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Influence of climate change on persistent organic pollutants and chemicals of emerging concern in the Arctic: state of knowledge and recommendations for future research

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Persistent organic pollutants (POPs) have accumulated in polar environments as a result of long-range transport from urban/industrial and agricultural source regions in the mid-latitudes. Climate change has been recognized as a factor capable of influencing POP levels and trends in the Arctic, but little empirical data have been available previously. A growing number of recent studies have now addressed the consequences of climate change for the fate of Arctic contaminants, as reviewed and assessed by the Arctic Monitoring and Assessment Programme (AMAP). For example, correlations between POP temporal trends in air or biota and climate indices, such as the North Atlantic Oscillation Index, have been found. Besides the climate indices, temperature, precipitation and sea-ice were identified as important climate parameters influencing POP levels in the Arctic environment. However, the physical changes are interlinked with complex ecological changes, including new species habitats and predator/prey relationships, resulting in a vast diversity of processes directly or indirectly affecting levels and trends of POPs. The reviews in this themed issue illustrate that the complexity of physical, chemical, and biological processes, and the rapid developments with regard to both climate change and chemical contamination, require greater interdisciplinary scientific exchange and collaboration. While some climate and biological parameters have been linked to POP levels in the Arctic, mechanisms underlying these correlations are usually not understood and need more work. Going forward there is a need for a stronger collaborative approach to understanding these processes due to high uncertainties and the incremental process of increasing knowledge of these chemicals. There is also a need to support and encourage community-based studies and the co-production of knowledge, including the utilization of Indigenous Knowledge, for interpreting trends of POPs in light of climate change.

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Environmental significance

Persistent organic pollutants (POPs) have accumulated in polar environments as a result of long range transport from urban/industrial and agricultural source regions in the mid-latitudes. Climate change has been recognized as a factor capable of influencing POP levels and trends in the Arctic, but little empirical data have been available until recently. This article introduces the themed issue on the "Influence of climate change on persistent organic pollutants and chemicals of emerging concern in the Arctic" and provides a detailed summary of key science findings and recommendations, knowledge gaps, and policy implications for science and chemical management.

1. Introduction

This themed issue of *Environmental Science: Processes & Impacts* presents a series of reviews on the influence of climate change on Persistent Organic Pollutants (POPs) and Chemicals of Emerging Arctic Concern (CEACs) in the Arctic. Several of the reviews, including this overview, originate from chapters in an assessment report prepared by the Arctic Monitoring and Assessment Programme (AMAP) in 2019–2020 and published in 2021.[1] They address observed and predicted changes in levels and trends of POPs and CEACs in the Arctic environment resulting from physical and ecological changes that are occurring in a warming Arctic, with some additional information from other cold climate regions. Two reviews specifically cover research findings from Antarctica and Tibet, where similar questions on the effects of climate change on POPs in cold climates are being studied. Here we introduce the topic by

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providing a brief retrospective of previous assessments and reviews of Arctic climate change and POPs. We also present key findings, general conclusions and recommendations for further research and monitoring derived from the AMAP assessment report, as also reflected in the review articles in this themed issue. Finally, we identify knowledge gaps and environmental policy implications in relation to the effects of climate change on the transport of POPs and CEACs to the Arctic and their fate within the Arctic.

1.1. Retrospective

The Arctic Monitoring and Assessment Programme (AMAP) was established in 1991 as an international program for monitoring and assessing Arctic pollution under the Arctic Environmental Protection Strategy.[2] It is now a Working Group of the Arctic Council, with the mission to "monitor and assess the status of the Arctic region with respect to pollution and climate change issues by (i) facilitating and advancing the coordinated implementation of relevant circumpolar monitoring and research, (ii) documenting levels and trends, pathways and processes, and effects on ecosystems and humans, (iii) distinguishing human-induced changes from changes caused by natural phenomena and (iv) proposing actions to reduce associated threats for consideration by governments and relevant organizations".[3] In this context, AMAP has produced a series of assessments that address the occurrence and trends of POPs[4,5] and, more recently, of chemicals and groups of substances that may not meet the classical definition of POPs, within the Arctic.[6] The Arctic area defined by AMAP is shown in Fig. 1. It includes the Arctic Ocean, the northern seas of the North Atlantic Ocean and the Bering Sea, as well as adjacent land masses within circumpolar countries.

POPs are regulated under the United Nations Environment Programme (UNEP) Stockholm Convention on POPs, based on their ability to persist in the environment, to bioaccumulate, to be transported over long distances and to cause adverse effects.[7] The Stockholm Convention's POPs Global Monitoring Plan (GMP) tracks the effectiveness of bans and restrictions on listed chemicals using temporal trend data, including Arctic monitoring data, primarily from human tissues and air, but monitoring data for other media are accepted as well.

In the first Stockholm Convention GMP report it was stressed that climate change could have implications for interpreting POP temporal trend data.[8] In response, a joint UNEP/AMAP report entitled *Climate Change and POPs: Predicting the Impacts* was produced, which recognized climate change as a factor capable of influencing POP levels measured in the environment and humans.[9] Therefore, it is an issue that could potentially interfere with the interpretation of temporal trends used to monitor the effectiveness of the Stockholm Convention.

Very few data were available at that time, so the report mainly hypothesized how changes in temperature and other climatic parameters could affect the environmental behavior and fate of POPs based on their physical–chemical properties. Warmer temperatures were predicted to increase primary emissions of POPs associated with volatilization from in-use products and equipment, waste sites, and stockpiles and temperature increases were considered the most important and strongest effect of climate change on POP cycling. Due to expected changes in the environmental partitioning of chemicals,

