a horizon scan of priority actions and challenges

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Global production and emission of chemicals exceeds societal capacities for assessment and monitoring. This situation calls for improved chemical regulatory policy frameworks and increased support for expedited decision making within existing frameworks. The polar regions of the Earth represent unique sentinel areas for the study of global chemical behaviour, and data arising from these areas can strengthen existing policy frameworks. However, chemical pollution research and monitoring in the Antarctic is underdeveloped, with geopolitical complexities and the absence of legal recognition of international chemical policy serving to neutralise progress made in other global regions. This Personal View represents a horizon scan by the action group Input Pathways of Persistent Organic Pollutants to Antarctica, of the Scientific Committee for Antarctic Research. Four priority research and research facilitation gaps are outlined, with recommendations for Antarctica Treaty parties for strategic action against these priorities.

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Introduction

Globally, the increasing reliance on chemicals to meet industrial and societal needs has grown exponentially during the past 70 years, fundamentally altering nature's exposome.[1] More than 350 000 chemicals are commercially registered for production and use,[2] and the Chemical Abstract Service Registry has been growing by 10 million new chemical structures per annum in recent years.[3] *The* Lancet *Commission on Pollution and Health* estimated that 16% of global premature deaths were linked to pollution in 2015.[4] A subsequent progress update reported a 66% increase in the number of deaths related to air and toxic chemical pollution between 2000 and 2019.[5] Notably, both reports included only a narrow scope of chemical pollutants and so are likely to have markedly underestimated true numbers. Furthermore, a review of the planetary boundary of novel entities, such as chemicals, found that the unchecked production and diversity of synthetic chemicals exceeds the global capacity for their assessment and monitoring.[6]

Managing the myriad of chemicals present in the natural environment represents one of the greatest planetary health challenges of our time,[7] with the UN declaring chemical pollution as one of three planetary crises, alongside biodiversity loss and climate change.[8] In recognition of the advanced stages of this threat, the UN Environment Assembly, at its fifth assembly (UNEA-5.2), committed to a UN Intergovernmental Science-Policy Panel for the Sound Management of Chemicals and Waste and Pollution Prevention, to be established by 2024. This body is envisaged to serve in the same role as the Intergovernmental Panel on Climate Change—to provide policy makers with regular scientific assessments, on the basis of exhaustive review of the scientific, technical, and socioeconomic literature. As with climate change, data obtained from the polar regions of the planet will provide invaluable information for decision making and action. Despite the potential of such data to substantially support the efficiency of global chemical regulatory frameworks, Antarctic chemical pollution research and strategic monitoring is poorly supported, with the geopolitical complexities of the region having a neutralising effect on global progress. Crucially, international political advances with respect to chemical pollution on the global stage, and associated monitoring obligations, are not translated to the Antarctic region given that sovereignty, as the basis of international law, is absent under the Antarctic Treaty.

Key messages

- In 2021, the UN announced global chemical pollution to be part of a triplet planetary crisis, alongside climate change and biodiversity loss. The advanced stage of global chemical pollution calls for a step-change in the way in which chemicals are regulated worldwide.
- In response, in 2022 the UN Environment Assembly committed to establishing a UN Intergovernmental Science-Policy Panel for the Sound Management of Chemicals and Waste and Pollution Prevention, by 2024. This body is envisaged to serve in the same role as the Intergovernmental Panel on Climate Change—to provide policy makers with scientific assessments.
- Chemical pollution at the poles of the Earth serves as a barometer of planetary health, and robust data arising from these regions have a crucial role to play in the support of global chemical policy, assessments, and decision making.
- Pollution monitoring frameworks are absent for the Antarctic and Southern Ocean region, with global efforts neutralised by the absence of legal recognition of the international commitments and obligations of individual Antarctic Treaty parties in the region.
- Timely progress in the field of Antarctic chemical research calls for Antarctic Treaty consultative parties to transcend what is legally required of them, and to extend their national chemical monitoring programmes to their Antarctic research stations and territories.
- Holistically designed chemical research and monitoring programmes that encompass ecological drivers of change will facilitate the construction of novel longitudinal datasets that can be used to answer vital research questions for the protection of planetary health.

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Figure 1: **Targeted Antarctic field investigation of chemical redistribution in the coastal seasonal sea-ice zone during spring sea-ice melt**

In February, 2021, the action group Input Pathways of Persistent Organic Pollutants to Antarctica (known as ImPACT), of the Scientific Committee for Antarctic Research, held a workshop to identify priority challenges for Antarctic chemical research. This Personal View represents a horizon scan of priority research and facilitation gaps, and recommendations for action. In this context, we provide a road map for the holistic design of chemical research and monitoring programmes to facilitate the construction of novel longitudinal datasets that can be used to support global chemical policy and planetary health goals.

