Chemosphere 327 (2023) 138530

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Berlin statement on legacy and emerging contaminants in polar regions☆

Ralf Ebinghaus [a,*], Elena Barbaro [b], Susan Bengtson Nash [c], Cristina de Avila [d], Cynthia A. de Wit [e], Valeria Dulio [f], Janine Felden [g], Antonio Franco [h], Juergen Gandrass [a], Marco Grotti [i], Heike Herata [j], Kevin A. Hughes [k], Morten Jartun [l], Hanna Joerss [a], Roland Kallenborn [m,s], Jan Koschorreck [j], Anette Küster [j], Rainer Lohmann [n], Zhanyun Wang [o], Matthew MacLeod [e], Rebecca Pugh [p], Caren Rauert [j], Jaroslav Slobodnik [f], Roxana Sühring [q], Katrin Vorkamp [r], Zhiyong Xie [a]

[a] Helmholtz-Zentrum Hereon, Institute of Coastal Environmental Chemistry, Germany
[b] Institute of Polar Sciences, National Research Council, Italy
[c] Griffith University, Centre of Planetary Health and Food Security, Australia
[d] European Commission, Safe and Sustainable Chemicals, DG Environment, Belgium
[e] Stockholm University, Department of Environmental Science, Sweden
[f] NORMAN Association, France
[g] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, PANGAEA, Germany
[h] European Commission, Joint Research Centre (JRC), Ispra, Italy
[i] University of Genova, Department of Chemistry and Industrial Chemistry, Italy
[j] German Environment Agency (UBA), Germany
[k] British Antarctic Survey, Cambridge, United Kingdom
[l] NIVA - Norwegian Institute for Water Research, Norway
[m] Faculty of Chemistry, Biotechnology and Food Sciences (KBM), Norwegian University of Life Science, Norway (NMBU), Norway
[n] University of Rhode Island, Graduate School of Oceanography, USA
[o] Empa – Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory, 9014, St. Gallen, Switzerland
[p] National Institute of Standards and Technology, USA
[q] Department of Chemistry and Biology, Toronto Metropolitan University, 350 Victoria St, Toronto, ON M5B 2K3, Canada
[r] Aarhus University, Department of Environmental Science, Roskilde, Denmark
[s] University of the Arctic Oulo, Finland

HIGHLIGHTS

- To increase public and political awareness, improved visibility and open access of polar contaminant data is needed.
- The use of data for chemicals of emerging concern from polar regions, indicating long-range transport potential and persistence, should be enhanced in chemicals management.
- Closer exchange between the Arctic Monitoring and Assessment Program (AMAP) and the Antarctic Monitoring and Assessment Program (AnMAP) should be fostered.
- Environmental specimen banks, novel screening approaches and digital sample-freezing platforms should be integrated for improved assessments.
- Co-development frameworks in a permanent multi-disciplinary platform should be established for the environmental management of polar regions.

☆ These opinions, recommendations, findings, and conclusions do not necessarily reflect the views or policies of NIST or the United States Government.

* Corresponding author.
E-mail address: ralf.ebinghaus@hereon.de (R. Ebinghaus).

https://doi.org/10.1016/j.chemosphere.2023.138530
Received 15 December 2022; Received in revised form 23 March 2023; Accepted 26 March 2023
Available online 29 March 2023
0045-6535/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

ARTICLE INFO

Handling Editor: J. de Boer

Keywords:
Polar regions
Contamination
Legacy pollutants
Chemicals of emerging concern (CECs)
Arctic
Antarctica

ABSTRACT

Polar regions should be given greater consideration with respect to the monitoring, risk assessment, and management of potentially harmful chemicals, consistent with requirements of the precautionary principle. Protecting the vulnerable polar environments requires (i) raising political and public awareness and (ii) restricting and preventing global emissions of harmful chemicals at their sources. The Berlin Statement is the outcome of an international workshop with representatives of the European Commission, the Arctic Council, the Antarctic Treaty Consultative Meeting, the Stockholm Convention on Persistent Organic Pollutants (POPs), environmental specimen banks, and data centers, as well as scientists from various international research institutions. The statement addresses urgent chemical pollution issues in the polar regions and provides recommendations for improving screening, monitoring, risk assessment, research cooperation, and open data sharing to provide environmental policy makers and chemicals management decision-makers with relevant and reliable contaminant data to better protect the polar environments. The consensus reached at the workshop can be summarized in just two words: "Act now!"

Specifically, "Act now!" to reduce the presence and impact of anthropogenic chemical pollution in polar regions by.

•Establishing participatory co-development frameworks in a permanent multi-disciplinary platform for Arctic-Antarctic collaborations and establishing exchanges between the Arctic Monitoring and Assessment Program (AMAP) of the Arctic Council and the Antarctic Monitoring and Assessment Program (AnMAP) of the Scientific Committee on Antarctic Research (SCAR) to increase the visibility and exchange of contaminant data and to support the development of harmonized monitoring programs.

•Integrating environmental specimen banking, innovative screening approaches and archiving systems, to provide opportunities for improved assessment of contaminants to protect polar regions.

1. Introduction

We, as a group of scientists, are concerned about the consequences of long-term chemical contamination in the Arctic and Antarctica. A harmonized and multidisciplinary science-based approach across stakeholders is urgently needed for a comprehensive understanding, prevention, and reduction of pollution in polar regions.

This Statement represents the outcome of the workshop "Act now – Legacy and Emerging Contaminants in Polar regions" organized by the German Environment Agency and the Helmholtz-Zentrum Hereon on 25–26 January 2022. The workshop participants included environmental scientists with expertise in polar contaminant research, as well as representatives from chemicals regulatory authorities, Arctic pollution monitoring programs, environmental specimen banks, and information and data platforms. This "Berlin Statement" addresses the following priority topics: contaminant screening; source elucidation, monitoring and assessment of contaminants; cooperation between scientists with a focus on the science–policy interface; concepts, opportunities and technical solutions for data-sharing; and provision of tailored scientific information for policy makers.

Humanity is currently operating outside the planetary boundary of chemical pollution as a consequence of the rapid increase in production and release of anthropogenic chemicals that outstrips the global capacity to assess and monitor the associated risks (Persson et al., 2022). This means that humanity's use and release of chemicals, in this context referred to as "novel entities", would cause irreversible damage to the Earth system (Persson et al., 2022). As an example, it was recently proposed that global contamination by four per- and polyfluoroalkyl substances (PFASs) — so called "forever chemicals" — has breached a planetary boundary (Cousins et al., 2022).