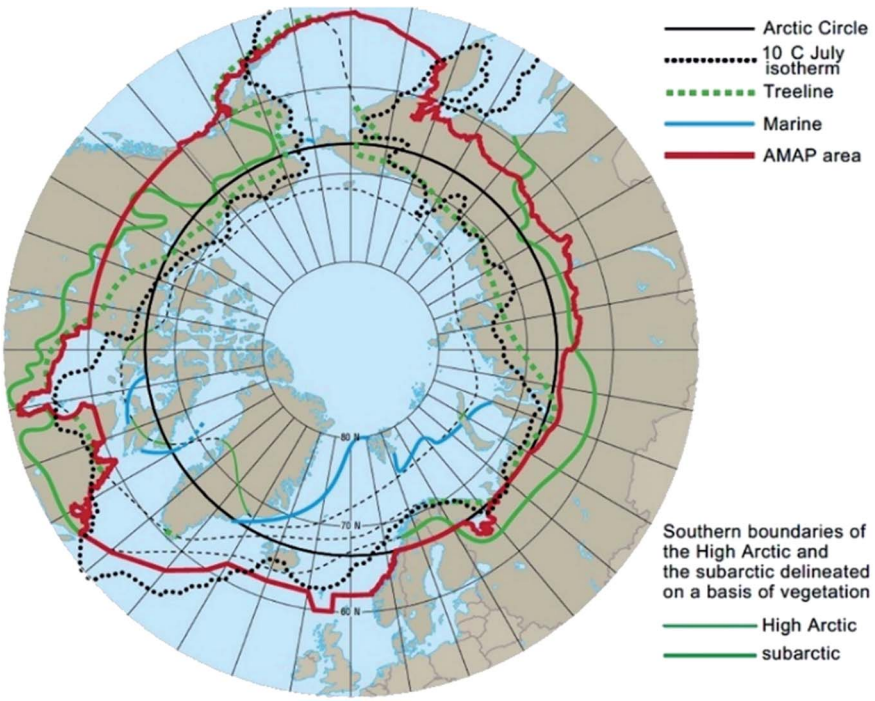

Fig. 1 Boundaries of the Arctic. The red line defines the AMAP area of the Arctic. The map shows other boundaries that are often used: the Arctic circle (66°30′N), the 10 °C July isotherm, the treeline as well as the marine boundary of the Arctic Ocean.

warming was also predicted to increase secondary emissions of POPs from environmental stores, including revolatilization from soil, water, and particulates, leading to increased air concentrations. Additionally, releases from soil and ice would increase POP levels in aquatic environments. The environmental fate, including long-range transport of POPs would also be influenced by climate-induced changes in wind speed, precipitation, ocean currents, biotic transport, frequency of extreme weather events, and the melting of polar ice caps and glaciers. Warmer temperatures would likely increase the degradation and transformation of POPs, potentially decreasing environmental concentrations of the emitted compounds, but increasing the proportion of degradation products present in the environment. Thus, changes to the physical environment both inside and outside the Arctic would affect the transport of POPs to and their behavior in the Arctic. A modeling exercise supported these projections for polychlorinated biphenyls (PCBs).[9,10]

Climate change and climate variability were also predicted to have effects on biodiversity, ecosystem composition and function, and food web structure and dynamics. Climate-induced changes in primary production had previously been noted as a factor that could influence the fate and bioavailability of POPs in the Arctic.[11] The UNEP/AMAP report[9] found that the available food web modeling for POPs,[12] and empirical observations for freshwater fish,[13] showed contradictory results, possibly due to different ecosystems being studied (pelagic marine *versus* benthic freshwater), and highlighted the lack of understanding regarding the effects of climate change on primary production and POP cycling. The report also considered the potential effects of warmer temperatures on toxicokinetics and the toxicity of POPs to wildlife and humans, *e.g.* toxic effects of POPs on wildlife could increase with stress caused by changes in environmental conditions.

The AMAP-coordinated Arctic Health Risks (ArcRisk) project[14–17] addressed many of the predicted effects of climate change on POPs with a focus on the European Arctic. ArcRisk used modeling tools to study the atmospheric and oceanic transport of POPs to the Arctic and the subsequent bioaccumulation of POPs in the Arctic marine food web under present climate conditions and projected future climate scenarios. Most modeling results projected only modest changes to levels of POPs in air, soils, and water as a result of a warming climate.[14,18] However, the ability to model climate-related impacts on POP bioaccumulation was limited by the lack of understanding regarding the effects of climate change on primary production, species distributions, and trophic interactions.

The rapid changes in the Arctic induced by increasing temperatures have been addressed by several organizations, including the Intergovernmental Panel on Climate Change.[19–21] Together with the International Arctic Science Committee (IASC) and the Working Group for the Conservation of Arctic Flora and Fauna (CAFF) of the Arctic Council, AMAP prepared the Arctic Climate Impact Assessment in 2005 [19] and recently published updates on climate change in the Arctic.[22,23] The annual average warming in the Arctic was found to be three times that of the global mean (Fig. 2A and B). Annual precipitation seems to be increasing as well, with less precipitation falling as snow and more as rain in some regions. Sea ice extent is decreasing (Fig. 2C), and multi-year sea ice is being increasingly replaced by annual ice. Other relevant climate change-related processes include ocean acidification, sea-level rise and a higher frequency of extreme weather events.[23] All these changes have direct and indirect effects on biodiversity and ecosystems.[22,23]

Recent reviews of climate and POP interactions[24,25] provide an additional foundation for this themed issue. McKinney *et al.*[24] reviewed the literature on climate change-induced ecological changes and alterations in POP exposures. They concluded that dietary changes linked to reduced sea ice were associated with higher contaminant levels in some marine species, but the influence of changing trophic interactions on POP levels and trends varied widely in both magnitude and direction. Ma *et al.*[25] found there was observational evidence indicating that climate variation had an effect on POP levels in biotic and abiotic environments. However, they noted that the statistical power of current Arctic time series for POPs in other media than air was limited and required more monitoring time points to detect associations with climate parameters.

Many of the wildlife species referenced in the review articles in this themed issue, such as seabirds, seals, and beluga (*Delphinapterus leucas*) form part of the diet of Arctic indigenous peoples,[27] and can thus provide evidence of climate change effects on POP trends that is valuable for understanding human exposures. The ArcRisk project considered human dietary-exposure scenarios related to the impact of climate change, but noted the complexity involved due to multiple unknowns, including future contaminant trends in fish, potential changes in fishery supply, and nutritional transitions in Arctic communities.[14,15] It should be noted that the review articles in this themed issue do not consider the possible combined effects of climate change and POPs on human health. However, recent AMAP Human Health assessments,[27,28] while not specifically focusing on exposure to POPs, have concluded that the combined effects of climate warming, anthropogenic contaminants, and zoonotic diseases represent a significant risk for subsistent food and drinking water supplies of northern communities.

The involvement of Arctic indigenous and local communities in environmental monitoring and research is an important aspect of the work on the influence of climate on contaminants and was addressed in the recent AMAP assessment on climate change and POPs/CEACs[1] and also in a forthcoming mercury assessment.[29] Close collaborations between scientists and local and indigenous communities, especially in the Canadian Arctic and Greenland, have enabled continuous monitoring of marine mammals and freshwater fish and development of strong time series for POPs. The recent assessments have addressed possible ways that Indigenous Knowledge of climate-related changes in local physical and ecological conditions could be more effectively utilized for interpreting the influence of climate change on POP and mercury trends in wildlife with additional capacity building.