Priority 1: Antarctica as a natural laboratory for the identification of persistent and mobile chemicals

Persistent organic pollutants (POPs) are a subset of synthetic chemicals that share the four risk criteria of persistence, mobility in the environment, toxicity, and ability to bioaccumulate. Concerns for human and environmental health from exposure to POPs led to the establishment of the Stockholm Convention in 2004, an international agreement that commits signatories to restrict and eliminate the use and production of such chemicals.[9] However, developing a robust global chemical regulatory framework has had challenges. The responsibility for chemical risk assessment frequently falls to governmental regulatory bodies. Obstacles preventing timely regulation under this model include recurring corporate lawsuits challenging regulatory decisions, and limitations on available chemical risk data.[10] Other barriers arise when there is a direct commercial and public health conflict relating to a chemical. Even when a chemical is identified as problematic to health or the environment, which might be decades after it has entered the environment, previous experience has shown that it could take many more years for an agreement to be reached to ban or restrict use of the chemical.[11] It might be many more additional years before legislation is reflected by decreasing amounts of the chemical in the environment.[11]

Environmental chemistry has a major role to play in strengthening efforts under existing chemical regulatory frameworks, and the polar regions of the Earth represent natural laboratories for the identification of new chemicals of concern, due to the remoteness, sparse populations, and low number of local contamination sources in these regions.[12] Antarctica is the most remote region on Earth, and therefore detection of a chemical in Antarctic environmental media can provide the strongest evidence for chemical persistence and mobility.

New and advanced technology developments are allowing for broadened, non-targeted analytical approaches[12,13] to identify contaminants without previous knowledge of their presence, effectively moving the question from “Is this chemical here?” towards “What chemicals are here?” Such approaches should be implemented on specially collected Antarctic environmental media, to provide a true picture of present-day chemical pollution in Antarctica. Information regarding the environmental presence of chemicals in the most remote region of the planet provides substantive evidence of both chemical persistence and mobility. Gathering sufficient data to confidently profile the risk of a chemical is a key barrier for the approval of any proposal for a new chemical inclusion under the Stockholm Convention. The criteria of both persistence and mobility are frequently assessed via theoretical modelling approaches; however, without accompanying environmental occurrence data, theorical predictions have substantial uncertainty. Evidence of Antarctic occurrence of a chemical directly serves regulatory needs by reducing or removing such uncertainty, potentially supporting smoother, and expedited, adoption of new proposals. Distinguishing between long-range global sources and in-situ human sources (eg, stations and maritime activities in the Antarctic region) should form an inherent quality assurance component of monitoring efforts. Local emissions identified in parallel will alert Antarctic managers, such as the Council of Managers of National Antarctic Programs, to any potential breaches of the Protocol on Environmental Protection to the Antarctic Treaty with respect to chemical emissions. Additionally, monitoring of Antarctic transboundary chemical pollution, in particular of chemicals transported through the atmosphere, will provide an integrated signal of southern hemisphere chemical usage patterns and trends. These patterns and trends are currently not captured under established north polar monitoring programmes due to separate tropospheric circulation systems of the respective hemispheres. However, southern hemisphere chemical profiles are likely to be undergoing considerable changes in parallel with the rapid development of major southern hemisphere nations.

Priority 2: Chemical behaviour, fate, and effects in changing Antarctic ecosystems

All major drivers of organic chemical behaviour and fate are likely to be affected in a warming climate.[14] These drivers include air and sea temperature, cryosphere dynamics, organic carbon cycling, ocean pH, and food web connections.[15] Changes to the abiotic environment will affect biogeochemical cycles, and ultimately animal chemical exposure. Similarly, altered food web connections, driven by, for example, a reduction in sympagic species or poleward shifts in species ranges, are expected to influence chemical exposure and fate within an ecosystem. Investigating, and temporally tracking, chemical dynamics in Antarctica in response to directional biophysical change is fundamental for accurate interpretation of observations and trends. Robust chemical and ecosystem surveillance networks, such as those advocated under Priority 4 in this Personal View, combined with targeted field[16,17] and laboratory[18] experimentation, are recommended (figure 1).

