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Local sources *versus* long-range transport of organic contaminants in the Arctic: future developments related to climate change†

Derek Muir, *[ab] Maria J. Gunnarsdóttir, [c] Krystyna Koziol, [d] Frank A. von Hippel, [e] Danuta Szumińska, [d] Nicoletta Ademollo, [f] Simonetta Corsolini, [g] Amila De Silva, [a] Geir Gabrielsen, [h] Roland Kallenborn, [i] Żaneta Polkowska, [j] Eva Krümmel [k] and Katrin Vorkamp *[l]

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Local sources of persistent organic pollutants (POPs) and Chemicals of Emerging Arctic Concern (CEACs) from use in communities, shipping, and industrial activity contribute to contamination as does long-range environmental transport. Increased human activity in the Arctic as the climate warms may enhance the significance of local sources. Furthermore, climate change may lead to secondary sources of POPs and CEACs from existing reservoirs in the Arctic. This review examines the emerging evidence for releases from these secondary sources of formerly deposited POPs and CEACs as the Arctic climate warms and the potential for future releases with increased infrastructure development and economic activity. Arctic permafrost degradation represents an important source of natural and anthropogenic polycyclic aromatic hydrocarbons (PAHs), and indications exist of releases of POPs related to permafrost thaw, from previous deposition as well as waste sites. Deposition of POPs and some CEACs to Arctic glaciers is relatively well studied while fewer studies explore the impacts of remobilization. Expansion of economic development has the potential for increasing emissions or creating new sources of CEACs in the Arctic. The predicted northward expansion of agriculture, aquaculture, and ship traffic could bring increased emissions of CEACs to northern waters, including pesticides not previously used in the Arctic. Increased industrial chemical use, *e.g.* fire-fighting foams, flame retardants, lubricant and plastic additives, is likely to occur following the expansion of infrastructure such as airports, seaports, mining, and oil and gas development. While PAHs are relatively well-studied, there is an urgent need for environmental measurements and modelling of emissions of CEACs associated with the expansion of economic activity in the Arctic as well as to predict the future release of legacy POPs from secondary sources, particularly from permafrost.

Environmental significance

Arctic permafrost and glaciers represent important reservoirs of past atmospheric inputs of persistent organic pollutants (POPs) and chemicals of emerging Arctic concern (CEACs), mainly resulting from long-range transport. In addition, local emissions can occur due to past or current use in northern communities, industrial sites, and other related activities (shipping, fishing, agriculture), which are likely to increase in a warming Arctic. There is an urgent need for studies of CEACs associated with the expansion of economic activity in the Arctic and for prediction of the future release of legacy POPs from secondary sources, particularly from permafrost.

[a] *Environment and Climate Change Canada, Aquatic Contaminants Research Division, Burlington, ON, L7S 1A1, Canada*

[b] *School of Environmental Sciences, University of Guelph, Guelph, ON, N1G 2W1, Canada. E-mail: derek.muir@sympatico.ca*

[c] *Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland*

[d] *Department of Environmental Change and Geochemistry, Faculty of Geographical Sciences, Kazimierz Wielki University in Bydgoszcz, Pl. Kościeleckich 8, 85-033 Bydgoszcz, Poland*

[e] *Mel & Enid Zuckerman College of Public Health, University of Arizona, Tucson, Arizona, 85721-0036, USA*

[f] *Institute of Polar Sciences, National Research Council (ISP-CNR), Bologna, Italy*

[g] *Department of Physical, Earth and Environmental Sciences, University of Siena, Siena, Italy*

[h] *Norwegian Polar Institute, Fram Centre, NO-9296 Tromsø, Norway*

[i] *Faculty of Chemistry, Biotechnology and Food Sciences, Norwegian University of Life Sciences, 1432 Ås, Norway*

[j] *Department of Analytical Chemistry, Faculty of Chemistry, Gdansk University of Technology, 80-233 Gdańsk, Poland*

[k] *Inuit Circumpolar Council—Canada, Ottawa, ON, K1P 5E7, Canada*

[l] *Department of Environmental Science, Aarhus University, Roskilde, Denmark. E-mail: kvo@envs.au.dk*

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1 Introduction

The Arctic has been warming nearly four times faster than the global average over the period of 1979 to 2021.[1] The impacts and projected future changes are discussed in detail in the 2021 AMAP Arctic Climate Change Update[2] and include changing air temperature, precipitation and extreme weather events, permafrost thaw, inland flooding, coastal erosion, wildfires, sea ice changes, land ice (glacier) mass declines and changes in riverine inputs. Many of these emerging environmental impacts that relate to Arctic warming have the potential to release contaminants that entered terrestrial environments *via* long-range transport and deposition from the atmosphere. Additionally, contaminants sequestered in frozen soils, glaciers and waste sites near urbanized areas, in industrial sites such as oil and gas developments and mining, and in former military sites, have the potential to be released.[3,4]

As discussed in Kallenborn *et al.*,[5] local emissions of some Persistent Organic Pollutants (POPs) and Chemicals of Emerging Arctic Concern (CEACs; *e.g.*, unregulated polyfluoroalkyl and perfluoroalkyl substances (PFAS), current-use flame retardants, plastic additives, polycyclic aromatic hydrocarbons (PAHs)), and other organic contaminants, have been documented near Arctic communities, military and industrial sites. Economic development activities (*e.g.*, shipping, tourism, oil and gas development, fisheries, mining) are likely to increase with future changes in climate, leading to potential increases in local emissions of contaminants within the Arctic (Fig. 1).

In this review we address a key question from the AMAP assessment on "POPs and Chemicals of Emerging Arctic Concern: Influence of Climate Change" that relates to local sources and climate change: How do local sources contribute to Arctic contamination compared to long-range transport under climate change scenarios?[6,7] We document the emerging evidence for secondary sources of POPs and CEACs as the Arctic climate warms with a focus on locations where local communities may be impacted. These secondary sources may include contaminants originally transported to the Arctic *via* long-range transport as well as locally emitted and temporarily retained compounds, thus it might not always be possible to distinguish original emission sources and pathways. In the case of pollutants that were formerly transported with the atmosphere and deposited on ice surfaces, their release would still reflect long-range transport although it might now result in a locally limited pulse into aquatic systems. Increased human activity in the Arctic as the climate warms may enhance the significance of local sources. Therefore, future developments of commercial activities such as shipping, tourism and fishing as well as expansion of industrial and public infrastructure in the Arctic which could lead to increasing emissions or new sources of POPs and CEACs are also addressed.

Many of the above issues related to local and secondary sources of POPs and CEACs, and the future impacts of greater human activity and climate change, also apply to the Antarctic.[8] In order to avoid dispersion of the information in the text, this review includes a separate section on the Antarctic which highlights the differences between the contamination sources and processes in the Arctic and Antarctic region and identifies questions to be addressed.

2 Releases of contaminants related to climate change

2.1 Melting glaciers as secondary emission sources in the Arctic

Glaciers can be a reservoir of POPs and CEACs that were atmospherically transported to the Arctic. As glaciers and ice-

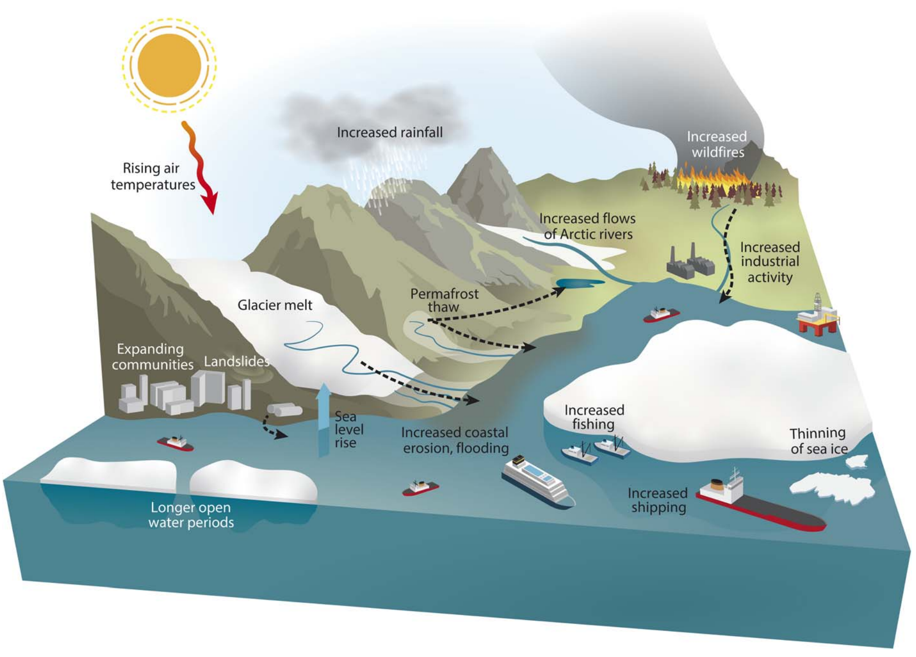

Fig. 1 Schematic of some of the key changes in climate and infrastructure in the Arctic which may affect the contribution of local and secondary sources of POPs and CEACs in the Arctic environment.

sheets melt as a consequence of climate change,[9] these formerly deposited chemicals can be released again, turning glaciers from a temporary sink into a secondary source of pollutants. Melting glaciers as a source of POPs deposited decades ago to downstream lake and river ecosystems were first recognized in studies in the Rocky Mountains of Western Canada[10] and studied extensively in the European Alps[11–13] and in the Tibetan plateau.[14,15]

Risk assessments based on measured concentrations of organochlorine (OC) pesticides and polychlorinated biphenyls (PCBs) in glacial streams and lake sediments in European alpine regions suggest that aquatic food webs could be impacted as glaciers continue to melt.[16] It has also been demonstrated that glacier meltwater was a source of POPs in marine food webs of Greenland fjords.[17] The issue is particularly important for Arctic Indigenous Peoples, who often have the highest levels of contaminant exposures and experience high risks of food insecurity, which is amplified by effects of climate change.[18] It is also important for local communities that rely on marine and freshwater organisms as a food resource[19] as well as for Arctic countries and regions that rely on commercial fishing and fish exports (*e.g.*, Alaska, Nunavut and Nunatsiavut (Canada), Greenland, Iceland, Faroe Islands, the Lofoten region of Norway).