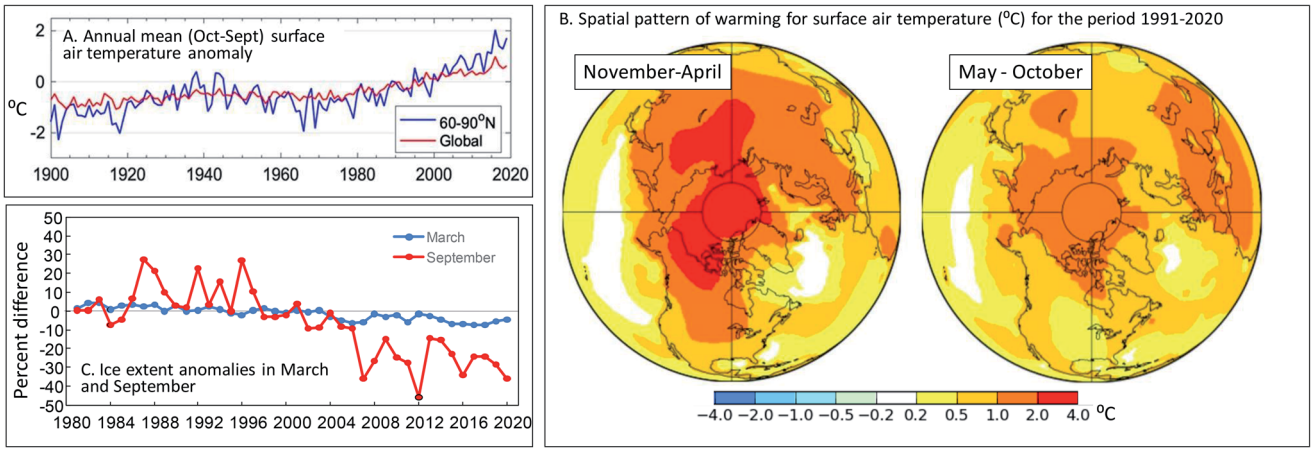

Fig. 2 Temperature and sea ice change in the Arctic. (A) Arctic (blue line) and global (red line) mean annual land surface air temperature anomalies for the period 1900–2019 relative to the 1981–2010 mean value. Arctic measurements taken from land stations north of 60°N.[26] (B) Spatial pattern in Arctic seasonal surface air temperature for the period 1991–2020 relative to a base period of 1950–1981 in cold (November–April) and warm (May–October) seasons. Source: NASA Goddard Institute for Space Studies, http://data.giss.nasa.gov/gistemp/maps/, and (C) Arctic Ocean sea ice extent in March (maximum) and September (minimum) relative to mean for 1981–2010 (https://nsidc.org/data/seaice_index/).

1.2. Key science questions

The growing scientific literature addressing effects of climate on trends of POPs, as well as climate change-induced ecological changes in the Arctic, over the past 10 years has meant that there is now a basis for a more detailed scientific assessment. It was organized along a set of key science questions identified at a workshop organized by the AMAP POPs Expert Group and attended by forty scientists from circumpolar countries as well as China, Germany, Italy, Spain and the UK. The following policy-relevant science questions were developed:

(1) What are the primary sources of POPs, how do they reach the Arctic, and how are emissions and source locations of current and potential future POPs affected by climate change?

(2) Does climate change within the Arctic exacerbate or diminish contaminant transport, accumulation, and occurrence in different abiotic media?

(3) How do local sources contribute to Arctic contamination compared to long-range transport under climate change scenarios?

(4) How well can we anticipate how old and new environmental contaminants, including microplastics, will impact the Arctic in a changing future climate?

(5) What are the key climate change-driven physical and/or ecological processes influencing POPs in Arctic wildlife and how will climate change affect levels of POPs in Arctic biota and food webs?

(6) Are temporal trends of POPs in biota linked with changes in climate parameters and/or food webs?

(7) Do the findings related to temporal trends in POPs in air and biota have implications for national and international regulations of chemicals?

(8) How can Indigenous Knowledge contribute to the discussion of climate-related effects on trends of POPs?

These questions are addressed in the individual review articles of the themed issue. Each review article summarizes the current status of knowledge regarding climate change-driven effects on POPs in the Arctic and presents specific conclusions, recommendations and knowledge gaps. Bartlett *et al.*[30] focus on modeling of emissions and long-range transport of POPs under climate change scenarios. Hung *et al.*[31] review the growing number of climate-related effects on levels and trends of POPs and CEACs in abiotic media, such as air and ice cores, and also address the potential impacts of increased human activity on contaminant levels in the Arctic. Borgå *et al.*[32] examine the climate-induced changes in ecosystem structure and function that may impact POP exposure, as observed in food webs and migratory species. Vorkamp *et al.*[33] review the growing literature on climate-related effects on temporal trends of POPs in Arctic biota, based on time-series datasets on POPs in Arctic biota, with some additional information from Antarctica.[5,34] Also included in this themed issue are reviews of relevant research findings from Antarctica and Tibet, where similar questions on the effects of climate change on POPs in cold climates are being studied.[35,36]

Most information regarding effects of climate change is available on legacy POPs (Table 1). When referring to 'POPs' we are including both the initial POPs and new POPs (*e.g.* polybrominated diphenyl ethers (PBDEs) and per- and polyfluoroalkyl substances (PFASs)), as defined by the Stockholm Convention.

Selected CEACs, including halogenated natural products (HNPs), halogenated and organophosphate ester flame retardants, and polycyclic aromatic hydrocarbons (PAHs) are also referenced in the review articles in this themed issue due to the increasing number of reports on these contaminants[6] (Table 1). Although not listed under the Stockholm Convention, PAHs are listed by the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air

Table 1 Persistent organic pollutants (POPs) and chemicals of emerging Arctic concern (CEACs) discussed in the themed issue or referenced herein[a]

	Primary sources			
Chemical/chemical group	Industrial and consumer uses	Agricultural and disease control uses	Unintentional byproducts	Natural products
Legacy POPs				
Polychlorinated biphenyls (PCBs)	X		X	
Hexachlorobenzene (HCB)	X		X	
Polychlorinated dibenzo-*p*-dioxins (PCDDs)	X		X	X
Polychlorinated dibenzofurans (PCDFs)	X		X	X
Dichlorodiphenyltrichloroethane and its degradation products (DDTs)		X		
Chlordanes		X		
Heptachlor		X		
Toxaphene		X		
Mirex		X		
New POPs				
Polybrominated diphenyl ethers (PBDEs)	X			
Hexabromocyclododecane (HBCDD)	X			
Perfluorooctane sulfonic acid (PFOS)	X			
Perfluorooctanoic acid (PFOA)	X			
Short-chain chlorinated paraffins (SCCPs)	X			
Pentachlorophenol (PCP)	X	X		
α-, β- and γ-hexachlorocyclohexanes (HCHs)		X		
Endosulfan		X		
Polychlorinated naphthalenes (PCNs)	X		X	
Other chemicals & substances				
Perfluorocarboxylic acids (PFCAs)	X			
Perfluorohexane sulfonic acid (PFHxS)	X			
Fluorotelomer alcohols	X			
Organophosphate esters (OPEs)	X			
Dacthal		X		
Chlorpyrifos		X		
Trifluralin		X		
Pentachloronitrobenzene (PCNB)		X		
Polycyclic aromatic hydrocarbons (PAHs)			X	X
Pentachloroanisole (PCA)			X	
Microplastics	X			
Halogenated natural products (HNPs)				
Bromoanisoles (BAs)				X
Hydroxylated PBDEs (OH-PBDEs)	X			X
Methoxylated PBDEs (MeO-PBDEs)				X

[a] Legacy POPs: chemicals included in the original 'dirty dozen' listed under the 2004 Stockholm Convention. New POPs: chemicals listed under the Stockholm Convention between 2005–2019.