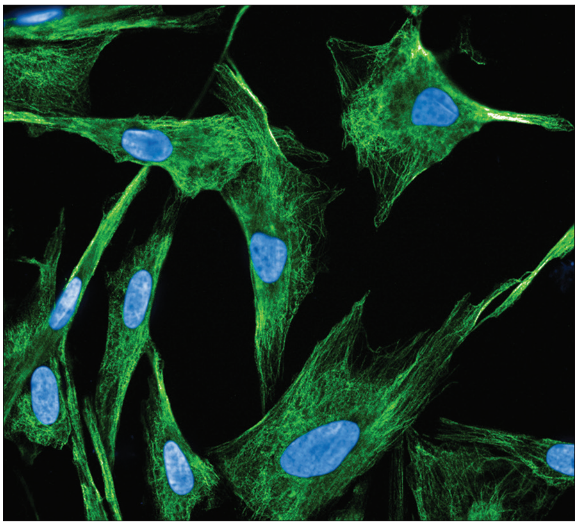

Figure 2: **Southern hemisphere humpback whale (*Megaptera novaeangliae*) fibroblast cells cultured for in-vitro toxicity assessment**

Figure 3: **Norway's atmospheric observatory established in Queen Maud Land, Antarctica, in 2008**

Priority 3: Toxicological sensitivity of endemic Antarctic biota

Assessment of chemical toxicity is crucial to robust chemical regulation.[19] This risk criterion is typically assessed via standardised assays and a narrow selection of temperate test species. However, there is a scarcity of testing and understanding around the sensitivity of polar species to contaminants.[20,21] Polar species have adapted to the seasonal productivity of high latitude environments. Common adaptations include slower metabolism, extended lifespans,[22] and behavioural life history adaptations such as hibernation, fasting, and migration.[23] Seasonal productivity has also driven a dependence of polar biota on lipid-rich prey sources.[24] In combination, a lipid-rich diet and adaptations that markedly affect lipid dynamics might influence sensitivity to, and expression of, the toxicological effects of lipophilic organic chemicals. Therefore, advancing understanding of the comparative toxicological sensitivity of Antarctic biota is a priority research gap.[19] Ecotoxicological investigation with Antarctic test species either requires advanced testing facilities in the Antarctic, or improved species maintenance and culturing facilities at institutional centres for Antarctic science. Enhanced capabilities for ecotoxicological experimentation are needed. Furthermore, an increased focus on the development and validation of species-specific in-vitro and in-silico approaches, to overcome the costs and limitations of working with Antarctic biota, is advocated (figure 2).

Priority 4: Sustained circumpolar surveillance

Capturing change requires continuous, sustained, and standardised monitoring with time and on a large spatial scale.[25] The challenging working conditions in the Antarctic and Southern Ocean region mean that such observations are difficult to obtain. Therefore, monitoring efforts are vulnerable to missed observations, due to environmental factors, national political or scientific funding climates, and more recently, the global COVID-19 pandemic. Missed observations in a timeline substantially reduces the power of the dataset to detect change. As such, optimised chemical monitoring efforts should be simple, and, where possible, automated, with low associated logistical and financial costs, raising the feasibility of sustained measurements through societal stochasticity. Furthermore, where possible, these efforts should be integrated with, and ideally led by, national chemical monitoring programmes as ongoing commitments with clear lines of reporting against national and international policy obligations.

A global monitoring plan (GMP) forms one component of the effectiveness evaluation of the Stockholm Convention.[26] The GMP seeks to provide a harmonised organisational framework for the collection of comparable monitoring data on the presence of POPs from all regions, and recommends longitudinal monitoring of

Figure 4: **Annual biopsy sampling of humpback whales conducted under the Humpback Whale Sentinel Programme for circumpolar surveillance of the Antarctic sea-ice ecosystem**

core media, including ambient air and seawater.[26] We advocate that the environmental agencies and national Antarctic programmes of high-income consultative parties to the Antarctic Treaty, and ratifying nations to the Stockholm Convention, extend their national GMP monitoring efforts to their Antarctic stations and territories to undertake three actions at minimum. First, these bodies should install permanent, semiautomated, high-volume air sampling equipment (figure 3), and provide service agreements for the collection and transport of samples to approved laboratories for analysis or archiving. Second, annual collection of surface seawater in a north-south transect across the Antarctic circumpolar current should be undertaken, to identify ocean transport of hydrophilic chemicals. Low-effort sampling could be done via re-supply shipping voyages. Service-level agreements should be obtained to support sampling and subsequent transport of samples to approved laboratories for analysis or archiving. The spatial extent of these air and water sampling approaches might be further enhanced via the inclusion of a network of semiquantitative air and seawater passive samplers. Such networks could be integrated into larger networks, such as the Global Atmospheric Passive Sampling network[27] and the Aquatic Global Passive Sampling monitoring programme for POPs in the waters of the world.[28] Both passive air and water samplers have previously been successfully deployed at polar latitudes,[29,30] and such sampling improves on cost-efficiency and thus feasibility of participation for middle-income consultative parties to the Antarctic Treaty.