Polar ecosystems, once pristine habitats, are being severely threatened by pollution (Tin et al., 2009; AMAP, 2017; Waller et al., 2017; AMAP, 2021a, b). Hundreds of chemicals of emerging Arctic concern (CEACs) have been identified (AMAP, 2017). As mixtures or individually, these chemicals can have a variety of adverse effects on the environment and human and wildlife health, due to their toxicity, accumulation in biota, and environmental mobility and stability (Dietz et al., 2019). However, only approximately 35 individual chemicals or chemical groups are currently listed or proposed for global regulation in the Stockholm Convention on Persistent Organic Pollutants (http://chm.pops.int/).

Polar environments are sentinel regions considered as harbingers for indicating hazardous consequences of global anthropogenic pollution. While the Arctic has previously been described as "a messenger for global processes" (AMAP, 2011), corresponding considerations for the Antarctic or a connection between the polar regions have been sparse. We therefore recommend an international open accessible pollutant-monitoring and data-sharing system for both polar regions as a forecasting tool set for systematic priority pollutant identification and risk evaluation. This advanced monitoring scheme can then be further extended to the global scale beyond the poles (see Fig. 1). The development of a harmonized monitoring system will require international prioritizations and contributions of the global scientific and policy-making communities, as well as coordination between circum-polar countries and all nations with interest in the polar regions. The data sharing system proposed here needs to be harmonized with already ongoing monitoring programs under the Arctic Council Working Groups, in particular the Arctic Monitoring and Assessment Programme (AMAP); and with an Antarctic counterpart AnMAP as well as the Antarctic environmental monitoring programs. The following 10 sections describe the key elements of the conceptual framework developed during the Act Now workshop (Fig. 1).

2. Raise public and political awareness on chemical pollution

Mitigation of chemical pollution in polar regions is a common responsibility. Even if the problem occurs far from most people's doorsteps, the global dimension of chemical production, use and environmental dispersal means that the planet's polar regions are interlinked with the rest of the world. Chemical pollution, climate change, and biodiversity loss are strongly interlinked planetary environmental crises. Climate change, which is most pronounced at the poles of the Earth, has substantial impacts on the distribution and fate of chemicals, including the remobilisation and redistribution of legacy chemicals from environmental reservoirs (Xie et al., 2020; AMAP, 2021b; Corsolini and Ademollo, 2022; de Wit et al., 2022; Hung et al., 2022). In addition, new inputs seem likely as a consequence of increasing human activity as the Arctic and Antarctic become more easily accessible. Chemical pollutants add to a multi-stressor situation enhancing the loss of biodiversity in polar environments (Garnett et al., 2022; AMAP, 2021b; Xie et al., 2022). In fact, in a rapidly changing environment, polar ecosystems may be more vulnerable to chemical

pollution compared to stabilised ecosystem structures (Jenssen, 2006; Borga et al., 2022). Tailored communication is needed to raise political and public awareness of the vulnerability of the polar environments, involving traditional and online communication media together with educational projects and interactions at the science-policy interface, as a cornerstone for enhancing action. Likewise, it is important that indigenous and local communities that are directly concerned by Arctic contamination are partners in the co-creation of research priorities and operating monitoring programmes.

3. Follow the precautionary principle

The precautionary principle is a fundamental strategic approach also adopted by the Arctic Council, founded in 1996 by the Arctic States (Arctic Council, 1996) as the leading intergovernmental forum in the Arctic. This approach is also implemented in the environmental regulation in the Antarctic Treaty System, consisting of the Treaty itself and other international specialised agreements concerning conservation and environmental protection in the Antarctic region (Antarctic Treaty System, 2021).

The precautionary principle allows timely decisions or measures to be taken for the protection of the Arctic and Antarctic environments without the necessity of a documented complete proof of harm. A better understanding of the current state of the Antarctic environment, and the long-term adverse effects of environmentally stable and other relevant pollutants on organisms and food chains, would support ambitions of the Antarctic Treaty Parties with pre-defined necessary decisions. Such decisions will be in place for the protection of the Antarctic environment in accordance with the Protocol on Environment Protection to the Antarctic Treaty (also known as the Environment Protocol).

The implementation of the precautionary principle should be based on various aspects of chemical pollution, e.g. toxicity, persistence and environmental mobility, either individually or in combination. Regulatory measures are to be developed that allow a rapid and flexible decision based upon, e.g., automated surveys of national and international chemical monitoring data arising from the respective polar regions. With special reference to the Arctic, the precautionary principle is not just about using the Arctic ecosystem as a sentinel for global distribution processes. It must also include aspects of chemical exposure of local communities, via local food, drinking water and other sources.

The protection of humans and life quality is one specific goal of the Arctic Environmental Protection Strategy, and recent developments have regarded ecosystem and human health in a One Health approach (e.g. Sonne et al., 2017). Importantly, the precautionary principle and related monitoring, mitigation and removal strategies need taking into account indigenous and traditional knowledge that is rooted in extensive understanding of the land, seasonal changes, and associated activities (Charlie et al., 2022).

4. Strengthen networking and co-development

Progressing from awareness to action requires effective networking and communication among relevant actors and stakeholders. This includes policy makers and regulators at the national and international level, the research community, non-governmental organisations, indigenous communities, industry, and the public. Among other benefits, such networks can enable timely action by the science communities, addressing policy-relevant research questions and generating scientific evidence needed by the national and international authorities (e.g., European Commission, European Chemicals Agency, Stockholm Convention). The networks can be used to ensure the co-creation of research projects with northern communities that are built on the principles of indigenous research priorities and the principles of ethical and responsible handling of Indigenous knowledge and data (ITK, 2018 ; Wilkinson et al., 2016). The indigenous data ownership, control, access, and possession (OCAP) was developed by the First Nations Information Governance Centre to recognize the collective rights of First Nations communities in Canada to information collected from their territories (FNIGC, 2014); Carroll et al. (2021). A broad approach to Indigenous data governance is summarized as Collective benefit, Authority to