The release of POPs from melting glaciers into receiving waters has been demonstrated in Svalbard,[20–22] Ellesmere Island, Canada,[23,24] Nuup Kangerlua (Godthåbsfjorden), Greenland,[25] and the Alaska Range.[26] In addition to POPs, related studies have identified PAHs from melting glacier snow packs in Svalbard.[27] Additional studies exist on PFAS, organophosphate flame retardants and other CEACs, such as bisphenols and nonylphenols, as detailed below. The studies show that both marine and freshwater recipients can be affected by POPs and CEACs from glacier runoff.

Pawlak *et al.*[28] estimated the extent of this phenomenon by reviewing literature on concentrations of various POPs (OC pesticides, PCBs, polybrominated diphenyl ethers (PBDEs)), and PAHs in glacial environments of the Northern Hemisphere and time-resolved glacier melt predictions. For the Arctic, the concentrations of POPs in air, snow, glacier ice, and glacial runoff fell within wide concentrations brackets (Table S1†) and they may reach concentrations exceeding those in the European Alps, especially for ΣDDTs in snow, ΣPCBs in glacier ice, and ΣPAHs in both these media. However, the upper end concentrations in the Arctic may reflect the influence of local sources, *e.g.*, for PAHs in snow in Svalbard.[27,29,30]

2.1.1 Glacial releases of legacy POPs. Several studies conducted in Kongsfjorden, Svalbard (Fig. 2) show the impact of melting glaciers on contaminant levels in the fjord. The loss of sea ice, the ablation and melting of the Kongsvegen Glacier, and the melting of perennial snow cover led to a secondary release of contaminants into the fjord. Ademollo *et al.*[20] documented the occurrence, spatial distribution, and seasonal pattern of PCBs, PFAS and some CEACs (bisphenol A, nonylphenols, PAHs) in the marine environment to delineate primary *versus* secondary emissions. The summer and winter concentrations of the selected contaminants in seawater were investigated. PCBs showed higher concentrations in the summer, together with decreasing concentrations with increasing distance from the glacier, indicating that the Kongsvegen Glacier was a likely secondary source (Fig. 2). The study also identified local pollution sources such as PAHs from diesel fuel, which were linked to the increasing number of ships visiting the fjord. The distribution of PCBs was dominated by low-chlorinated PCB congeners, supporting the influence of atmospheric long-range transport.[31,32] In addition to PCBs, hexachlorobenzene (HCB), and the legacy OC pesticides chlordane and DDTs were reported in glacier-sourced rivers that discharge to Kongsfjorden. These results highlight the possibility that melting glaciers will increasingly act as secondary POP sources and may become more important than primary sources in a long-term global perspective.[33]

Glacial characteristics and post-depositional processes modify the potential of glaciers to become secondary pollution

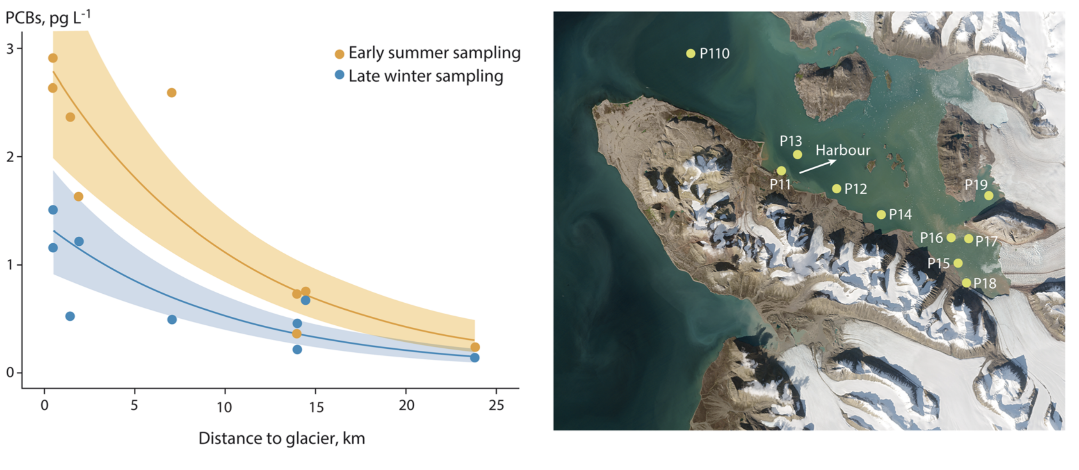

Fig. 2 Study area and location of the sampling points along a transect of Kongsfjorden for ΣPCBs in seawater. ΣPCBs was higher in June than in March and decreased with increasing distance from the glacier in both sampling seasons (modified from Ademollo *et al.*[20]). Blue-coloured items denote late winter, orange-coloured ones denote early summer.

sources.[28,34,35] Variation could occur due to the degree of influence of local anthropogenic primary emissions, the age of the melting glacial ice, the extent of glaciation in each area, and whether glaciers are tidewater or land-terminating.[34] Furthermore, fjords affected by glacial inflows typically have different concentrations of POPs than the open ocean. For example, in Svalbard, glacial melt resulted in elevated concentrations of selected (dissolved) POPs in waters of Kongsfjorden[20] and Hornsund Fjord[21,22] compared to measurements in the open Arctic Ocean. In contrast, Johansen *et al.*[36] also noted a dilution effect when comparing concentrations of PCBs and HCB in riverine suspended particulate matter (SPM) and in outer marine sediments of the Isfjorden area of Spitsbergen and concluded that increased terrestrial inputs in the future could lead to reduced concentrations of POPs in coastal sediments as the SPM is deposited.

Fluxes of POPs have increased in Lake Hazen (Ellesmere Island, Canada), the largest lake by volume north of the Arctic Circle.[23] Surface temperatures of glacier-covered regions of the Lake Hazen watershed experienced a 2.6 °C warming over the period 2000 to 2012 with the greatest change occurring from 2007 to 2012. Glacial runoff for the period 2007–2012 increased lake outflow by 370% relative to 1996–2006. Sediment accumulation rates post-2007 were on average eight times higher relative to the pre-1948 baseline. Legacy OC pesticides, PCBs and HCB were measured in a sediment core from the deepest point (267 m) in the lake (Table S1,† footnote #1). Concentrations and fluxes of PCBs and OC pesticides peaked in the 1970–80s, consistent with the known uses of major OC pesticides (DDT, chlordanes, hexachlorocyclohexanes (HCHs)) and the global use of PCBs. However they also showed rising concentrations post-2000, reflecting remobilization of OC pesticides and PCBs previously deposited and stored in glaciers.[23] Previous studies based on a core collected in 1990 at the same location showed low fluxes of OC pesticides and PCBs.[37,38]

Alaskan glaciers are losing mass at an increasing rate[39] but have received little study in terms of releases of pollutants. Miner *et al.*[26] measured DDT and HCHs in an ice core from the Jarvis Glacier in eastern Alaska (63.74°N, 145.65°W) and in the runoff in proglacial Jarvis Creek which feeds the larger Tanana River and eventually the Yukon River. The Tanana River is a major river in Eastern Alaska and habitat for salmonids which are an important food source for Alaskan communities in the region. Glacial meltwater accounts for over 50% of the annual flow of the Tanana River. DDT and HCH isomers were detected throughout the 79 m ice core, possibly reflecting high water mobility between ice layers and sorption of the OC pesticides on particles released by sediment rich layers in the glacier (Fig. 3). Meltwater concentrations in Jarvis Creek slightly exceeded concentrations found in the ice core, with *p*,*p*′-DDE predominating (average June: 0.69 ng L^{-1}, July: 0.73 ng L^{-1}). The stream water concentrations of OC pesticides were higher than those

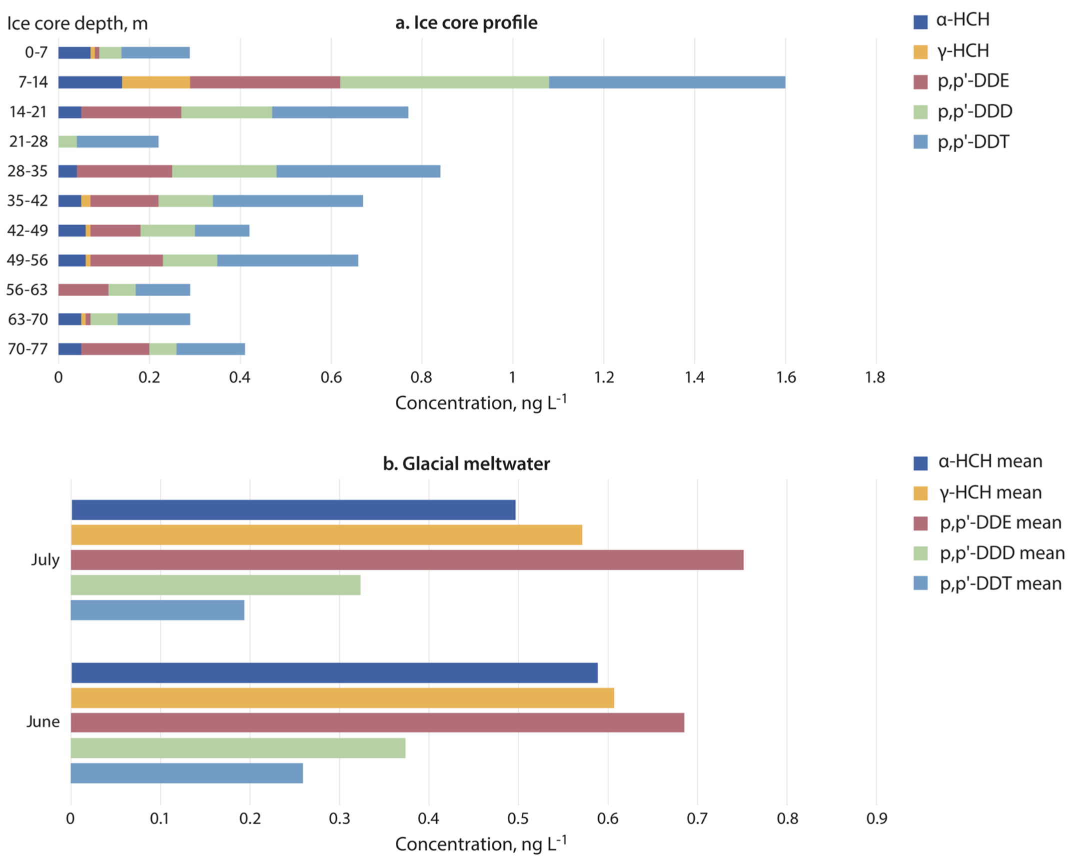

Fig. 3 Concentrations of DDT and HCH related isomers in (a) a core from the Jarvis Glacier (depth from 0 to 77 m) collected in 2017 and (b) glacial meltwater (unfiltered) from proglacial Jarvis Creek (redrawn from Miner *et al.*[26]).