Pollution[37] and there are substantial data for pyrogenic-related PAHs in the Arctic.[38] Current knowledge of climate change-related effects on microplastic pollution in the Arctic is also included, due to the growing concern for plastics as an emerging pollution issue in the Arctic.[6,39]

2. Key science findings and recommendations

2.1. Overview

Over the past ten years, a growing number of studies have addressed the consequences of climate change for the fate of Arctic contaminants, for example targeting correlations between POP temporal trends in air or biota and climate indices. These are large-scale climate parameters reflecting variations in air pressure for a certain region, with consequences for air mass transport, temperature and precipitation. The Arctic Oscillation Index (AO), North Atlantic Oscillation Index (NAO) and Pacific/North American Pattern (PNA)[40] have been found to be particularly relevant for climate patterns in the Arctic.

In general, there are now many observations that suggest linkages exist between climate-induced changes and the fate of Arctic contaminants. However, these linkages are mainly

correlative and the causal relationships behind these observations are still poorly understood. This is related to the multitude of direct and indirect effects of climate change on biological, chemical and physical processes that interact to influence the fate of contaminants within a rapidly warming Arctic, as illustrated in a conceptual approach in Fig. 3.

Previous assessments of POPs and CEACs in the Arctic under the auspices of AMAP[5,6] have not typically considered data from the fields of meteorology, hydrology and glaciology. These have been included in other AMAP reports addressing climate change and its impacts on the Arctic environment and living conditions in the Arctic.[19,41,42] However, the reviews in this themed issue illustrate that the complexity of physical, chemical, and biological processes, and the rapid developments with regard to both climate change and chemical contamination, require greater interdisciplinary scientific exchange and collaboration. Going forward there is a need for a stronger collaborative approach to understanding the influence of climate change on POPs and CEACs due to high uncertainties and the incremental process of increasing knowledge of these chemicals.

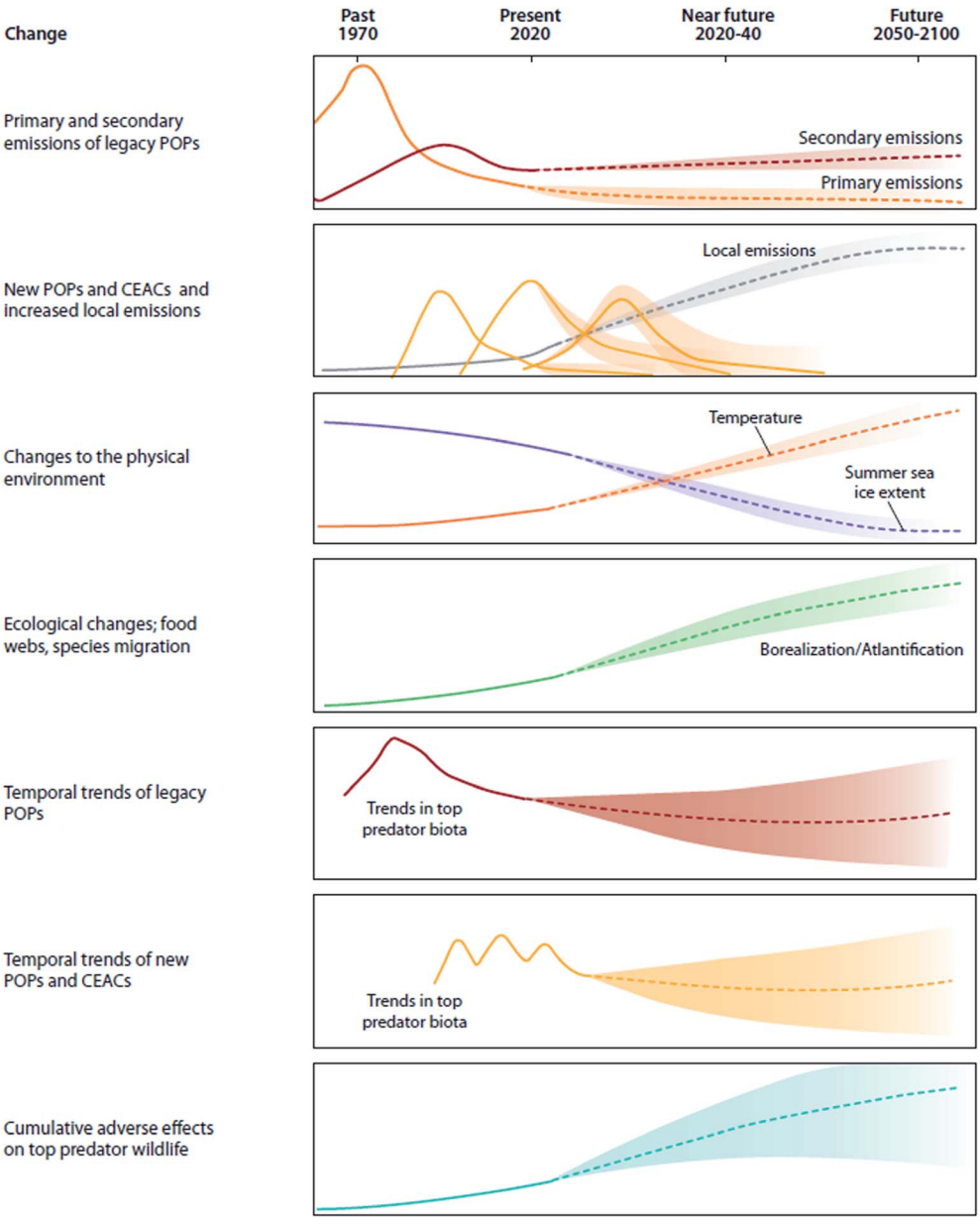

Fig. 3 Conceptual approach to changes in chemical emissions, environmental conditions, and ecosystems that took place in the past and are projected for the next 100 years, illustrating the complexity in trends of POPs and CEACs in the Arctic under future climate change. Temporal trends of PCBs are used as examples of legacy POPs. Dashed lines indicate predicted relative trends compared to modelled or measured trends (solid lines) for the period from 1970–2020. Shaded areas indicate relative uncertainty in projected trends.