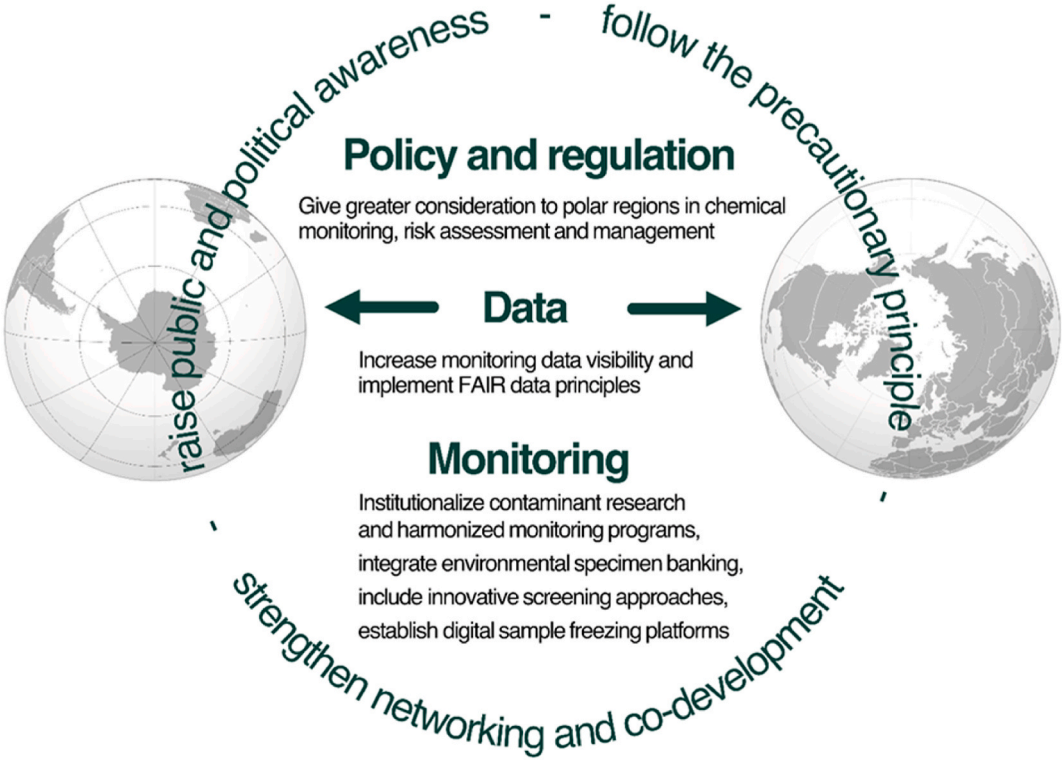

Fig. 1. Conceptual framework across stakeholders – the individual elements are addressed in the 10 sections below.

control, Responsibility, Ethics (CARE) (Carroll et al., 2021). To establish such networks, a co-creation framework can be adapted to facilitate collaboration, information sharing, and knowledge transfer, building on participatory stakeholder mapping and network analysis (Briley et al., 2015; Adler et al., 2018; Bremer et al., 2019; Chambers et al., 2021; Tsatsaros et al., 2021). Already established Arctic/Antarctic networks (e.g., AMAP; ACAP), relevant international conventions (e.g., Stockholm Convention on POPs) and future intergovernmental Science-Policy Panel on Chemicals, Waste and Pollution Prevention (Wang et al., 2021) should be included as stakeholders or active contributors.

More data, including spatial-temporal data coverage, are available from the Arctic compared to the Antarctica or many cold high-altitude regions of the globe. Given that priority target contaminants and associated analytical challenges for trace-level quantification are similar in both polar regions, collaboration between scientists working in the Arctic and Antarctic should be encouraged. Connections with research and monitoring initiatives in other non-polar regions are also important, for a better understanding of the global fate of contaminants, especially for links to source areas of contaminant emissions. It is, hence, acknowledged that wider and more intensified scientific collaborations are needed to exchange and refine information and prioritization.

This is of special importance for assessing the fate and impacts of chemicals on a wider geographical scale such as shown in circumpolar assessments by AMAP (AMAP, 2017).

5. Enhance use of monitoring data from the polar regions in chemicals management

For the monitoring and assessment of chemicals of emerging concern (CECs), prioritization is required among the more than 350,000 chemical substances currently registered (Wang et al., 2020). Monitoring data from the polar regions are particularly useful for schemes that identify, prioritize and classify chemical risks, in particular long-range environmental transport (LRET) and persistence (as used in the identification of POPs under the Stockholm Convention). Monitoring data from the polar regions are also instrumental to assess the effectiveness of regulatory restrictions of chemicals (Riget et al., 2016; UNEP, 2017; Wong et al., 2021). Indeed, long-term coordinated monitoring and data collection under AMAP (since 1991) has been an important data contribution to the Stockholm Convention and the Minamata Convention on Mercury (Platjouw et al., 2018; Rottem et al., 2020; Steindal et al., 2021).

It is essential that harmonized data on the occurrence of chemicals in the Arctic and Antarctic are generated regularly and coordinated with joint sampling and analytical protocols. Furthermore, these data should be made accessible through quality-controlled databases in an open and FAIR (**F**indable, **A**ccessible, **I**nteroperable, and **R**eusable) manner (Wong et al., 2021). International instruments such as the Stockholm Convention, the Minamata Convention, and the future Science-Policy Panel on Chemicals, Waste and Pollution Prevention as well as the Strategic Approach to International Chemicals Management (SAICM) and its successor, can be of special importance as key users of the Arctic and Antarctic data, for chemicals assessments and management as well as effectiveness evaluations (Convention, 2021). Therefore, clear linkages and communication mechanisms among monitoring programs and the above listed instruments are warranted.

6. Update regulatory paradigms to protect the polar regions

The number of anthropogenic contaminants detected in the polar environments is constantly increasing. This fact raises the question whether or not existing chemicals assessment and management approaches are sufficiently protective. Evidence is growing that a number of chemicals (such as current-use pesticides (CUPs) and industrial contaminants) are confirmed in Arctic and Antarctic environments, although they were not expected to be persistent and transported over long distances (AMAP, 2017). AMAP currently maintains a list of several hundred CEACs to be evaluated for inclusion in Arctic pollution monitoring, originally published as an electronic annex to the report on CEACs (AMAP, 2017; https://chemicals.amap.no/). For the Antarctic, a comparable compound list does not yet exist.