recorded in Svalbard (Table S1†), but data are not directly comparable because the Alaskan study was based on bulk water whereas the studies from Svalbard analysed filtered water.[32]

2.1.2 Releases of PFAS from Arctic glaciers. While the presence of legacy POPs (*e.g.*, PCBs, DDT, PBDEs), and PAHs in snow, firn and ice of Arctic glaciers has been studied since the mid-1990s (as reviewed by ref. 28) studies of PFAS in glaciers have been conducted more recently. Because PFAS are particularly amenable to remobilization through glacier melt due to their higher water solubility compared to the hydrophobic legacy POPs, their presence in glaciers is of particular concern. PFAS have been identified in high Arctic glaciers including the Devon Ice Cap in Canada,[40,41] Mt. Oxford Icefield in Canada,[41,42] the Lomonosovfonna Glacier in Svalbard,[35] and the Longyearbreen Glacier in Svalbard.[43] While these locations are at high altitude and distant to any potential local primary sources associated with settlements or industry (except Longyearbreen Glacier, which is close to the town of Longyearbyen), these studies reveal the significant reservoir of PFAS in the upper layers of Arctic ice caps which could be mobilized in glaciers feeding rivers near northern communities. PFAS deposition is more recent than deposition of PCBs and OC pesticides, therefore the highest concentrations of PFAS are generally found in the top 10 meters of snow/firn.[43,44] Hartz *et al.*[35] showed that PFAS may be remobilized from melting Arctic glaciers and noted that trifluoroacetic acid (TFA), a degradation product of both hydrofluorocarbons and PFAS, including perfluorooctane sulfonate (PFOS), was mobile during meltwater percolation. They concluded that seasonal snowmelt and runoff from previous atmospheric deposition and accumulation on glaciers could be a significant seasonal source of PFAS to ecosystems in Arctic fjords. Kwok *et al.*[43] sampled the glacial stream flowing from the Longyearbreen Glacier through Longyearbyen and noted that the highest concentrations were in waters from the section of the stream flowing through the urbanized area, illustrating additional effects of local sources on PFAS concentrations in the fjord.

Exponentially increasing fluxes of several PFAS were also observed in Lake Hazen sediment cores (1963–2011) with doubling times corresponding to 6 to 8 years, depending on the compound[45] (Fig. 4). This increase was also attributed to particle deposition from glacial runoff. In the same study, a sediment core from Lake B35 (64° 19.94 N, 95° 54.18 W), a small lake that does not receive glacier melt, about 5 km from the community of Baker Lake, Nunavut (population 2100), had slower doubling times for PFOA and PFOS. PFOS was below detection limits in Lake B35 except for one surface sample (Fig. 4). The higher fluxes in Lake Hazen, despite being much further from potential local sources in the community illustrate the importance of the glacial meltwater releases.

Analysis of proglacial rivers in the Lake Hazen watershed further supports contaminant transport. Six rivers were sampled on the northern shore of Lake Hazen that travel from land terminating glaciers of the Northern Ellesmere Icefield. Timing of sampling events was used to distinguish between snow melt (early June) and glacier melt (July). Summed PFAS in rivers sampled in July 2015 (mostly glacier melt) corresponded to 1.1 to 4.1 ng L^{-1} and based on riverine fluxes, this corresponded to 1.6 ± 0.72 kg of ΣPFAS to Lake Hazen.[24] In comparison, summed PFAS in rivers sampled in June (mostly snow melt) corresponded to 0.44 ± 0.32 kg of ΣPFAS released into Lake Hazen.

2.1.3 Release of organophosphate esters and other CEACs from glaciers. The release of organophosphate ester (OPE) flame retardants into proglacial streams has been studied in Svalbard and in the Canadian Arctic. Six proglacial rivers on the northern shore of Lake Hazen were analyzed for OPEs, with total OPEs (Σ_{14}OPEs) corresponding to 4.5 to 32 ng L^{-1}. These concentrations translated to a total input of 7.0 ± 3.2 kg of Σ_{14}OPEs to Lake Hazen *via* proglacial river flows.[46] Gao *et al.*[47]

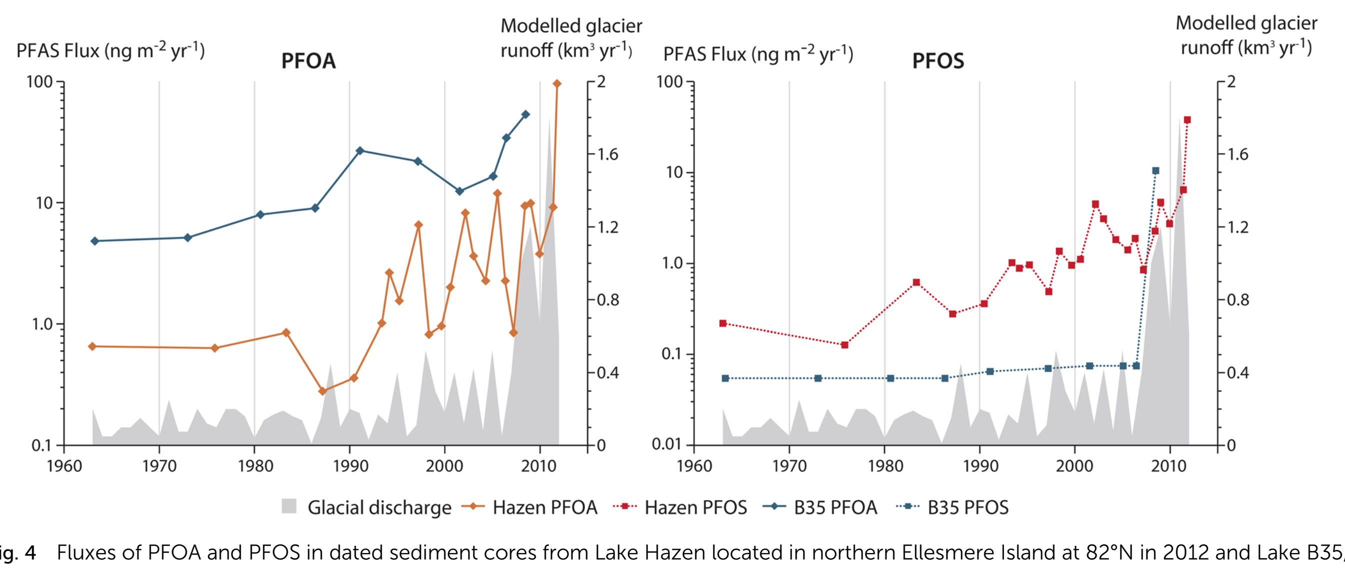

Fig. 4 Fluxes of PFOA and PFOS in dated sediment cores from Lake Hazen located in northern Ellesmere Island at 82°N in 2012 and Lake B35, located in central Nunavut at 64°N in 2009 (redrawn from ref. 45). Grey area denotes the period of elevated glacial runoff and higher sedimentation rates.

determined concentrations of OPEs in two proglacial streams near the Ny-Ålesund research station on Svalbard using passive water sampling in July 2017 when glacial runoff was near its maximum. The chlorinated OPEs, tris(2-chloroethyl) phosphate (TCEP) and tris(1-chloro-2-propyl)phosphate (TCIPP), were the predominant compounds, averaging 24 and 35 ng L^{-1}, respectively. Gao *et al.*[47] also detected TCIPP in glacial stream sediments. A more detailed study of OPEs in sediments of a proglacial stream near Ny-Ålesund also found that TCIPP was the predominant OPE.[48] However, Fu *et al.*[48] also detected the degradation products of dialkyl/aryl OPEs, which they attributed to photodegradation of OPEs during atmospheric transport or in glacial snows. These studies illustrate that besides glaciers being secondary sources of OPEs proglacial sediments form yet another reservoir that can be released during summer melt and *via* erosion during extreme weather events.