Below we summarize the key findings from the assessment, structured along the four reviews focused on the Arctic. Based on these key findings, the key science questions were discussed, and recommendations were developed for future research and monitoring in the respective field.

2.2. Key findings

Model predictions of emissions and long-range transport of POPs and CEACs under climate change (Bartlett *et al.*[30]). • Concentration changes of POPs in Arctic air and ocean waters driven by climate change are predicted to be small compared to reductions in concentrations that can be achieved by reducing primary emissions.

• Greater rates of primary and secondary emissions of many POPs can be expected globally under climate change due to temperature-driven increases in volatilization.

• Chemical volatilization and degradation are two counteracting climate-sensitive processes affecting Arctic air concentrations. Both are expected to increase under higher temperatures related to climate change although magnitudes are not known.

• Other predicted climate change-related developments and events likely to affect POP sources and emissions include increased economic activity and population growth in the Arctic.

Effects of climate change on levels and trends of POPs and CEACs in the physical environment (Hung *et al.*[31]). • Climate change perturbations are resulting in the re-mobilization of POPs within and between air, water, ice, snow, soils, and sediments in the Arctic. Examples include increased POP concentrations in lake sediments resulting from melting glaciers and permafrost slumps.

• Increasing concentrations observed for some POPs in Arctic air in recent years have been attributed to their release and volatilization from melting and diminished extent of sea ice.

• Increased primary productivity under climate change is enhancing the drawdown and transfer of contaminants from surface waters to deeper waters through the process known as the 'biological pump'. This process is likely leading to increased sequestration of POPs from the atmosphere into deep ocean waters and sediments.

• Positive correlations exist between some POP concentrations in Arctic air and climate oscillation indices. Larger seasonal variations occurred in POP concentrations when the Arctic Oscillation index was negative.

• Local emissions of some POPs and CEACs (*e.g.* PCBs, PFASs, flame retardants, PAHs) have been shown near Arctic communities, military and industrial sites, and infrastructures (*e.g.* airports). Human activities (*e.g.* shipping, tourism, oil and gas development, fisheries) are likely to increase with future changes in climate, leading to potential increases in local emissions of contaminants within the Arctic.

• There are indications that the reduction of sea ice due to climate warming is leading to a general increase of sea spray aerosols in the Arctic. This implies that re-emissions of water-soluble, surface-active POPs such as PFASs to air and coastal environments will increase as well.

• Extreme weather events (*e.g.* severe rain events, snowstorms, and unseasonal warming in parts of the Arctic) as well as forest fires, are becoming more frequent. Short-term elevated air concentrations of PAHs and PCBs in the high Arctic have been traced to wildfires in boreal forests of Canada and Russia. Increased discharge volumes from Eurasian rivers have been associated with increased loading of PAHs to the Arctic Ocean.

• Natural halocarbons (nHCs) are likely to increase in the Arctic over this century due to climate change effects on producing species (phytoplankton and macroalgae) with potential, but uncertain impacts on stratospheric ozone.

Influence of climate change on accumulation of POPs in Arctic food webs (Borgå *et al.*[32]). • First-year ice now dominates ice coverage over large parts of the Arctic and is coupled with earlier or erratic thawing. The melting of brine-rich, first-year ice may result in more efficient delivery of POPs to organisms at the base of the marine food web.

• Permafrost thaw has been shown to impact lake water chemistry in the Canadian Arctic and influence the condition of landlocked Arctic char *via* impacts on their dietary sources.

• Significant dietary shifts are being observed in Arctic animals due to climate-driven migrations of species from temperate waters (*i.e.* borealization), and declines in sea ice that are changing movements and behaviors of ice-dependent species (*e.g.* polar bears shifting from hunting on pack ice to foraging on land).

• The combination of contaminant exposure and sea ice decline has synergistic adverse effects on lipid metabolism in polar bears, as differences between biomarker responses of less- and more-polluted bears showed greater contrast during a period with poor sea ice conditions.

• There are too many unknowns and variable results among species and ecosystems to firmly conclude the net effect of climate change-driven impacts on species interactions and food web contaminant accumulation.

Associations between climate change and temporal trends of POPs in Arctic biota (Vorkamp *et al.*[33]). • Positive associations have been found between annual mean concentrations of many POPs in biota and climate oscillation indices over time, sometimes with time lags, suggesting that changes in air mass transport from North America and Europe toward the Arctic can influence POP levels in biota.

• Positive associations were also found between some POP levels in landlocked Arctic char and climate-related parameters, including temperature and precipitation. Thawing permafrost and the resulting release of particulate matter and carbon into lake systems was generally linked with increased POP levels in Arctic char and freshwater amphipods.

• Annual mean concentrations of many POPs in biota were associated with sea ice extent (including both negative and positive associations). Some associations between climate parameters and POP levels showed time lags.

• Dietary changes affected POP exposures of some Arctic animals. In general, effects on long-term trends of POPs were

small, but temporary perturbations or changes in long-term rates were observed.

• Including climate parameters in time trend analyses did not affect the overall direction of the trends (*i.e.* increase or decrease of POP concentrations) but could affect the magnitude of the annual changes (*i.e.* towards a faster or slower rate of change).

• Effects of climate on trends of POPs have not been studied in the Antarctic to any significant degree, but are likely to occur given the similarities in polar environments.[35]

2.3. Addressing key science questions and recommendations

What are the primary sources of POPs, how do POPs reach the Arctic, and how are emissions and source locations of POPs and CEACs affected by climate change? As noted by Bartlett *et al.*[30] information about primary emissions, including variations over time and space, is fundamental for assessing changes in the fate of POPs and CEACs, including their transport to the Arctic and distribution processes between different media. Temporally- and spatially-resolved global or circumpolar emission inventories only exist for a few POPs (PCBs, DDT, HCHs) and PAHs. Therefore, new approaches, such as inverse modeling are required to establish emission patterns, in particular for those contaminants where emissions are associated with the entire lifecycle of consumer products (*i.e.* production, use, and disposal) rather than, for example, industrial or agricultural sources.

Recommendation: there is a need for temporally- and spatially-resolved emission inventories at circumpolar and global scales for more POPs and CEACs similar to what has been achieved for PCBs, DDT, HCHs, and PAHs. Emissions estimates derived from inverse or 'top down' modeling (i.e. estimating emissions from measurements where large datasets of levels and trends are available), should be employed to address this data gap. This is a high priority over the short to medium term.