Hence, current regulatory paradigms need to be revisited and strengthened to minimize the emissions and subsequent transport of chemicals to polar regions. A regular update is needed to evaluate the potential contamination of polar areas, before it actually happens, including pesticide-related contamination due to new agricultural areas close to the Arctic as a consequence of climate change. New risk assessment methods under development in the recently started Horizon Europe Partnership for the Assessment of Risks from Chemicals (PARC) (Marx-Stoelting et al., 2023) and by the CEFIC-LRI ECO-42 project on complex chemical mixtures (Sühring et al., 2022) could also be applied in other regions and provide more harmonized approaches.

An important goal should be to avoid “regrettable substitutions” (i.e., replacement of banned chemicals with similarly problematic chemicals) by, e.g., adopting grouping approaches. A prominent example are the PFASs, a class of thousands of chemicals, where extensive use restrictions for the entire chemical class are being discussed by regulatory authorities in the EU and other regions (Cousins et al., 2020; Umweltbundesamt, 2020; UNEP, 2022).

7. Expand contaminant research and harmonize monitoring in the polar regions

While the long-term and coordinated monitoring of chemicals is well-established in the Arctic, through national programmes coordinated by AMAP, identification and monitoring of CECs at high southern latitudes has been largely restricted to project-based screening events (Nash, 2011). More importantly, the Antarctic Treaty does not obligate Parties with National Antarctic Programs (NAPs) to proactively extend their national monitoring programs to the Antarctic Treaty area. The implementation of a chemical monitoring program should be prioritised in the Committee for Environmental Protection (CEP) regarding monitoring ambitions of the Antarctic Treaty Consultative Meeting (ATCM). As a first step, CEP has requested the Scientific Committee on Antarctic Research (SCAR), the principal body charged with providing objective scientific advice to the ATCM, to consider systematic sampling and data collection of chemical contamination in the Antarctic.

It is equally important to identify local pollutant emissions related to human activities in polar regions, such as oil and gas extraction as well as mining, military installations, municipal infrastructure, industrial activities, transportation (particularly ship traffic and airports), research station operation, large-scale fishery, tourism, and settlements (Granberg et al., 2017; Evenset et al., 2018). Although most of these activities are not permitted in Antarctica, data on local emissions are pivotal to better understand the current state of chemical pollution of the Arctic and Antarctic environments, to be precise in the assessment of LRET, and to target risk management for the protection of local and Indigenous communities in the Arctic. Data from Antarctica could significantly contribute to assessments of local versus remote sources as local sources are fewer and more easily accounted for. The new global AQUA-GAPS/Monet passive sampling initiative of POPs in water could be expanded to permanent sites to initiate regular monitoring in the Antarctic (Lohmann et al., 2017).

The need for an Antarctic Monitoring and Assessment Programme (AnMAP) as a coordinating body for strategic and harmonized data collection has been repeatedly flagged, both in the scientific literature (Nash, 2011), and directly to the ATCM, via the SCAR (Fuoco et al., 2008; Abass et al., 2018; Nash et al., 2021). The SCAR Action Group, ‘Input Pathways for Persistent Organic Pollutants to Antarctica’ (ImPACT), was established in 2017 to undertake initial work towards potential development of an AnMAP body. In 2021, AnMAP was endorsed by the UN as an Ocean-Decade activity, and currently the strategic plan is under co-development with AMAP, with the explicit

goal of transferring proven AMAP systems and frameworks to the Antarctic region. These include harmonized protocols and quality-assurance checks for collecting, transport, storing, and analysing environmental samples, as well as recommendations for the selection of standardized abiotic and biotic matrices for monitoring. Such efforts will help to ensure the long-term collection of high-quality and comparable data from all campaigns, which in themselves represent significant logistical and financial investments.

8. Develop innovative screening programs for the polar regions

Since analytical standards are often not available and screening studies targeting pre-selected compounds require specific and complex method development, they should be combined with other non-targeted approaches aiming at the identification of new CECs. *In silico* modelling and prioritization based on physico-chemical properties of chemicals in commerce are an important basis for the selection of compounds for chemical screening in samples from polar regions (Reppas-Chrysovitsinos et al., 2017; Muir et al., 2019). Non-Targeted Screening (NTS) and suspect screening techniques using high-resolution mass spectrometry (HRMS) are powerful tools for identifying previously unknown or overlooked contaminants in polar samples, including transformation products (Lee et al., 2019). So far, confirming structures with high confidence remains labour intensive, despite many advances in data science, and the data obtained with NTS and suspect-screening approaches are often qualitative or semi-quantitative (Hollender et al., 2019). Machine learning tools for predicting the eco-toxicity of unidentified chemicals and complex mixtures have recently been described and offer a potential for less time- and labour-consuming future applications (Peets et al., 2022).

The monitoring of contaminants for regulatory purposes will continue to require optimized targeted analyses of specific contaminants. Effect-directed analyses have the potential to add important information on toxicity for use/prioritization in chemicals assessments. Integrating effect-based methods and NTS techniques is an area of research that should also be directed at CECs in the polar environments.

9. Expand environmental specimen banks

Environmental specimen banks (ESBs) are facilities that maintain formal programs that develop and use standardized protocols to collect, process and archive samples from the environment for future research and monitoring purposes. ESBs are maintained by countries and scientific institutions to provide opportunities for retrospective assessment, temporal and geographic trend analyses, method evaluation, and long-term assessment (Becker et al., 1993; Soggia et al., 2001; Odsjo, 2006; Kuster et al., 2015). ESBs also support today's chemicals management and provide biological and environmental samples for real-time monitoring and basic research for the analysis of contaminants (Grotti et al., 2016; Fliedner et al., 2022). In the Arctic, contaminant programs are already supported by ESBs, which have enabled retrospective time trends and screening studies (Riget et al., 2016; Vorkamp et al., 2022). In contrast, the use of samples from ESBs into contaminant programs for Antarctica has been lacking to date. A broader initiative to establish ESBs that provide archived specimens from the Antarctic is much needed to complement the current single Antarctic ESB at the University of Genova, Italy (https://bcaa.unige.it/en). Expanding existing or establishing more ESBs can help to secure biological and environmental specimens and shape contaminant research in the changing polar environments. Combining samples from Arctic and Antarctic ESBs in, for instance, screening studies on CECs will provide important knowledge of differences and similarities in aspects of their global occurrence and temporal trends.