Other CEACs have been the subject of few studies in Arctic glaciers, meltwaters and receiving waters. The study in Kongsfjorden (Svalbard) showed decreasing concentrations of bisphenol A, nonylphenols and PAHs with increasing distance from the glacier (and a harbour as a potential local sources), but no effect of season.[20] This finding was different from that for PCBs. A study of a partly glacier-fed river system in Hornsund Fjord in southwestern Spitsbergen detected relatively high concentrations of the sum of phenols and formaldehyde (0.24 mg L^{-1} in June and 0.35 mg L^{-1} in September) at Revelva River estuary.[49] The increases in phenols may be related to a shift from waters released from snow melt to permafrost thaw as discussed in Section 2.3. Fragrance chemicals (benzyl salicylate, amyl salicylate, hexyl salicylate, peonile) were detected in glacial snow near Ny-Ålesund, although only low concentrations were found in seawater of Kongsfjorden.[29]

Lyons *et al.*[50] investigated glaciers in the Chugach National Forest and Kenai Fjords National Park of the Kenai Peninsula in southern Alaska specifically for 4-nonylphenol (4NP), a widely used chemical and transformation product of nonylphenol polyethoxylate surfactants, which was also included in the study on Svalbard.[18] They discovered that 4NP was widely present in glacial environments with the average concentrations in snow, ice, meltwater, and glacial till of 0.77 ± 0.017 μg L^{-1}, 0.75 ± 0.006 μg L^{-1}, 0.26 ± 0.053 μg L^{-1}, and 0.016 ± 0.004 μg g^{-1}, respectively. These were high concentrations compared to OC pesticides and PFAS (Table S1†), which was also reported for the study in Svalbard.[18] They also noted that Anchorage, Alaska (population 290 000 in 2021; about 100 to 180 km north of the glacier sampling sites) could be a source area.[51]

2.1.4 Release of microplastics from glaciers. The presence of 4NP and OPEs in glacial snows and meltwater in the Arctic could also relate to deposition of microplastics (MPs) since these are common plastic additives. Zhang *et al.*[52] reviewed reports of MPs in the Arctic cryosphere and in lake waters and sediments, while Hamilton *et al.*[53] reviewed studies on MPs in the cryosphere and the atmosphere of the Arctic, with a view to combined monitoring. Most of the sampling was conducted in remote areas and the main focus had been measurements of plastic particles in sea ice, seawater and marine sediments. However, Stefánsson *et al.*[54] reported MPs in snow cores from the Vatnajökull Ice Cap (64.434°N and 16.437°W) in Iceland, and noted that atmospheric transport from nearby small communities (nearest one was 65 km from the sampling site) could be a source. The presence of MP in glacial waters in Iceland might lead to a risk of contamination of drinking water; however, this has not been studied in detail.[55] Sub-micrometer particles of different plastic polymers and tire rubber were also detected in a Greenland firn core.[56] There are reports of deposition of MPs in remote glaciers in Tibet[57,58] and in the Collins Glacier (King George Island) in Antarctica,[59] indicating the importance of long-range atmospheric transport of the particles. In relation to glaciers, Huntington *et al.*[60] reported higher particle counts for MPs accumulating in sediment in front of the Belcher Glacier on Devon Island, implying possible releases during summer melting. Considering the high number of chemicals used as plastic additives[61] releases of MPs also lead to a relocation of associated chemicals. However, their leaching from MPs, possibly affected by the plastic weathering, is not yet fully understood.

2.1.5 Contamination of marine food webs from glacial meltwaters. The releases of bioaccumulative contaminants from melting glaciers can cause new ecosystem exposure to long-banned chemicals. This has potential for broader environmental and societal impacts due to the potential contamination of food webs important for top predators and fisheries, which are also critical subsistence food sources of Arctic Indigenous Peoples.[19] Risk assessments related to drinking water contamination from glacial runoff have not indicated elevated risks of cancer, however, model results indicate that even with low levels of organic pollutants in glacial meltwater, high fish consumption by subsistence communities in the area increased the risk of cancer and hazard impacts above acceptable limits.[19] In the assessment, the actual concentrations of POPs and CEACs in glacial runoff were compared with the environmental norms of the US Environmental Protection Agency (EPA) and the EU Groundwater Directive.[19]

Spataro *et al.*[17] investigated the occurrence of POPs (HCHs, endosulfan, DDT and DDE) and CEACs (chlorpyrifos and dacthal) in polar cod (*Boreogadus saida*) sampled within Bessel Fjord, Greenland (76°13′N 19°54′W) and on the continental shelf outside the fjord. These two habitats differ markedly in thermohaline parameters and current patterns. The fjord habitat is impacted by glacial meltwater runoff, while the shelf is characterized by full oceanic salinity and cold Arctic water as part of the main East Greenland current.[62,63] Higher concentrations of DDTs in cod were detected in the fjord population compared to those sampled on the shelf; these authors ascribed this pattern to the release of POPs from summer ice melting, and reported that it is not seen for all compound groups of the study (Fig. 5).

2.1.6 Conclusions on glacier inputs. Studies of glaciers have revealed a wide range of organic contaminants and MPs present in snow/firn and meltwaters. While legacy POPs have been the most studied group, the results also suggest that PFAS releases from summer melting of glaciers could be an important issue for Arctic Indigenous Peoples, local communities and ecosystems. Furthermore, CEACs such as NPs and OPEs have

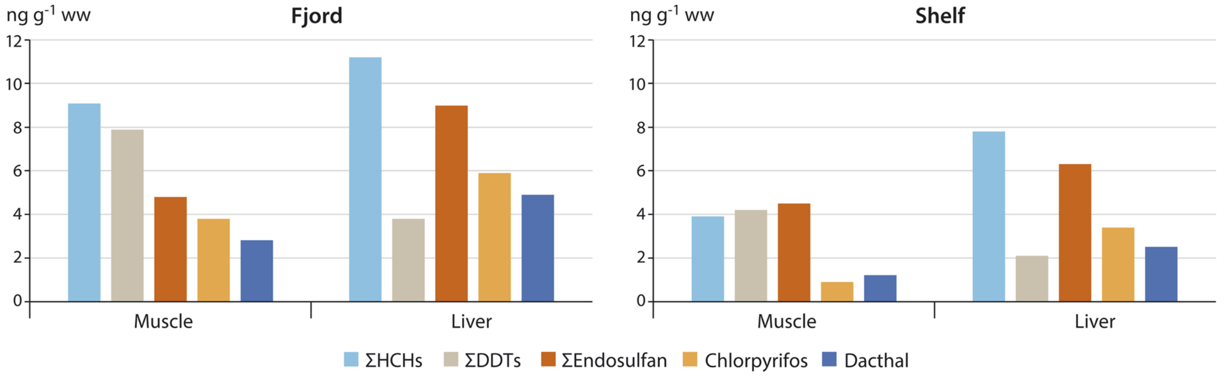

Fig. 5 OC pesticide concentrations in fish tissues sampled in the fjords ($n = 19$) and on the shelf ($n = 22$) of Northeast Greenland (data from Spataro *et al.*[17]).

been detected in glacial runoff at much higher concentrations than legacy POPs or PFAS. Therefore, it is likely that other widely used organic chemicals are present in glaciers and future research needs to focus on a broader array of contaminants, including other plastic-associated chemicals. However, the accumulation zone area on Arctic glaciers has been shrinking, which may limit the spatial extent of potential contaminant accumulation. The changing glacial accumulation and melt regime would be best expressed through a pollutant release model. As part of this modelling approach, it would be relevant to estimate the potential quantity of POPs stored in these reservoirs and their spatial distribution in the glacier, in three dimensions. Such a model would also help to identify maxima in the remobilization of legacy POPs already accumulated in glacial ice. In the short-term, remobilization is likely to increase, yet the locations and timing of remobilized plumes of POPs/CEAC are difficult to foresee or even document post-factum due to limited spatial data.

2.2 Ice and riverine transport of POPs, CEACs and microplastics in a warming climate

Transport in sea ice has long been known as a pathway for moving contaminants from near-shore and ocean-shelf regions into the open Arctic Ocean and ultimately into the North Atlantic.[64,65] Sea ice can entrap pollutants from air and water locally and release them, potentially in a different location, as the ice melts.[66] Early work focused mainly on transport of radionuclides[64] and shelf sediments,[67] whereas recent studies have also shown the presence of MPs in sea ice.[68]

During spring melt, nearshore areas receive river ice and water which may have been contaminated by deposition onto the upstream ice during winter. This discharge deposits its particle load in the nearshore zone where sediment-sorbed contaminants can be incorporated directly into the offshore Arctic ice pack *via* flooding of river waters or into the developing ice cover after resuspension in fall and winter storms.[67] This is likely an especially important pathway for the Russian Arctic given that eight of the ten largest rivers flowing into the Arctic Ocean and Bering Sea are in Russia (the Mackenzie River and the Yukon River are the others).[69] The importance of rivers for the long-range transport of contaminants is discussed in more detail in Hung *et al.*[70] Besides the ice-related transport of contaminants, river inflows (km^3 per years) to the Arctic Ocean have been increasing at an average rate of 0.22% per year since the 1980s,[71] implying potential for greater contaminant fluxes. Modelling of global river flows using the Intergovernmental Panel on Climate Change (IPCC) SSP1-2.6 and SSP5-8.5 scenarios also predicts greater runoff for rivers flowing into the Arctic Ocean.[72] Smaller river inputs could also be important sources of CEACs to coastal waters given that many northern communities are located on them. Coastal catchments dominate land-ocean inputs along much of the Arctic coastline.[73]

Sources of MPs that have been found in sea ice in the Central Arctic Ocean include riverine discharge from Russian and Canadian rivers, inflows of Pacific and Atlantic waters, and discharge from vessels operating in the Arctic, as well as atmospheric deposition.[74] Studies in Svalbard show that local sources from wastewater discharge are important sources of MPs. MPs were considerably higher in Kongsfjorden (up to 48 MPs L^{-1}), which is influenced by the effluent from the research center of Ny-Ålesund, than in remote Rijpfjorden (up to 7.4 MPs L^{-1}) on the north coast of Nordaustlandet.[75]

Peeken *et al.*[68] measured the particle load and types of MPs in ice cores from Fram Strait and the central Arctic Ocean and evaluated the sea ice trajectories. They concluded that even in remote regions such as the Arctic Ocean, certain types of MP polymers indicate the presence of localized sources. They attributed some of the high loadings of MPs in sea ice to increasing commercial fishing efforts in the eastern Bering Sea, Barents Sea, north of Svalbard, and north of Franz Josef Land, implying a localized input, although off shore. Ship traffic in the Arctic has increased substantially in the past 20 years, especially for vessels operating in open water.[76,77] Fisheries account for a major share of the ship traffic in the Arctic Ocean[76] and also the major share of plastics litter in the Barents Sea region.[74] The role of potential local sources of POPs, CEACs and MPs related to increased human activity in a warming climate will be discussed in Section 3.