Does climate change within the Arctic exacerbate or diminish contaminant transport, accumulation, and occurrence in different abiotic media? Increasing temperatures and cryospheric changes have increased the mobility and transfer of POPs between physical environmental compartments of the Arctic through various mechanisms, including enhanced volatilization of contaminants from water, snow and ice, and re-mobilization of contaminants from melting of sea ice (*i.e.* multi-year and first-year ice), glacier ablation, and permafrost thaw, degradation and slumping.[30,31]

Recommendation: more research is needed to better understand the implications of accelerated thawing of the cryosphere and resulting re-mobilization of stored contaminants on the accumulation and exposure of marine and freshwater environments and biota to POPs. Simultaneous multimedia assessments of contaminant redistribution (e.g. particulate-bound versus dissolved concentrations), and accumulation in food web organisms should be conducted in the Arctic, the Antarctic, and the Tibetan plateau, to systematically quantify such impacts. Given the logistical challenges this should be viewed as a priority over the long term.

How do local sources contribute to Arctic contamination compared to long-range transport under the climate change scenarios? Climate change and a diminishing cryosphere will likely increase human activity in the Arctic, including shipping, tourism, and industrial operations, as well as promote the expansion of urban areas.[30,31] Additionally, adaptations to climate change might also include changes in lifestyles, behaviors and policies. These potential developments should be considered in future research and monitoring of contaminants in the Arctic, as they can involve the use of chemicals and thus have the potential to contribute to local releases of substances widely used in consumer and industrial products, some of which may be CEACs (Fig. 3).

Recommendation: given the likelihood of increased human activity and development in the Arctic due to climate change, there is a need to evaluate emissions of newly listed POPs, as well as current-use chemicals in consumer and industrial products within the Arctic. It will be relevant to assess the sources of these chemicals and the relative contributions of long-range transport and local emissions to their occurrence in the Arctic. It is also recommended that a broader list of substances be assessed for Arctic contamination potential, and that time trend monitoring studies be expanded to include a broader range of chemicals, as well as other media such as water. This is a high priority in the short to medium term.

How well can we anticipate how POPs and CEACs, as well as microplastics, will impact the Arctic in a changing future climate? As outlined in Section 1.2, the reviews have mainly addressed POPs included in the Stockholm Convention and selected CEACs (Table 1). The largest amount of data is available for these compound groups but focusing on these data-rich substances might result in an incomplete assessment of the consequences of climate change for Arctic contaminants. Some CEACs, such as the short-chain PFAS, HNPs, and organophosphate ester flame retardants, have much higher solubility in water than legacy and new POPs, while others, like the volatile neutral PFAS precursors, have much greater volatility. These differences in physical–chemical properties have implications for climate-related changes in long-range atmospheric or oceanic transport to the Arctic and accumulation thereafter.

Recommendation: a broader range of contaminants should be included in research and monitoring studies addressing climate-related effects on contaminants in the Arctic to account for differences in physical–chemical properties between compounds and associated differences in their long-range transport and fate. Given the challenges of assessing biological effects this should be viewed as a priority over the long term. However, some aspects, e.g. climate-related effects on CEAC levels and trends, can be addressed in the short and medium term, to the extent data for CEACs are available.

Microplastic pollution is an important emerging issue in the Arctic. Microplastic particles can contain, bind and leach POPs and CEACs, and thus may serve as a source or transport vector of contaminants to the Arctic. There is a general lack of knowledge with regard to climate change-related effects on microplastics and associated contaminants, especially concerning the processes and rates of microplastic incorporation

within sea ice, the effect of microplastics on sea ice properties, and the potential release of microplastics and associated contaminants from melting ice.

Recommendation: the role of microplastic particles present in snow and ice as climate forcers requires further study. In addition, the exposure of Arctic biota to microplastics, and the role of microplastics as vectors for contaminant transport and biotic exposure needs further investigating. This is a high priority over the short to medium term which is being actively addressed by AMAP.

What are the key climate change-driven physical and/or ecological processes influencing POPs in Arctic wildlife and how will climate change influence levels of POPs in Arctic biota and food webs? The reviews by Borgå *et al.*[32] and Vorkamp *et al.*[33] demonstrate that there are a vast diversity of processes through which climate change may affect contaminant exposure in Arctic ecosystems. The direction and extent of changes in POP concentrations in biota are not consistent but vary between species, ecosystems and locations. In general, higher temperatures are leading to the release of stored POPs from melting ice, glaciers and thawing permafrost into aquatic systems, where higher temperatures can also affect the uptake and elimination of POPs in cold-blooded organisms. Variations in climate oscillation indices,[40] which reflect changes in air mass movements, ocean currents, and thus contaminant transport, are correlated with changes in POP accumulation in some Arctic biota. Reductions in the amount and extent of sea ice are influencing the air–water exchange of contaminants and prey accessibility. In addition, the northward movement of subarctic species from the Atlantic and Pacific (*i.e.* Atlantification and borealization) also leads to increased prey-switching, with consequences for POP exposure and tissue levels (Fig. 3). Changes in the structure and function of Arctic ecosystems are not currently predictable, but disruptive impacts on a broad range of habitats, species, and processes are likely, which in turn will disrupt the dynamics of POPs in the Arctic.

Recommendation: research on climate-induced changes in ecosystems and consequences for POP exposure and accumulation in wildlife should reflect the diversity of Arctic ecosystems and the complexity of potential impacts and feedbacks of climate change on ecosystems. National monitoring programs should include ancillary biological and ecological data (e.g. body condition, fatty acid signatures, and stable carbon, nitrogen and sulfur isotope ratios), along with physical parameters (e.g. temperature, precipitation amounts, and ice coverage and quality) at the local scale, to better understand the factors that influence the accumulation of POPs in biota under climate change. Given the challenges of assessing effects at the ecosystem level this should be viewed as a priority over the long term.

Can we link changes in temporal trends of POPs with climate parameters and/or food web changes? As Hung *et al.*[31] and Vorkamp *et al.*[33] have demonstrated, many POP time trends established for Arctic air and biota have now achieved the statistical power needed to evaluate relationships with climate parameters.[5] However, only a few POP time series from the Arctic have been investigated for correlations with climate parameters to date. Some of these time series do show associations between changes in POP concentrations and climate parameters (*e.g.* climate oscillation indices, sea ice extent, precipitation) over time and provide important indications of covariates to consider in the interpretation of POP time trends, as further detailed in Hung *et al.*[31] and Vorkamp *et al.*[33]

Recommendation: existing time trend monitoring data should be used to explore associations between climate parameters and POP concentrations in the Arctic to a greater extent. POP time series of sufficient length are available from most Arctic countries, in many cases covering many compounds in air and/or multiple species of biota. Studying correlations between climate data and POPs could provide a basis for formulating hypotheses about the most important mechanisms of climate effects on POPs in the Arctic and other polar environments. Given the large number of time series available this can be viewed as a high priority over the short to medium term.