10. Ensure open data access

So far, centralised access to data for legacy and emerging contaminants in the polar regions is lacking. Instead, data can be retrieved from established data platforms, or are published in scientific reports or articles. If these are behind paywalls, their accessibility, visibility, and use may be limited. Data repositories should ensure that all polar contaminant data are FAIR, while also considering CARE principles (Carroll et al., 2021). Currently, the Norwegian Institute for Air Research (NILU) maintains the circum-Arctic atmospheric pollution database (ebas.nilu.no), and the International Council for the Exploration of the Sea (ICES) maintains the 'Contaminants in biota: Temporal trends' database for AMAP (https://www.ices.dk/data/assessment-tools/Pages/amap-ahat.aspx). In this respect, data archiving is more developed for the Arctic than for the Antarctic (Wong et al., 2021). A similar circum-Antarctic data repository should be developed, preferably based on existing platforms with established governance structures. Besides those used for Arctic data, value options include EU IPCHEM (https://ipchem.jrc.ec.europa.eu/) or the NORMAN network (https://www.norman-network.net/). Data should also be made available to other researchers, risk assessors, and regulators in a timely manner to allow for quick reactions to emerging issues. Research funders should enforce policies that ensure FAIR data management. For example, EU-funded research including significant monitoring work should be obliged to store data in IPCHEM and make data accessible.

11. Establish digital-sample freezing platforms and virtual ESBs

"Digital-Sample Freezing Platforms" or "virtual ESBs" are promising approaches for an extended use of existing screening data from the polar environments. As they digitally store raw HRMS chromatograms of samples, each containing typically several thousands of compounds, they are always available for retrospective exploitation of the data in suspect screening or non-targeted analysis mode. This approach has already been established in the NORMAN network, for example, with an open-access Digital-Sample Freezing Platform (https://dsfp.norman-data.eu/) supported with NTS data from different research and monitoring activities (Alygizakis et al., 2019; Badry et al., 2022). Because generic NTS protocols cannot yet cover all organic compounds (Hajeb et al., 2022), ESBs, including digital-sample freezing, are essential as a backup for optimized methods or other innovations in contaminant monitoring.

12. Conclusions and outlook

As the polar environments are connected with the rest of the world, the entire world shares the common responsibility for their protection. Broad political and public awareness are, consequently, prerequisites to protect the polar regions from chemical pollution data from polar environments play a particular role in the identification, assessment and management of CECs, and should be included in regulatory assessment processes worldwide, in addition to their well-established use in the framework of the Stockholm Convention. To achieve this, we have identified a number of priority actions, primarily in the management and research domains, and recommend their facilitation through a multi-stakeholder co-development framework for both polar regions. Ongoing and future screening, monitoring and assessment activities should be combined with advanced modelling that has the potential to characterize CECs and their potential to become polar contaminants. While Arctic cooperation is well-established under the Arctic Council and its Working Groups, the Parties to the Antarctic Treaty and its Environment Protocol should consider aligning their strategic ambitions with respect to chemical pollution research and monitoring on the basis

of SCAR's advice on systematic sampling and data collection of chemical contamination in the Antarctic Treaty area (ATCM XLIV, 2022). This includes the development of AnMAP in close cooperation with the CEP of the ATCM, modelled on the successes of AMAP, as well as collaboration between researchers in the polar environments. Here we see a strong potential to provide a basis to better understand similarities and differences in CEC sources, their transport and effects on ecosystems and to strengthen the global perspective in contaminant research, monitoring, assessment and action.

It is our hope that the Berlin Statement will serve as a nucleus for the development of a network that will be fostered and expanded to create a regular platform for polar collaborations, also involving work that is ongoing or planned under the Arctic Council and AnMAP. To open the Berlin Statement for supporting signatures of scientists, regulators, decision-makers and interested laymen we established the following internet webpage https://www.coastalpollutiontoolbox.org/that allows signing the statement. It is now up to politicians, scientists and society to respond and provide resources to ensure that these particularly vulnerable ecosystems are preserved for future generations.

Credit Author statement

Ralf Ebinghaus: scientific committee, workshop chair, session chair, conceptualization, coordination, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Elena Barbaro: workshop presenter, continuous development of manuscript draft and finalization of manuscript, Susan Bengtson Nash: workshop presenter, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Cristina de Avila: workshop presenter, continuous development of manuscript draft, Cynthia A. de Wit: workshop presenter, session chair, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Valeria Dulio: working group chair, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Janine Felden: workshop presenter, continuous development of manuscript draft, Antonio Franco: workshop presenter, continuous development of manuscript draft and finalization of manuscript, Juergen Gandrass: scientific committee, workshop organizer, workshop presenter, conceptualization, coordination, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Marco Grotti: workshop presenter, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Heike Herata: scientific committee, workshop chair, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Kevin A. Hughes; workshop presenter, continuous development of manuscript draft and finalization of manuscript, Morten Jartun: workshop presenter, continuous development of manuscript draft, Hanna Joerss: working group chair, continuous development of manuscript draft, Roland Kallenborn: workshop presenter, working group chair, continuous development of manuscript draft and finalization of manuscript, Jan Koschorreck: scientific committee, workshop presenter, working group chair, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Anette Küster: scientific committee, continuous development of manuscript draft and finalization of manuscript, Rainer Lohmann: workshop presenter, continuous development of manuscript draft and finalization of manuscript, Matthew MacLeod: working group chair, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Rebecca Pugh: session chair, continuous development of manuscript draft, Caren Rauert: continuous development of manuscript draft, Jaroslav Slobodnik: workshop presenter, continuous development of manuscript draft and finalization of manuscript, Roxana Sühring: session chair, continuous development of manuscript draft and finalization of manuscript, Katrin Vorkamp: workshop presenter, original draft preparation, continuous development of manuscript draft and finalization of manuscript, Zhanyun Wang: workshop presenter, continuous development of manuscript draft and finalization of manuscript, 0Zhiyong Xie: scientific committee, workshop presenter, working group chair, continuous development of manuscript draft and finalization of manuscript.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

References

Abass, K., Emelyanova, A., Rautio, A., 2018. Temporal trends of contaminants in Arctic human populations. Environ. Sci. Pollut. Control Ser. 25, 28834–28850.

Adler, C., Hadorn, G.H., Breu, T., Wiesmann, U., Pohl, C., 2018. Conceptualizing the transfer of knowledge across cases in transdisciplinary research. Sustain. Sci. 13, 179–190.