2.2.1 Conclusions on local sources and ice and riverine transport. Riverine transport of POPs, CEACs and MPs to the Arctic and ice-related transport within the Arctic have been addressed in some studies as reviewed by ref. 70, but little is known about how climate change will impact these processes. Much of the focus on riverine inputs of contaminants to the open ocean has been for transfer from coastal to offshore ice and into the transpolar drift of sea ice. Wastewater as well as local atmospheric deposition from urban and industrial areas are likely important sources. Given the size of the drainage areas of Arctic rivers these sources could be in sub-Arctic and north temperate regions well south of the Arctic Ocean. Local communities along the rivers could be impacted by riverine transport of contaminants in terms of drinking water quality and contaminants in freshwater and marine wildlife. There is an obvious need for further data from Russia given the huge influence of freshwater inputs from the region, as well as from rivers in North America. While new research has identified MP transport with rivers and ice, no clear links have been established to the occurrence of MPs in fish and other biota consumed by Arctic Indigenous Peoples, and local communities or even effects on ecosystem and humans. Being a highly dynamic system with seasonal variation and different types of anthropogenic influences, river- and ice-related processes will be further affected by climate change, with likely consequences for contaminant releases, which are far from understood.

2.3 Permafrost thaw – release of contaminants from atmospheric deposition and failing infrastructure

2.3.1 Overview of permafrost thaw. Permafrost degradation in the circumpolar Arctic and in the Antarctic as a result of climate warming is an environmental issue of global concern.[78,79] The impacts of permafrost thaw on terrestrial and aquatic ecosystems, landscapes, infrastructure, and carbon release, have been the focus of much research and assessment.[78,80–84] Releases of anthropogenic contaminants from thawing permafrost have received less attention,[85] although releases of mercury have been documented in Alaska, Canada and Sweden.[86] The situation in the Antarctic is discussed in Section 4.

Retrogressive thaw slumping along lake shorelines of ice-rich soils and peatlands is occurring in the Mackenzie Delta region of the Northwest Territories and in many other regions of the Arctic and is anticipated to increase with further climate warming.[87] Thermokarst, the thawing of ice-rich permafrost ground causing formation of detached layers of land and creation of shallow lakes and wetlands due to land subsidence, can influence watershed hydrology and delivery of dissolved and particulate organic carbon to lakes and the ocean.[80,88,89] For example, slumping increased ionic concentrations and alkalinity in disturbed lakes.[88] The deepening of the permafrost active layer and opening of new taliks may also impact contaminant fate in permafrost catchments.[90] Ultimately these changes will affect inputs of POPs and CEACs to lake surface waters and catchments, with consequences for bioaccumulation and food web biomagnification.

A study of lakes on Banks Island in the western Canadian Arctic archipelago found that 288 lakes were impacted by retrogressive thaw slumps. This was evident by a colour change in the satellite imagery, from dark blue to turquoise or beige over the period 1984 to 2015.[91] The authors attributed the color change to increased turbidity. Studies of stream catchments in the Toolik Lake area of the North Slope of Arctic Alaska demonstrated that small areas of thermokarst activity delivered large amounts of sediments to streams through mass wasting.[89]

2.3.2 Permafrost thaw and sources of contaminants. Atmospherically mobilized POPs and CEACs have been deposited in Arctic terrestrial environments *via* snow, rainfall and gas exchange with vegetation (Fig. 6). In addition, PAHs and other volatile organics emitted from wildfires have been deposited for millennia. While the contaminants can be re-emitted *via* volatilization and runoff during snowmelt, they are also incorporated into Arctic surface vegetation and soils,[93] and then ultimately into frozen soils. Increasing vegetation cover in the Arctic[94] could influence exchange of POPs with the atmosphere and with the underlying soil environment. Cabrerizo *et al.*[93] noted that PCB re-emission from Arctic soils may be retarded with increasing vegetation.

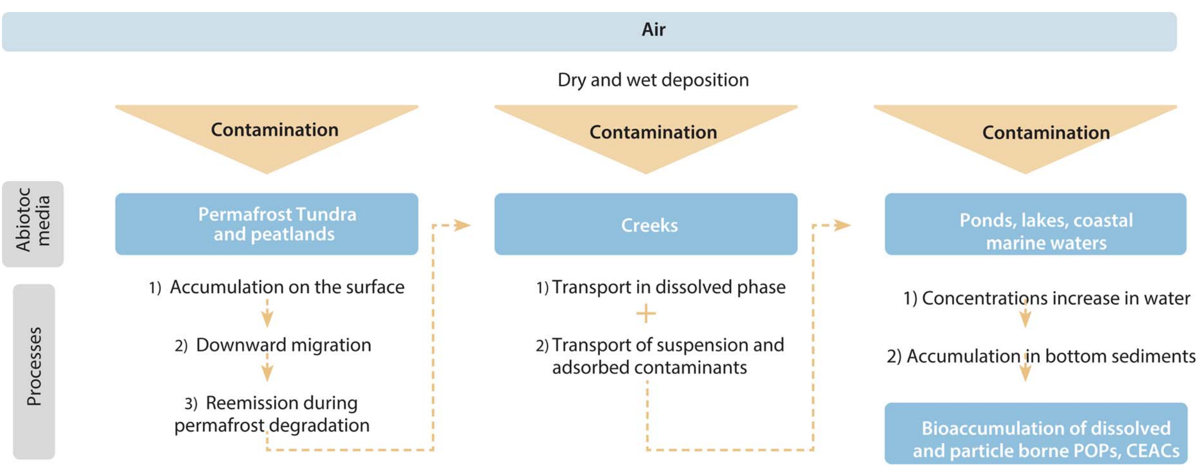

Fig. 6 Environmental fate of organic contaminants delivered to Arctic terrestrial environments *via* long-range atmospheric transport and incorporated into abiotic components. From Potapowicz *et al.*[92]

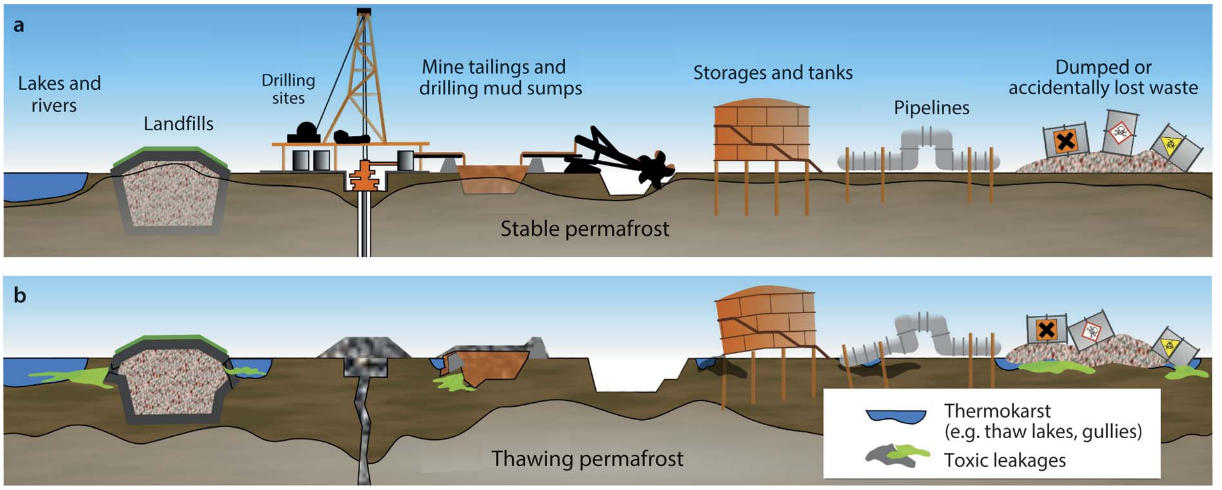

Fig. 7 Past and present industrial activities in the Arctic that may result in release of POPs, PAHs, and other organic contaminants. Previously frozen disposal sites (a) are "unlocked" by warming and thawing of near surface permafrost when foundations and containment structures are destabilized, (b) thermo-hydrological erosion and lateral flow of water increases as permafrost thaw intensifies, leading to dispersion of contaminants (redrawn from Langer *et al.*[3]).

In addition to the atmospheric deposition sources, industrial activity (mining, oil and gas exploration and development) and military facilities (*e.g.*, radar stations) have created contaminated sites and waste.[4] In many cases waste from these activities has been deliberately placed in permafrost based on the assumption that permafrost would serve as a permanent repository.[85] Permafrost was assumed to provide a good hydrological barrier for movement of contaminants from solid and liquid wastes.[95,96] Langer *et al.*[3] identified over 4500 industrial sites where potentially hazardous substances are actively handled or stored in the permafrost-dominated regions of the Arctic. These sites include landfills, drilling sites for oil and gas and exploration, mines, storage tanks, pipelines, and other waste dumps (Fig. 7).

2.3.3 Release of PAHs from permafrost. The majority of the work on organic contaminants in Arctic soils has been on PAHs. Peat soils, river sediments, and coastal marine sediments in the Russian, Canadian, Norwegian and United States Arctic and in adjacent regions of discontinuous permafrost (*e.g.*, Mongolia, northeast China) contain unsubstituted and alkylated 2- to 6-ring PAHs at concentrations from 10s to 1000s of ng g^{-1} dry weight (dw) (Table S2†). They are present as a result of centuries of plant diagenesis and biomass combustion, as well as from more recent fossil fuel related industrial sources.[69,97] Although PAHs can have natural sources, some are highly toxic and classified as human carcinogens.[98,99] New releases of PAHs from thawing permafrost can therefore result in adverse effects on ecosystems and humans.

2.3.3.1 PAHs released from permafrost in the Russian Arctic. The PAH concentrations in peatlands and frozen soils have been most extensively investigated in the Russian Arctic.[100–107] Concentrations of total PAHs reported in these studies range from 2.3 to 8500 ng per g dw. Predominant PAHs reported include naphthalene, pyrene, phenanthrene, chrysene, and benzo[*ghi*]perylene. Vasil'chuk *et al.*[108] studied the composition of PAHs from the soil material in ice wedges of the Yakutian yedoma (eastern Russian Arctic) and concluded based on the $\delta^{13}C$ values and PAH profiles (mainly naphthalene homologs and phenanthrene) that their origin was from plant residue and wildfires. Due to the low mobility of PAHs in an aqueous environment with a high content of organic matter, their vertical diversity in peat cores is strongly connected with the individual peat layers, the type of peat, and its total organic carbon content.[104–106] Vertical distributions in peat cores from remote locations indicate that PAHs can be of ancient origin although vertical distributions in core samples differ by location. While PAH concentrations in cores from the Komi Republic (Russia) exhibited constant concentrations with depth,[106] peat hummocks in the Seida River Basin (Russia) showed variability with depth, possibly due to percolation during the annual thaw.[101] Ji *et al.*[109] analysed soil profiles and noted that 5- to 6-ring-PAH concentrations as well as total organic carbon increased near the bottom of the active layer (Fig. 8), showing that permafrost is an effective barrier to these less water-soluble PAHs. However, the increasing depth of the active layer, caused by climate warming, may affect PAH movement, particularly of more soluble 2- and 3-ring compounds.