Do the findings related to temporal trends in POPs in air and biota have implications for the national and international regulation of chemicals? Temporal trends of contaminants in the Arctic are used as indicators in effectiveness evaluations of the Stockholm Convention, which regulates primary emissions of POPs. In general, POP concentrations have been decreasing in the Arctic environment and biota.[5,34] However, some POP time series have shown recent perturbations in these decreasing trends that seem to be associated with climate-related changes in physical processes or ecosystems. The reduction of primary emissions is still considered to be the main driver of POP time trends (Fig. 3), however, for some compounds, the rate of concentration decline changed (negatively or positively) when adjusted for climate-related parameters.

Recommendation: there is a need for further research to identify and characterize the direct and indirect linkages between climate-induced changes in the long-range transport of contaminants to the Arctic and their accumulation in wildlife to aid the interpretation of trend data. Given the complexity this should be viewed as a long term priority.

How can Indigenous Knowledge contribute to the discussion of climate-related effects on trends of POPs? Arctic indigenous peoples possess a rich repository of environmental knowledge and are directly affected by contaminants and climate change. Thus, their involvement and contributions are essential for assessing the effects of climate change on POPs and CEACs in the Arctic. Questions that would benefit from specialized Indigenous Knowledge and the co-production of knowledge include local and regional changes in environmental conditions (*e.g.* sea ice) and food webs that may affect POPs trends but would not be reflected in circumpolar scale climate indices or biodiversity assessments.

Recommendation: Indigenous Knowledge, and the participation of indigenous and local communities in the collection of observations of sea ice and other climate-related changes (including the timing of events), animal distribution, behavior, diet and body condition, and many other variables, would substantially benefit the interpretation of trends of POPs and associations between climate change and POPs. Additional capacity building of research programs, scientists, northern communities and particularly, indigenous youth, is needed to support and encourage community-based studies and the co-production of knowledge, including the utilization of Indigenous Knowledge for interpreting POP trends in light of climate change. This is a high priority over the short term.

3. Knowledge gaps

The review articles in this themed issue have highlighted a set of knowledge gaps that warrant priority for future research to build a knowledge base that would serve Arctic communities, government decision-making, and policy needs. Although the effects of climate change on the fate of POPs in the Arctic, Antarctic,[35] and Tibet[36] are understood better now than they were 10 years ago, empirical data providing evidence of predicted changes are still limited.

3.1. Emissions and long-range transport

• Emission estimates are limited to a few POPs such as PCBs, legacy chlorinated pesticides, and some CEACs, such as PAHs. These need to be updated as well as extended to ensure sufficient temporal and spatial resolution for modeling of transport to the Arctic and other polar environments.

• Knowledge is lacking on the relative source attribution of POPs and selected CEACs in the Arctic to distant, regional and local sources.

• Uncertainties in the physical–chemical properties of chemicals of interest, especially CEACs, impede estimations of emissions and modeling efforts.

• Sensitivity analyses on model simulations need to be improved to evaluate the effects of climate-related changes in atmospheric composition and meteorological conditions on POP and CEAC concentrations in the Arctic.

• The potential effects of regime shifts in climate conditions that result from transgressing "tipping points" in the climate system (*e.g.*, such as complete loss of summer sea ice) on POP and CEAC concentrations, have yet to be considered.

• There is a need for detailed studies of processes affecting the long-range transport of POPs and CEACs, including the joint analysis of modeling results and monitoring data (*e.g.* gas-particle partitioning, degradation, surface–air exchange, *etc.*).

3.2. Physical environment – levels and trends

• There is a need to address local sources of POPs, CEACs and other, as of yet unstudied, current-use chemicals that could increase as a consequence of greater human activity in the Arctic related to climate change.

• Knowledge of contaminant re-mobilization due to permafrost thaw and erosion is limited to a few studies and locations. Thus, the relevance of such processes to biotic exposures in freshwater systems is currently difficult to assess due to the limited geographic scope of existing data.

• Natural halocarbons (nHCs) are likely to increase over this century due to the effects of climate change on producing species (*i.e.* phytoplankton and macroalgae) and biogeochemical cycles. The impacts of increased emissions of nHCs on stratospheric ozone are uncertain and need further investigation.

• The role of microplastic particles present in snow and ice as climate forcers is currently unknown.

• There is a lack of knowledge on the contaminant loadings from precipitation to polar marine surfaces (*e.g.* open water, ice melt ponds) and the relative input of these sources *versus* oceanic transport to the Arctic, Antarctica and the Tibetan plateau. Evaluations of model-based predictions of POP and CEAC deposition are lacking.

• The rapid replacement of multi-year ice by brine-rich first-year ice in a warming Arctic necessitates studies investigating the exposure of sympagic organisms (*e.g.* ice algae and associated zooplankton in brine channels) to contaminants and the contaminant loadings from first-year ice to ocean waters.

• While it is foreseeable that extreme weather events (*e.g.* severe rain events, floods, snowstorms and unseasonal warming in parts of the Arctic) will become more frequent due to climate change, studies examining the role of such events on the distribution pathways of POPs are currently lacking.

3.3. Influence of climate change on accumulation of POPs in Arctic food webs

• No data are currently available on the net effect of increased temperatures on the uptake and elimination rates of POPs in cold-blooded Arctic organisms.

• Changes in POP levels of biota resulting from the direct effects of declining sea ice cover cannot be separated from the indirect effects of changes in food web structure and function with the present state of knowledge.

• Increased terrestrial run-off from snow and glacier meltwater is expected to influence both the exposure levels and food web biomagnification of POPs in lakes and estuarine waters, but there are few empirical data available to confirm this.

• There is a general lack of understanding regarding the impact of climate-driven changes in the phenology of ecological events (*e.g.* seasonal timing of migration, reproduction and food availability) on POP levels in Arctic biota.

• The net effect of climate-related increases in freshwater and marine primary production on the bioavailability and bioaccumulation of POPs in Arctic biota is not well understood.

• Climate-driven migrations of species from more southerly latitudes may introduce new sources of contaminants into Arctic food webs, however, the importance of these biovectors in transporting contaminants to the region is largely unknown.

• Changes in seabird and marine mammal foraging patterns due to climate change have the potential to impact their exposure to POPs, but few data exist.

• There is a general lack of understanding of how climate change and other environmental stressors affect the toxicity of POPs to Arctic biota.

• Mechanistic process-oriented models combining physical–chemical transport models with bioenergetics and food web models can be used to project the overall bioaccumulation of POPs in Arctic biota, but there is insufficient understanding or empirical data to parametrize these models.

3.4. Climate change and temporal trends of POPs in Arctic biota

• While associations between POP time trends and climate parameters (*e.g.* sea ice coverage, air temperatures, oscillation indices) have been identified, and included in trend modelling,

the mechanisms underlying these correlations are not understood.

• Climate oscillation indices, sea ice, temperature and precipitation have been the predominant climate parameters used to evaluate associations between climate change and contaminant temporal trends in the Arctic thus far, but it is not known if other parameters might be equally or more important.