Alygizakis, N.A., Oswald, P., Thomaidis, N.S., Schymanski, E.L., Aalizadeh, R., Schulze, T., Oswaldova, M., Slobodnik, J., 2019. NORMAN digital sample freezing platform: a European virtual platform to exchange liquid chromatography high resolution-mass spectrometry data and screen suspects in "digitally frozen" environmental samples. Trac. Trends Anal. Chem. 115, 129–137.

Amap, 2011. The Arctic as a Messenger for Global Processes - Climate Change and Pollution. Conference. Copenhagen, Denmark, pp. 3–6. May 2011.

Amap, 2017. AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, p. xvi+353pp.

Amap, 2021a. Mercury in the arctic. Arctic Monitoring and Assessment Programme (AMAP),Tromsø, Norway 324 (uncorrected proofing draft).

Amap, 2021b. POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change. Summary for Policy-Makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, p. 16.

Antarctic Treaty System, 2021. Compilation of Key Documents of the Antarctic Treaty System, fifth ed. Secretariat of the Antarctic Treaty, Buenos Aires. 2021. 196.

Arctic Council, 1996. Joint Communique of the Governments of the Arctic Countries on the Establishment of the Arctic Council, vol. 19. Ottawa Declaration, Ottawa, Canada, September, 1996.

ATCM XLIV, 2022. Final report of the Antarctic Treaty Consultative Meeting, p. 287.

Badry, A., Slobodnik, J., Alygizakis, N., Bunke, D., Cincinelli, A., Classen, D., Dekker, R., Duke, G., Dulio, V., Gockener, B., Gkotsis, G., Hanke, G., Jartun, M., Movalli, P., Nika, M.C., Rudel, H., Thomaidis, N.S., Tarazona, J.V., Tornero, V., Treu, G., Vorkamp, K., Walker, L.A., Koschorreck, J., 2022. Using environmental monitoring data from apex predators for chemicals management: towards harmonised sampling and processing of archived wildlife samples to increase the regulatory uptake of monitoring data in chemicals management. Environ. Sci. Eur. 34.

Becker, P.R., Koster, B.J., Wise, S.A., Zeisler, R., 1993. Biological specimen banking in arctic research - an alaskan perspective. Sci. Total Environ. 140, 69–95.

Borga, K., McKinney, M.A., Routti, H., Fernie, K.J., Giebichenstein, J., Hallanger, I., Muir, D.C.G., 2022. The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs. Environmental Science-Processes & Impacts 24, 1544–1576.

Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R., van der Sluijs, J., 2019. Toward a multi-faceted conception of co-production of climate services. Climate Services 13, 42–50.

Briley, L., Brown, D., Kalafatis, S.E., 2015. Overcoming barriers during the co-production of climate information for decision-making. Climate Risk Management 9, 41–49.

Carroll, S.R., Herczog, E., Hudson, M., Russell, K., Stall, S., 2021. Operationalizing the CARE and FAIR principles for indigenous data futures. Sci. Data 8, 108.

Chambers, J.M., Wyborn, C., Ryan, M.E., Reid, R.S., Riechers, M., Serban, A., Bennett, N. J., Cvitanovic, C., Fernandez-Gimenez, M.E., Galvin, K.A., Goldstein, B.E., Klenk, N. L., Tengo, M., Brennan, R., Cockburn, J.J., Hill, R., Munera, C., Nel, J.L., Osterblom, H., Bednarek, A.T., Bennett, E.M., Brandeis, A., Charli-Joseph, L., Chatterton, P., Curran, K., Dumrongrojwatthana, P., Duran, A.P., Fada, S.J., Gerber, J.D., Green, J.M.H., Guerrero, A.M., Haller, T., Horcea-Milcu, A.I., Leimona, B., Montana, J., Rondeau, R., Spierenburg, M., Steyaert, P., Zaehringer, J. G., Gruby, R., Hutton, J., Pickering, T., 2021. Six modes of co-production for sustainability. Nat. Sustain. 4, 983–996.

Charlie, A., Proverbs, T.A., Hodgson, E.E., Hovel, R.A., 2022. Shifting seasons and threats to harvest, culture, and self-identity: a personal narrative on the consequences of changing climate. GeoHealth 6 (12).

Convention, S., 2021. All POPs Listed in the Stockholm Convention.

Corsolini, S., Ademollo, N., 2022. POPs in Antarctic ecosystems: is climate change affecting their temporal trends? Environmental Science-Processes & Impacts 24, 1631–1642.

Cousins, I.T., DeWitt, J.C., Gluge, J., Goldenman, G., Herzke, D., Lohmann, R., Miller, M., Ng, C.A., Scheringer, M., Vierke, L., Wang, Z.Y., 2020. Strategies for grouping per-