One of the key questions concerning PAHs in permafrost research is whether they have an atmospheric origin – and of what type. The published works indicate atmospheric accumulation from pyrogenic sources in both the past and the present (forest fires, grass fires, peatland fires, fossil fuel combustion; Table S2†). Gabov and Beznosikov[103] noted that the contemporary sources of PAHs in Arctic tundra soils are connected with atmospheric transport, deposition and accumulation in plant remains, mostly in the upper organic levels. Industrial sources of PAHs have also been monitored using surface soils and vegetation in the Russian Arctic. Yakovleva *et al.*[107,110] demonstrated a gradient of PAH concentrations in tundra soils and vegetation with distance from coal mines and a thermal power plant, exceeding background values by 2 to 5 times. Ji *et al.*[109] also reported declining concentrations of PAHs in soils sampled along a gradient from a major mining area in the Yamal region of Arctic Russia. Changes observed in the permafrost environment in the Russian Arctic, including the deepening of the active layer,[111] the shrinking of permafrost extent and the retreat of its respective zones,[112,113] give rise to assumptions that previously accumulated organic contaminants may be mobilized.

PAH levels and potential releases from permafrost have also been documented in northeast China and in Mongolia. Li *et al.*[114] studied PAHs in different layers of a permafrost core of northeast China and concluded that trapped PAHs in the ice-rich permafrost layer might thaw due to climate warming, which will result in PAHs accumulating upon the relatively non-permeable permafrost and migrating into underground water. Szopińska *et al.*[115] studied the release of PAHs from frozen soils into surface waters in a region of discontinuous permafrost in Mongolia. They found PAHs ranging from 36–365 ng L^{-1} with naphthalene, fluorene and phenanthrene constituting the major compounds in the total sum of 16 unsubstituted PAHs with a significant input to surface waters. Release of organic carbon due to permafrost degradation was identified in the lower parts of the rivers but sources of PAHs were complex and included groundwater, local surface erosion (*e.g.*, during the snow melt in spring) as well as riverine transport of suspended sediments.

2.3.3.2 PAHs released from permafrost in Svalbard, northern Norway and Iceland. Rivers draining permafrost catchments in the Hornsund Fjord region of southwestern Spitzbergen have been studied extensively for organic contaminant loads (Table S2†).[49,116–118] Stream outflow on the Fuglebekken River averaged 3.3 ng L^{-1} in summer sampling (2009), however, concentrations ranging up to 603 ng L^{-1} were found in some individual streams within the catchment, mainly due to the presence of higher levels of naphthalene.[118] Kosek *et al.*[49] reported increases in higher molecular weight PAHs in the rivers that may be related to permafrost thaw. Elevated concentrations of lower molecular weight PAHs (naphthalene, acenaphthene and acenaphthylene) were found in stream waters of the Revelva River catchment in June compared with September due to snow melt.[119] However, greater concentrations of anthracene and fluoranthene were detected in the Revelva River catchment in September compared to June at the time when permafrost and glacial thaw may have released them, and they co-occurred with an increased concentration of phenols and geogenic trace elements (Al, Ba) in the river waters.

A survey of PAHs in dated sediment cores from coastal lakes in northern Norway (Nordland, Troms and Finnmark) found increased concentrations from the 1950s to the mid-2000s.[120]

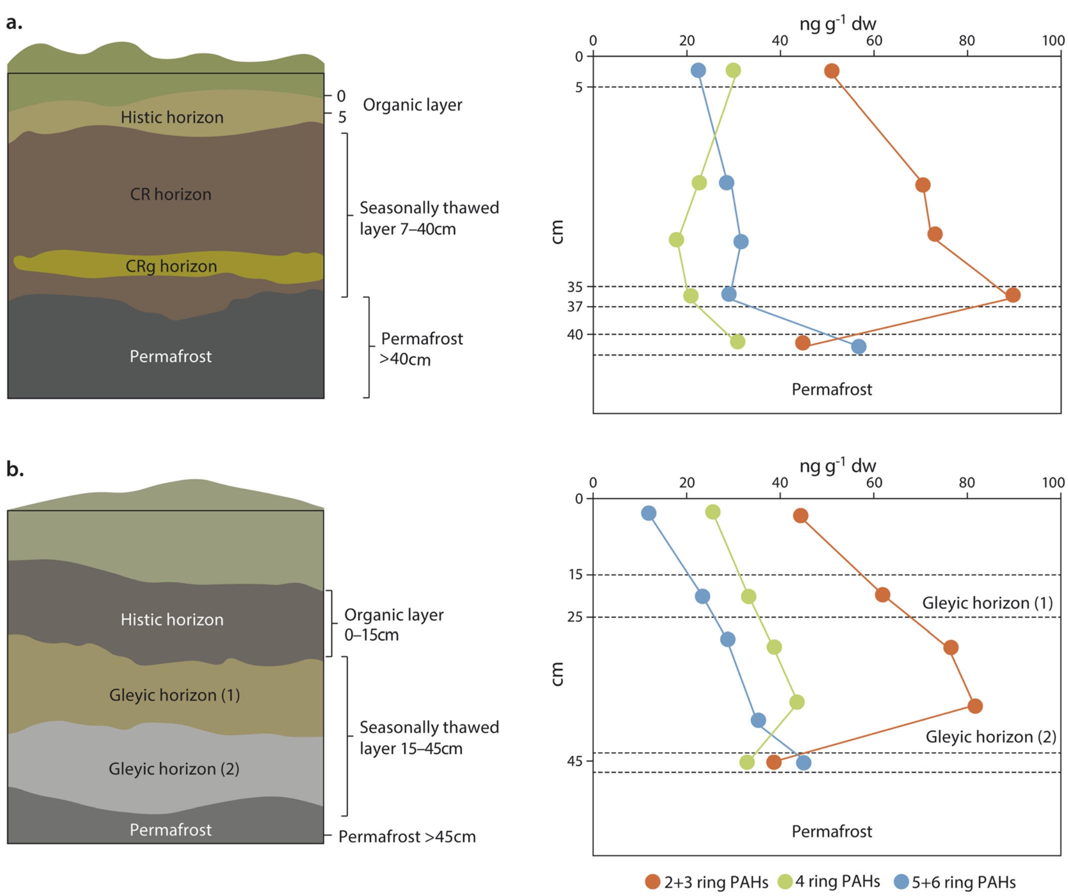

Fig. 8 Distribution of 2- to 3-ring, 4-ring, and 5- to 6-ring unsubstituted PAHs in vertical soil profiles from three soil groups in the Yamal mining area, Russia. Soils are defined as (a) histic glysol and (b) gleyic stagnosol. Reproduced from Ji *et al.*[109]

However, the authors did not attribute the increasing concentrations to climate warming or permafrost thaw. In Iceland, permafrost is found above 800 to 900 meters altitude in many parts of the high mountains and such areas comprise about 8% of the country.[121] The main permafrost areas close to settlements are in the north and east. Many farms and small towns in Iceland harness water from springs in mountain slopes gaining the advantage of gravity flow. Landslides often damage water intakes and these occur after heavy rain. Thus, the potential exists for similar inputs of PAHs from permafrost to surface waters. Landslides are discussed further under extreme events (Section 2.6).

2.3.3.3 PAHs released from permafrost in northern Canada and Alaska. Data for PAHs in permafrost soils of the North American Arctic are more limited than data from Russia and Scandinavia and mainly based on sampling and analyses in the 1980s and early 1990s. Steinhauer and Boehm[122] conducted a large survey of saturated alkanes and aromatic hydrocarbons in peat river sediments of coastal northern Alaska. Concentrations of total PAHs (including alkylated 2- and 3-ring compounds and perylene) ranged from 40–700 ng g^{-1} in peat and 40–640 ng g^{-1} in river sediments (Table S2†). Four- and five-ring PAH compounds were relatively more important components, representing 45% of the ΣPAHs in the peat samples. Yunker *et al.*[123] conducted similar studies of PAHs in coastal peat soils along the Canadian Beaufort Sea coast. Both studies noted the importance of coastal erosion along the entire Beaufort Sea coast and concluded that erosional inputs may be responsible for significant contributions of PAHs to the Beaufort shelf marine environment. The rate of erosion has accelerated since the 1990s along the entire Beaufort coast.[124] However, no information is yet available on PAH releases related to thawing permafrost in the region.

2.3.3.4 Conclusions on PAH inputs from permafrost degradation. A substantial amount of information is available on PAHs in Arctic peatlands and river and lake sediments. Layers enriched in PAHs are present in both mineral and organic-rich permafrost, and PAH burdens pre-date anthropogenic activity records due to a mix of PAH sources: plant material decomposition/peat accumulation and pyrogenic sources from biomass burning and volcanic activity to modern age fossil fuel combustion. Climate change and the deepening of the active layer may induce vertical migration of PAHs, and also increase in PAH migration *via* new groundwater paths (possible migration of contaminants into deeper aquifers and to other compartments of the environment). The 2- and 3-ring PAHs appear to be readily released into surface waters from permafrost thaw, while 5- to 6-ring PAHs are most likely accumulating at the bottom of the active layer.[109] However, since permafrost degradation involves thaw slump formation and coastal erosion, and thus sediment movement, all PAH constituents may become remobilized and transported out in significant amounts. The quantification of such remobilization remains a challenge.