• The relationship of climate parameters and contaminant time trends in biota varies between species and locations. The reasons for these variations (*e.g.* influence of local or regional conditions) are not known.

• Information on the effects of climate change on POP time trends in low trophic level organisms is generally lacking. In addition, there are no systematic studies of climate change effects on POP time trends in Arctic terrestrial ecosystems currently available.

• Processes related to permafrost thaw, degradation and slumping have been associated with elevated POP levels in freshwater Arctic biota. The mechanisms underlying this connection are not fully understood, but increased particle loads and enhanced biological activity likely play a role.

• Observations of stable or increasing HCB concentrations in Arctic biota are frequently reported, but lack explanation.

• Although iceberg calving has been identified as a potential source of POP release and accumulation in marine biota in the Antarctic,[35] no studies have examined this phenomenon in the Arctic.

• While the overall effects of climate change parameters on long-term contaminant time trends appear small at present, this may be a momentary observation. Updated information is needed as primary emissions will presumably continue to decrease, while the effects of climate change may become increasingly evident and can be expected to lead to complex feedback reactions.

4. Policy implications for science and chemical management

Arctic data play an important role in the risk assessment and potential regulation of chemicals as their occurrence in remote areas can indicate long-range transport, and data in Arctic wildlife can reflect bioaccumulation. In addition, the GMP of the Stockholm Convention uses Arctic data to evaluate the effectiveness of global chemical regulations under the Stockholm Convention. Monitoring data from the Arctic is also relevant for national or European regulations as well as general process understanding of the environmental fate of POPs and CEACs. In the following bullet points, we summarize where results of the assessment of influences from climate change on POPs and CEACs in the Arctic can have implications for policy-related work.

• Although climate change is impacting POP levels and trends in the Arctic, the reduction of primary emissions is currently considered the main driver of POP time trends. Thus, continued efforts to include more POP-like chemicals in chemical management initiatives at the global level (*e.g.* the Stockholm Convention), and at national or regional levels are needed.

• Results from the reviews presented in this themed issue are relevant to other regional, national or international forums addressing contaminants and climate change, such as the recent Global Environmental Facility Scientific and Technical Advisory Panel initiative on the co-benefits of sound management of chemicals and waste.[43]

• The relative contributions of long-range transport *versus* local emissions of POPs and CEACs to the Arctic may be changing due to climate change. There is a need to identify local sources and re-evaluate their contribution to Arctic pollution in order to inform chemical management decisions within and outside the region to reduce contaminant loads to the Arctic environment.

• There are indications of climate change leading to increased human activity in the Arctic, and thus potentially increased use of chemicals within the region. Therefore, there may be a need for additional risk assessments that are not solely based on the criteria used for POPs or similar chemicals (*e.g.* persistence, bioaccumulation and toxicity under EU REACH), but also include, for example, criteria related to chemical persistence and mobility, and emissions from consumer products.

• Climate change can influence secondary emissions of POPs, as well as the physical, chemical and biological processes that affect their long-range transport and bioaccumulation, and thus, their long-term time trends in Arctic air and biota. These effects are outside the scope of the Stockholm Convention but need to be taken into account in relation to effectiveness evaluations.

• Without further action on climate change, alterations in the Arctic ecosystem are expected to continue and may impact the effectiveness of policies seeking to reduce POP exposures in Arctic people and wildlife through primary source reductions alone. It is important for decision-makers to recognize the diversity and complexity of climate change-induced effects on POPs and that specific measures can have a variety of outcomes *via* physical, chemical and biological interactions and feedback reactions.

• There is a need for funding agencies to support international and interdisciplinary approaches that would bring scientists working on climate impacts in the atmosphere, cryosphere and oceans into close collaboration with environmental scientists studying the effects of climate change on the fate of POPs and CEACs in the Arctic. Long-term studies are crucial in this context.

• With the complexity of climate change impacts on contaminants in Arctic ecosystems, it is important to plan for integrated monitoring, which includes the collection of ancillary climate parameters, biological and ecological data in addition to contaminant data. This includes, but is not limited to, data on climate indicators and local meteorological conditions, as well as information on the physiology, biology and ecology of Arctic organisms. To be operative, integrated monitoring requires a stable institutional background and the agility

to integrate short-term and local efforts and resources into a coherent service.

• In some cases (*e.g.* reducing combustion sources) there are co-benefits from actions on climate change that can also help mitigate chemical exposure problems in the Arctic.

• A precautionary approach to the management of persistent chemicals is prudent due to the poorly reversible consequences of global exposure and the range of hazards that are difficult to anticipate. These risks are compounded by deficiencies in our present understanding of how climate change might affect the global fate and transport of chemicals.

• Community involvement in Arctic monitoring activities should be extended and expanded to include interdisciplinary issues at the interface of contaminants and climate change. This will require circumpolar countries to build and support research and monitoring programs, involving scientists and northern communities that encourage community-based studies and the co-production of knowledge, in close cooperation with existing programs.

• Monitoring programs and individual research studies should comply with open data policies to ensure that quality-assured raw data on POPs and related ancillary data are publicly available for future study.

5. Conclusions

Considerable progress has been made in studies on the influence of climate change on the fate of POPs and some CEACs in polar/Arctic environments. The review articles in this themed issue provide evidence for climate-change induced re-mobilization and re-distribution of POPs and CEACs in the Arctic environment, and for ecological changes potentially influencing exposure to POPs at all levels of the food chain. Perturbations of some temporal trends have been observed, presumably as a consequence of these physical and/or ecological changes. However, most of the evidence is correlative and many open questions remain. A better mechanistic understanding of influences of climate change on long time series of POPs is important for effectiveness evaluations of international regulations of chemicals, but current evidence suggests already now that ancillary biological and climate parameters should be included as potential confounding factors in long-term trend modelling of POPs. The possibly growing influence of local sources of CEACs due to expansion of tourism and urban/industrial development in the polar regions is an emerging issue that needs further study, to meet local concerns and to ensure correct interpretation of monitoring data for potential policy actions. These and other questions would benefit from greater participation of indigenous communities and their knowledge of local and regional changes in environmental conditions. Given the speed and complexity of environmental changes in the Arctic, it is urgent to assess their influence on POPs and CEACs in the Arctic, including projections of potential future developments, and to regularly update the current knowledge base with new information. The coordinated research and monitoring approach under AMAP, and similar initiatives recently established for the Antarctic, will help provide new data to evaluate these emerging climate-contaminant issues. AMAP has experience with the monitoring and assessment of both contaminant and climate-related issues, based on close pan-Arctic and interdisciplinary scientific collaborations. This is an important basis for policy-advice that integrates findings from different scientific disciplines and that will target policies in the field of both chemicals management and climate protection.

Conflicts of interest

There are no conflicts to declare.

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