and polyfluoroalkyl substances (PFAS) to protect human and environmental health. Environmental Science-Processes & Impacts 22, 1444–1460.
Cousins, I.T., Johansson, J.H., Salter, M.E., Sha, B., Scheringer, M., 2022. Outside the safe operating space of a new planetary boundary for per- and polyfluoroalkyl substances (PFAS). Environ. Sci. Technol. 56, 11172–11179.
de Wit, C.A., Vorkamp, K., Muir, D., 2022. Influence of climate change on persistent organic pollutants and chemicals of emerging concern in the Arctic: state of knowledge and recommendations for future research. Environmental Science-Processes & Impacts 24, 1530–1543.
Dietz, R., Letcher, R.J., Desforges, J.-P., Eulaers, I., Sonne, C., Wilson, S., Andersen-Ranberg, E., Basu, N., Barst, B.D., Bustnes, J.O., Bytingsvik, J., Ciesielski, T.M., Drevick, P.E., Gabrielsen, G.W., Haarr, A., Hylland, K., Munro Jenssen, B., Levinn, M., McKinney, M.A., Dyrmose Nørregaard, R., Pedersen, K.E., Provencher, J., Styrishave, B., Tartu, S., Aars, J., Ackermanr, J.T., Rosing-Asvid, A., Barrettt, R., Bignert, A., Eborn, E.W., Branigan, M., Braune, B., Bryan, C.E., Dam, M., Eagles-Smith, C.A., Evans, M., Evans, T.H., Fisk, A.T., Gamberg, M., Gustavson, K., Hartman, C.A., Helander, B., Herzog, M.P., Hoekstra, P.F., Houde, M., Hoydal, K., Jackson, A.K., Kucklick, J., Lie, E., Loseto, L., Mallory, M.L., Miljeteig, C., Mosbech, A., Muir, D.C.G., Túni Nielsen, S., Peacock, E., Pedro, S., Peterson, S.H., Polder, A., Rigét, F.F., Roach, P., Saunes, H., Mikkel-Holger, S., Sinding, M.-H.S., Skaare, J.U., Søndergaard, J., Stenson, G., Stern, G., Treu, G., Schuur, S.S., Víkingsson, G., 2019. Current state of knowledge on biological effects from contaminants on arctic wildlife and fish. Sci. Total Environ. 696, 133792.
Evenset, A., Olsson, A., Harju, M., Gabrielsen, G., 2018. Settlements on Svalbard as sources for emerging contaminants, p. 60. Akvaplan-niva rapport nr 7874-1, 01.06.2018.
Fliedner, A., Rudel, H., Gockener, B., Krehenwinkel, H., Paulus, M., Koschorreck, J., 2022. Environmental Specimen Banks and the European Green Deal, vol. 852. Science of the Total Environment.
FNIGC, 2014. First Nations Information Governance Centre (FNIGC). Ownership, Control, Access and Possession (OCAP™): the Path to First Nations Information Governance. The First Nations Information Governance Centre, Ottawa, ISBN 978-0-9879882-8-7. May 2014.
Fuoco, R., Nash, S.M.B., Corsolini, S., Gambaro, A., Cincinelli, A., 2008. POPs in Antarctica; Report to Antarctic Treaty in Kiev 2-13 June, 2008. Environmental Contamination in Antarctica (ECA) 2008, Pisa.
Garnett, J., Halsall, C., Winton, H., Joerss, H., Mulvaney, R., Ebinghaus, R., Frey, M., Jones, A., Leeson, A., Wynn, P., July 2022. Increasing accumulation of perfluorocarboxylate contaminants revealed in an Antarctic firn core (1958-2017). Environ. Sci. Technol. https://doi.org/10.1021/acs.est.2c02592.
Granberg, M.E., Ask, A., Gabrielsen, G.W., 2017. Local contamination in Svalbard. Overview and suggestions for remediation actions, p. 52. Norsk Polarinstitutt Brief Report 2017/ 044.
Grotti, M., Pizzini, S., Abelmoschi, M.L., Cozzi, G., Piazza, R., Soggia, F., 2016. Retrospective biomonitoring of chemical contamination in the marine coastal environment of Terra Nova Bay (Ross Sea, Antarctica) by environmental specimen banking. Chemosphere 165, 418–426.
Hajeb, P., Zhu, L.Y., Bossi, R., Vorkamp, K., 2022. Sample preparation techniques for suspect and non-target screening of emerging contaminants. Chemosphere 287.
Hollender, J., van Bavel, B., Dulio, V., Farmen, E., Furtmann, K., Koschorreck, J., Kunkel, U., Krauss, M., Munthe, J., Schlabach, M., Slobodnik, J., Stroomberg, G., Ternes, T., Thomaidis, N.S., Togola, A., Tornero, V., 2019. High Resolution Mass Spectrometry-Based Non-target Screening Can Support Regulatory Environmental Monitoring and Chemicals Management, vol. 31. Environmental Sciences Europe.
Hung, H., Halsall, C., Ball, H., Bidleman, T., Dachs, J., De Silva, A., Hermanson, M., Kallenborn, R., Muir, D., Suhring, R., Wang, X.P., Wilson, S., 2022. Climate change influence on the levels and trends of persistent organic pollutants (POPs) and chemicals of emerging Arctic concern (CEACs) in the Arctic physical environment - a review. Environmental Science-Processes & Impacts 24, 1577–1615.
ITK, 2018. National Inuit Strategy on Research. Inuit Tapiriit Kanatami. National Inuit Strategy on Research, ISBN 978-0-9699774-2-1, p. 44pp. https://www.itk.ca/national-strategy-on-research-launched/Inuit-Tapiriit-Kanatami-(ITK).
Jenssen, B.M., 2006. Endocrine-disrupting chemicals and climate change: a worst-case combination for arctic marine mammals and seabirds? Environ. Health Perspect. 114, 76–80.
Kuster, A., Becker, P.R., Kucklick, J.R., Pugh, R.S., Koschorreck, J., 2015. The international environmental specimen banks-let's get visible. Environ. Sci. Pollut. Control Ser. 22, 1559–1561.
Lee, S., Kim, K., Jeon, J., Moon, H.B., 2019. Optimization of suspect and non-target analytical methods using GC/TOF for prioritization of emerging contaminants in the Arctic environment. Ecotoxicol. Environ. Saf. 181, 11–17.
Lohmann, R., Muir, D., Zeng, E.Y., Bao, L.J., Allan, I.J., Arinaitwe, K., Booij, K., Helrn, P., Kaserzon, S., Mueller, J.F., Shibata, Y., Smedes, F., Tsapakis, M., Wong, C.S., You, J., 2017. Aquatic global passive sampling (AQUA-GAPS) revisited: first steps toward a network of networks for monitoring organic contaminants in the aquatic environment. Environ. Sci. Technol. 51, 1060–1067.
Marx-Stoelting, P., Rivière, G., Luijten, M., et al., 2023. A walk in the PARC: developing and implementing 21st century chemical risk assessment in Europe. Arch. Toxicol. 97, 893–908.
Muir, D., Zhang, X.D., de Wit, C.A., Vorkamp, K., Wilson, S., 2019. Identifying further chemicals of emerging arctic concern based on 'in silico' screening of chemical inventories. Emerging Contaminants 5, 201–211.