Given the huge extent of the permafrost regions in the Arctic and limited measurements of PAH concentrations and fluxes major uncertainties exist with respect to the quality and quantity of PAHs and other pollutants in permafrost. Nevertheless, using the Schuster *et al.*[125] estimate of 472×10^9 t of C and assuming an average concentration of 18.5 μg per g C for 3 to 6-ring unsubstituted and alkylated PAHs (based on average PAH concentrations of 0.5 μg per g soil[101,126]), an estimated 8.73×10^6 t of PAHs are stored in the top 100 cm of Arctic permafrost soils and peatlands in circumpolar countries.[127] This is 15 times greater than the estimated annual emission of unsubstituted PAHs at their global peak in 1995 (5.9×10^5 t; ref. 128) and demonstrates the potential importance of releases from thawing permafrost at both local and global scale.

Future research should address not only constraining PAH remobilization fluxes and the factors driving them, but also provide information on the potential harmful impacts of such fluxes on ecosystems as well as water and food resources for Arctic Indigenous Peoples, and local communities, including through the agricultural use of permafrost soils.

2.3.4 PCB, PFAS and CEAC releases from permafrost. Reports of the presence or release of organic contaminants other than PAHs in permafrost are sparse. Recent data exist for PFAS and for PCBs in meltwater associated with permafrost soils. Distinguishing contributions from permafrost melt is challenging in the context of multiple sources of meltwater. For example, in the Lake Hazen watershed, the lake receives inputs from proglacial rivers, snow melt, and permafrost melt.[23] MacInnis *et al.*[24] noted elevated concentrations of perfluoroalkyl sulfonic acids, namely perfluorobutane sulfonate (PFBS), perfluorohexane sulfonate (PFHxS), perfluoroheptane sulfonate (PFHpS), and PFOS in glacial rivers compared to the open lake. Intensive study of the region led to the discovery of a permafrost seep.[129] Hydrologically, the permafrost seep was not a large contributor to Lake Hazen. However, the pattern of PFAS in the seep differed from that in the proglacial rivers and snow.[24] PFHxS and PFBS were more prominent in water at an upstream site influenced by the permafrost seep. The authors concluded that climate warming induced the deepening of the soil active layer and that warmer temperatures promoted the release of PFAS from ice in the active layer.

Szopińska *et al.*[115] detected dibutyl phthalate, tetrachloroethylene (TCE), long chain alkanes (*e.g.*, pentadecane), and fatty acid esters in water samples from sites on the Baydrag–Böön Tsagaan and Shargalyuut/Tuyn–Orog systems in Mongolia's Valley of the Lakes (45°00′N 99° 00′E to 46°30′N 101°00′E) that were influenced by discontinuous permafrost. Sources such as agricultural activity could have contributed to the presence of phthalates and other organic contaminants. While not in the Arctic, the site shows potential for various industrial chemicals to be found in permafrost thaw.

Eickmeyer *et al.*[130] found that slump-affected lakes in the Mackenzie Delta (Northwest Territories, Canada) had significantly higher total organic carbon (TOC) normalized concentrations of ΣPCBs, HCB and ΣDDT than nearby reference lakes that were unaffected by thaw slumps. The concentrations of POPs were positively correlated with mean sedimentation rate across lakes. Fluxes (ng per m^2 per year) of POPs in dated sediment cores from slump affected lakes were higher and more variable compared with reference lakes due to two-fold higher

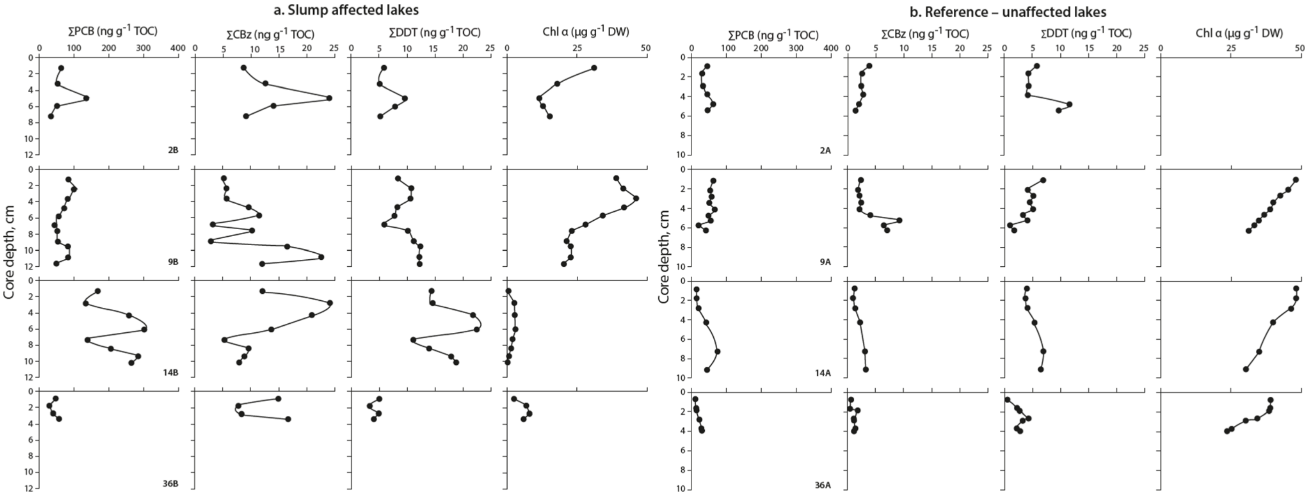

Fig. 9 Temporal distributions of ΣPCB, sum of tetra-, penta- and hexachlorobenzenes (ΣCBz), ΣDDT concentrations (ng g^{-1} TOC), inferred chlorophyll a concentration (μg g^{-1} dry weight) in (a) lakes affected by permafrost thaw slump activity, and (b) nearby unaffected reference lakes in the Mackenzie River Delta uplands, Canada.[131]

average sedimentation rates[131] (Fig. 9). The hypothesis that algal-derived organic C, which could increase with increases in lake primary productivity, would also increase the delivery of organic pollutants was not confirmed: fluctuations in the deposition profiles of POPs generally did not coincide with changes in chlorophyll a or algal-derived C.

Polkowska *et al.*[118] detected PCBs in stream waters of the Fuglebekken River catchment that drains into Hornsund Fjord, near the Polish Polar Station (Svalbard). Total PCBs (sum of 7 congeners) averaged 4.3 ng L^{-1} in the outflow stream and much greater concentrations were observed in some smaller tributary streams (3.9–406 ng L^{-1}). These concentrations were also elevated compared to the waters in Hornsund Fjord, where Σ_7PCBs averaged 0.116 ng L^{-1} (range 0.01 to 0.38 ng L^{-1}, dissolved phase) based on sampling in 2015–2016. Overall concentrations of PCBs in Hornsund, Kongsfjorden, and Adventfjorden (Svalbard) were over 100-fold higher than reported in the open Arctic Ocean.[132] However, these higher levels could not be clearly attributed to permafrost thaw, but are probably best explained by a combination of local sources (*e.g.*, wastewater entering Adventfjorden and ship traffic) and secondary sources from glacial and permafrost inputs.[21]

2.3.4.1 Case study of trends of POPs in permafrost impacted lakes. A long term study of two lakes on Melville Island in the Central Canadian archipelago documented declining conditions of Arctic char (*Salvelinus alpinus*) at Cape Bounty associated with increased turbidity of lake waters.[133] One of the lakes (West Lake) is impacted by permafrost degradation as well as subaqueous slumps which together have increased turbidity 50- to 100-fold compared to the nearby East Lake which has undergone little change.[134] Cabrerizo *et al.*[135] compared concentrations of PCBs and OC pesticides in river water from the West Lake catchment with the East River. PCB concentrations were similar in both rivers during the snowmelt period in mid-June (Fig. 10). PCB homolog profiles were also similar suggesting a similar source such as snow melt runoff. However, in the brief snow free summer period during July, concentrations and PCB homolog profiles differed between the two rivers. Much higher concentrations of dissolved and particulate PCBs and OC pesticides were observed in West River while lower proportions of di-, octa- and nonachloro-PCBs were found in the East River water, suggesting differing sources. Atmospheric deposition to these remote catchments is the only source of POPs.[135]

Higher concentrations of PCBs on SPM were also detected in the water column of West Lake (sum of 70 congeners (Σ_{70}PCBs) = 75 pg L^{-1}) in comparison to East Lake (where the Σ_{70}PCBs was 1 pg L^{-1}). West Lake has been impacted by several subaqueous slumps since 2007 which may be related to permafrost degradation.[133] Thus, the source of higher PCBs is likely a combination of greater catchment inputs and higher SPM in the lake. The higher amount of PCBs, entering West Lake with SPM, has also led to higher PCB concentrations in zooplankton, fish stomach contents, and char[135,136] (Fig. 11). In addition, concentrations have increased over time (Fig. 11A). In contrast, no difference was observed between the lakes in PFOS (Fig. 11B). The food webs from both lakes were similar and simple, with Arctic char at the top of the food web.[133,137]

Whether this effect on POP levels in lake water and biota is also observed in other turbid lakes or thermokarst-impacted lakes is unknown. Since 288 lakes were identified as being impacted by retrogressive thaw slumps in the study by Lewkowicz and Way,[91] the phenomenon might be more widespread than currently known.