Third, in the absence of human media (human hair and breastmilk are core media under the GMP), we propose that biological samples from one or more model species with a circumpolar distribution be selected for long-term chemical biomonitoring. Routine collection of sessile invertebrate bioindicator species is proposed, as is systematic and non-destructive sampling of vertebrates. The sampling of vertebrates could be done in conjunction with established biomonitoring programmes, such as the Commission for the Conservation of Antarctic Marine Living Resources Ecosystem Monitoring Program,[31] or the Humpback Whale Sentinel Programme (figure 4),[32,33] as two long-term Antarctic biomonitoring programmes for the surveillance of the Antarctic sea-ice ecosystem.

The systematic collection of environmental samples (air, seawater, and biological samples), led and coordinated by national environmental monitoring programmes, should include archiving in environmental specimen banks, which facilitate retrospective analysis when either new priority chemicals are identified or new advanced analytical methodologies become available. Similarly, associated chemical analysis of all Antarctic media should be done at laboratories committed to routine proficiency testing practices.

Priorities summary

Transboundary chemical pollution presents a unique management challenge in the Antarctic context, confounded by geopolitical complexities. In a similar manner to climate change,[34] the issue cannot be tackled at the regional scale and requires global action. Despite mitigation of human influences being identified as one of six priorities for Antarctic science,[35,36] chemical pollution has remained a low priority both within national Antarctic programme strategic plans and for the Committee for Environmental Protection of the Antarctic Treaty, which have primarily focused on regional solutions. Indeed, in the 50 years since agricultural pesticides were first detected in Antarctica,[37] no single coordinated multinational effort has been established to support chemical research and monitoring activities. The Antarctic Treaty System (ATS) outlines a series of agreements among signatories to preserve Antarctica for scientific investigation. However, Antarctica effectively became stateless with ratification of the ATS,[38] and so sovereignty, the basis of international law, was removed. Consequently, political advances with respect to chemical pollution on the global stage are neutralised in Antarctica due to the absence of legal recognition of the political commitments and obligations of parties in the region.

Chemical pollution is part of the triplet planetary crisis outlined by the UN.[8] As with climate change, chemical pollution at polar latitudes serves as a barometer of planetary health, and robust data arising from these regions have a crucial role to play in the support of global chemical policy, and in anticipated efforts of the nascent UN Intergovernmental Science-Policy Panel for the Sound Management of Chemicals and Waste and Pollution Prevention. The importance and value of Antarctica in this role denotes that timely action cannot be satisfactorily administered through the ATS, as a system encumbered by consensus decision making.[39] Instead, collaborative policy-led action[40] for timely progress in the field of Antarctic chemical research calls for ATS consultative parties to transcend what is legally required of them, and to act simply as good global citizens in the establishment of robust surveillance programmes. Norway, a nation familiar with the soft laws of the Arctic region[41] and respected for its green credentials, represents the single existing ATS consultative party to exercise this principle in the installation of an atmospheric monitoring observatory for POPs in 2008[42] (figure 3).

Holistic programme design

Chemical surveillance programmes implemented today can benefit from lessons learned from long-standing chemical surveillance programmes, such as those coordinated by the Arctic Monitoring and Assessment Programme (AMAP). AMAP assessments, such as a 2011 assessment of the combined effects of selected pollutants and climate change in the Arctic environment,[43] have highlighted the importance of viewing findings at a systems scale. In the context of the four priorities for Antarctic chemical research identified in this Personal View, applying a systems approach means integrating findings across the identified priorities and across monitoring efforts. For example, the expression of toxic effects is typically exacerbated by environmental factors, necessitating that chemical risk be considered in the context of multiple stressors and ecosystem health. Holistically designed chemical research and monitoring programmes that encompass identified ecological drivers of change will facilitate the construction of novel longitudinal datasets. Such datasets can enhance interdisciplinary collaborations between chemists, ecologists, and climate scientists, and can be used to answer important research questions for the protection of the Antarctic and Southern Ocean ecosystems, and overall planetary health.

Contributors

All authors participated in the 2021 workshop of the Input Pathways for Persistent Organic Pollutants to Antarctica action group, and contributed actively to the discussion and mapping of priorities for organic chemical research in Antarctica in the conceptualisation of this Personal View. SBN wrote the first draft of the manuscript and all authors participated in the editing of subsequent drafts.

Declaration of interests

We declare no competing interests.

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