Nash, S.B., 2011. Persistent organic pollutants in Antarctica: current and future research priorities. J. Environ. Monit. 13, 497–504.
Nash, S.M.B., Wild, S., Broomhall, S., Bohlin-Nizzetto, P., 2021. Brominated flame retardants in antarctic air in the vicinity of two all-year research stations. Atmosphere 12.
Odsjo, T., 2006. The environmental specimen bank, Swedish Museum of Natural History - a base for contaminant monitoring and environmental research. J. Environ. Monit. 8, 791–794.
Peets, P., Wang, W.C., MacLeod, M., Breitholtz, M., Martin, J.W., Kruve, A., 2022. MS2Tox Machine Learning Tool for Predicting the Ecotoxicity of Unidentified Chemicals in Water by Nontarget LC-HRMS. Environmental Science & Technology.
Persson, L., Almroth, B.M.C., Collins, C.D., Cornell, S., de Wit, C.A., Diamond, M.L., Fantke, P., Hassellov, M., MacLeod, M., Ryberg, M.W., Jorgensen, P.S., Villarrubia-Gomez, P., Wang, Z.Y., Hauschild, M.Z., 2022. Outside the safe operating space of the planetary boundary for novel entities. Environ. Sci. Technol. 56, 1510–1521.
Platjouw, F.M., Steindal, E.H., Borch, T., 2018. From arctic science to international law: the road towards the Minamata convention and the role of the arctic Council. Arctic Review on Law and Politics 9, 226–243.
Reppas-Chrysovitsinos, E., Sobek, A., MacLeod, M., 2017. Screening-level exposure-based prioritization to identify potential POPs, vPvBs and planetary boundary threats among Arctic contaminants. Emerging Contaminants 3, 85–94.
Riget, F., Vorkamp, K., Bossi, R., Sonne, C., Letcher, R.J., Dietz, R., 2016. Twenty years of monitoring of persistent organic pollutants in Greenland biota. A review. Environmental Pollution 217, 114–123.
Rottem, S.V., Soltvedt, I.F., Prip, C., 2020. Arktisk råd i spennet mellom forskning, forvaltning og politikk. Skandinavisk Tidsskrift for Internasjonale Studier 78, 284–310.
Soggia, F., Abelmoschi, M.L., Dalla Riva, S., De Pellegrini, R., Frache, R., 2001. Antarctic environmental specimen bank - first 5 years of experience. Int. J. Environ. Anal. Chem. 79, 367–378.
Sonne, C., Letcher, R.J., Jenssen, B.M., Desforges, J.-P., Eulaers, I., Andersen-Ranberg, E., Gustavson, K., Styrishave, B., Rune Dietz, R., 2017. A veterinary perspective on one health in the arctic. Acta Vet. Scand. 59, 84.
Steindal, E.H., Karlsson, M., Hermansen, E.A.T., Borch, T., Platjouw, F.M., 2021. From arctic science to global policy – addressing multiple stressors under the Stockholm convention. Arctic Review on Law and Politics 12, 80–107.
Sühring, R., Mayer, P., Leonards, P., MacLeod, M., 2022. Fate-directed risk assessment of chemical mixtures: a case study for cedarwood essential oil. Environ. Sci.: Process. Impacts 24, 1133–1143.
Tin, T., Fleming, Z.L., Hughes, K.A., Ainley, D.G., Convey, P., Moreno, C.A., Pfeiffer, S., Scott, J., Snape, I., 2009. Impacts of local human activities on the Antarctic environment. Antarct. Sci. 21, 3–33.
Tsatsaros, J.H., Bohnet, I.C., Brodie, J.E., Valentine, P., 2021. A transdisciplinary approach supports community-led water quality monitoring in river basins adjacent to the Great Barrier Reef, Australia. Mar. Pollut. Bull. 170.
Umweltbundesamt, 2020. What Matters – PFAS. Came to Stay. Magazine of the German Environment Agency, p. 47pp, 1/2020.
UNEP, 2017. Second Global Monitoring Report. UNEP/POPS/COP.8/INF/38. 23 January 2017. http://chm.pops.int/Implementation/GlobalMonitoringPlan/MonitoringReports/tabid/525/Default.aspx.
UNEP, 2022. Report of the Persistent Organic Pollutants Review Committee on the Work of its Seventeenth Meeting. UNEP/POPS/POPRC.17/13. 9 February 2022. http://www.pops.int/TheConvention/POPsReviewCommittee/ReportsandDecisions/tabid/3309/Default.aspx.
Vorkamp, K., Carlsson, P., Corsolini, S., de Wit, C.A., Dietz, R., Gribble, M.O., Houde, M., Kalia, V., Letcher, R.J., Morris, A., Rigét, F.F., Routti, H., Muir, D.C.G., 2022. Influences of climate change on long-term time series of persistent organic pollutants (POPs) in Arctic and Antarctic biota. Environ. Sci. J. Integr. Environ. Res.: Process. Impacts 24, 1643.
Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., Pacherres, C.O., Hughes, K.A., 2017. Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. 598, 220–227.
Wang, Z.Y., Altenburger, R., Backhaus, T., Covaci, A., Diamond, M.L., Grimalt, J.O., Lohmann, R., Schaffer, A., Scheringer, M., Selin, H., Soehl, A., Suzuki, N., 2021. We need a global science-policy body on chemicals and waste. Science 371, 774–776.
Wang, Z.Y., Walker, G.W., Muir, D.C.G., Nagatani-Yoshida, K., 2020. Toward a global understanding of chemical pollution: a first comprehensive analysis of national and regional chemical inventories. Environ. Sci. Technol. 54, 2575–2584.
Wilkinson, M., Dumontier, M., Aalbersberg, I., et al., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3, 160018. https://doi.org/10.1038/sdata.2016.18.
Wong, F., Hung, H., Dryfhout-Clark, H., Aas, W., Bohlin-Nizzetto, P., Breivik, K., Mastromonaco, M.N., Lunden, E.B., Olafsdottir, K., Sigurdsson, A., Vorkamp, K., Bossi, R., Skov, H., Hakola, H., Barresi, E., Sverko, E., Fellin, P., Li, H., Vlasenko, A., Zapevalov, M., Samsonov, D., Wilson, S., 2021. Time trends of persistent organic pollutants (POPs) and Chemicals of Emerging Arctic Concern (CEAC) in Arctic air from 25 years of monitoring. Sci. Total Environ. 775.
Xie, Z.Y., Wang, Z., Magand, O., Thollot, A., Ebinghaus, R., Mi, W.Y., Dommergue, A., 2020. Occurrence of legacy and emerging organic contaminants in snow at Dome C in the Antarctic. Sci. Total Environ. 741.
Xie, Z.Y., Zhang, P., Wu, Z.L., Zhang, S., Wei, L.J., Mi, L.J., Kuester, A., Gandrass, J., Ebinghaus, R., Yang, R.Q., Wang, Z., Mi, W.Y., 2022. Legacy and emerging organic contaminants in the polar regions. Sci. Total Environ. 835.