2.3.5 Thawing permafrost and legacy industrial contamination. As discussed for PAHs, contaminants in permafrost can originate from combinations of long-range transport and locally used chemicals. The assumption that permafrost is a long-term stable environment[95,96] caused widespread practices of intentional storage of industrial and post-industrial solid and liquid waste (including radioactive waste), on and in permafrost in the Arctic.[3] Oil and gas exploration sumps rely on the presence of

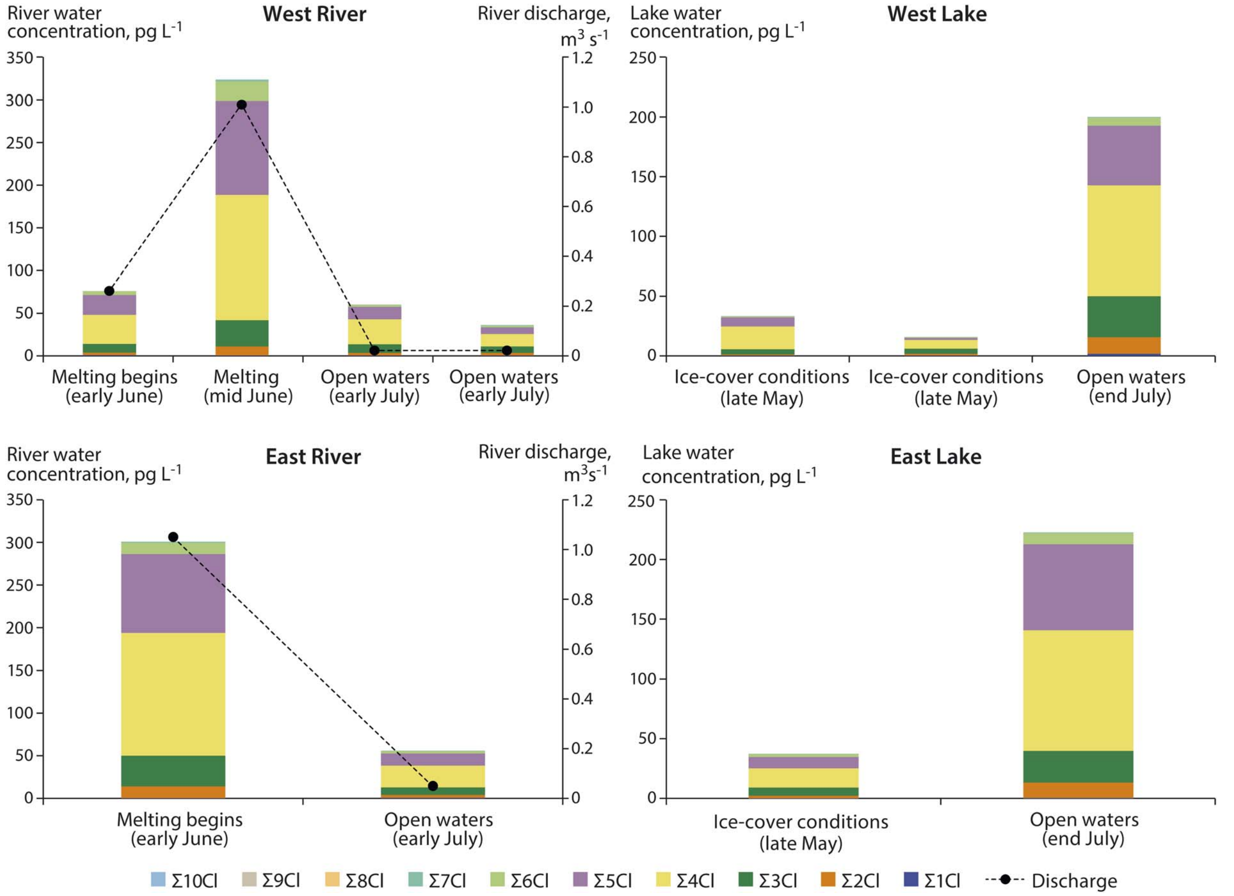

Fig. 10 PCB concentrations (sum of 70 congeners of varying chlorination level, Cl_1 to Cl_{10}) in dissolved phase during snowmelt runoff (mid-June) and ice free conditions (mid-July) in West and East Rivers on Melville Island, 2016. Redrawn from Cabrerizo *et al.*[135]

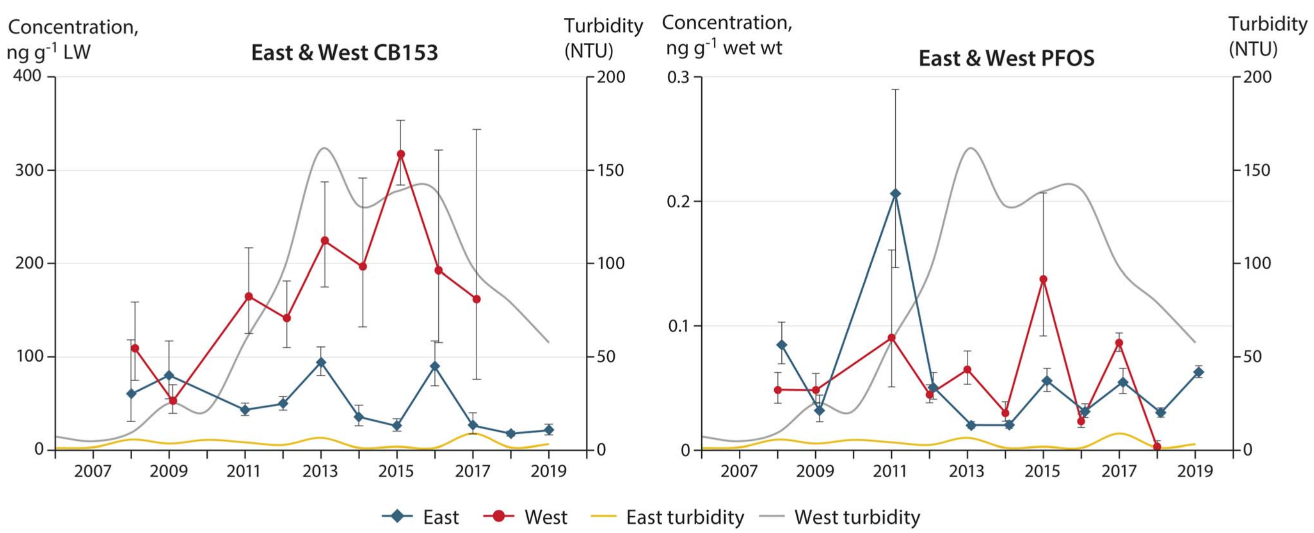

Fig. 11 Long term trends in concentrations of (A) hexachlorobiphenyl PCB153 (ng per g lipid weight (LW)), and (B) perfluorooctane sulfonate (PFOS) (ng per g wet wt) in muscle of landlocked Arctic char from West Lake and East Lake (Melville Island, Canada) (Cabrerizo *et al.*[135] and unpublished data). The trends of turbidity (NTUs) in West and East Lake are also shown.

permafrost to prevent migration of drilling wastes into the surrounding environment.[138,139] Failure of permafrost as a waste containment medium may cause impacts to freshwater sources in sensitive tundra and sub-Arctic environments.[139] Elevated chloride levels indicated movement of water-soluble drilling waste components near a sump compromised by permafrost degradation, but PAH concentrations were not elevated.[139] Substantial subsurface movement of petrogenic PAHs after legacy fuel spills into an area of continuous permafrost may also occur despite the permafrost barrier.[140,141]

In the Russian Arctic, eight main types of dumps and waste storage exist in the permafrost zone.[95] These are: industrial waste storage facilities (slag, sludge and tailing dumps, ash dumps); dumps of rock in mining sites; household waste accumulations; dumps of wood processing waste in the centers of the timber industry; abandoned residential and industrial buildings resulting from a decrease in the population of northern settlements; storage areas for fuels and lubricants; tank farms for storing petroleum products in settlements and cities of the north; and storage areas for contaminated snow exported from built-up areas.[95]

Hjort *et al.*[83,142] estimated that 120 000 buildings, 40 000 km of roads and 9500 km of pipelines are located in permafrost areas of the Northern Hemisphere (Arctic region and Tibet), and that 75% of the current population in permafrost areas may be affected by damage to infrastructure associated with permafrost thaw. Hjort *et al.*[83] estimated that 80% of the oil pipeline infrastructure in the Russian Arctic and 35% in the North American Arctic would be susceptible to ground instability from near-surface permafrost thaw by 2050. As a result, oil spills could become more frequent.

Langer *et al.*[3] collected information on the number and location of industrial and post-industrial sites in the circumpolar Arctic, estimated the number of contaminated sites, and compiled a database of those in the permafrost dominated region of the Arctic (*i.e.* where permafrost occurrence probability exceeded 50%). The authors also collated predictions on permafrost degradation in a range of climate change scenarios. This information enabled a discussion of the hazards related to contaminant remobilization (including POPs) into the environment in the 21st century.

Due to the database omitting pipeline networks of oil and gas transportation (9500 km of pipelines in the Arctic and Tibet, according to Hjort *et al.*[83,142]) and the underestimation of results as compared to the Sentinel-1/2 derived Arctic Coastal Human Impact (SACHI) dataset by 40 ± 20%, the authors claimed that the number of industrial sites in their study is not exaggerated (their estimate may be conservative). Langer *et al.*[3] also analysed the existing data on the locations of contaminated sites in Alaska and Canada. Based on the relationship between the occurrence of industrial sites and contaminated locations within the permafrost extent in North America, they extrapolated the probability of finding contaminated sites in other parts of the Arctic where detailed records on contaminated sites were not available (*i.e.*, Russia, Greenland, and Svalbard).

The authors identified in the permafrost-dominated regions about 4500 industrial sites contaminated by potentially hazardous substances related to industrial activities. The results suggest that depending on the adopted model (PPM1 or PPM2; see Fig. 12), within the extent of the identified industrial sites the number of contaminated locations may amount to between 13 000 and 19 900.[3] Between 65 and 75% of these sites (depending on the adopted model) were located in Russia (Fig. 12). Notably, the density of contaminated sites in various parts of the Arctic is similar (Fig. 13), with the least contribution of the non-glaciated coastal parts of Greenland, the glaciated mountains of Alaska, fragments of eastern Canada, and the Krasnoyarsk Region in Russia (areas marked in yellow in the map, Fig. 13).

The analysis of detailed data on the contaminated sites in Alaska shows that the most numerous are connected to industrial processes and products (*e.g.*, mines and energy sectors such as oil and gas extraction). The latter two categories were responsible for >50% of contamination but only represented 16% of all contaminated sites in the permafrost region of Alaska. On the other hand, as much as 21.3% of contaminated sites were classified as having an uncertain source of contamination.[3] The contaminants identified in Alaska were in almost half of all cases related to fuels: diesel fuel, petroleum, kerosene, and gasoline. They included PCBs and PAHs (especially naphthalene and 2-methylnaphthalene) as well as other hydrocarbons, such as BTEX (benzene, toluene, ethylbenzene

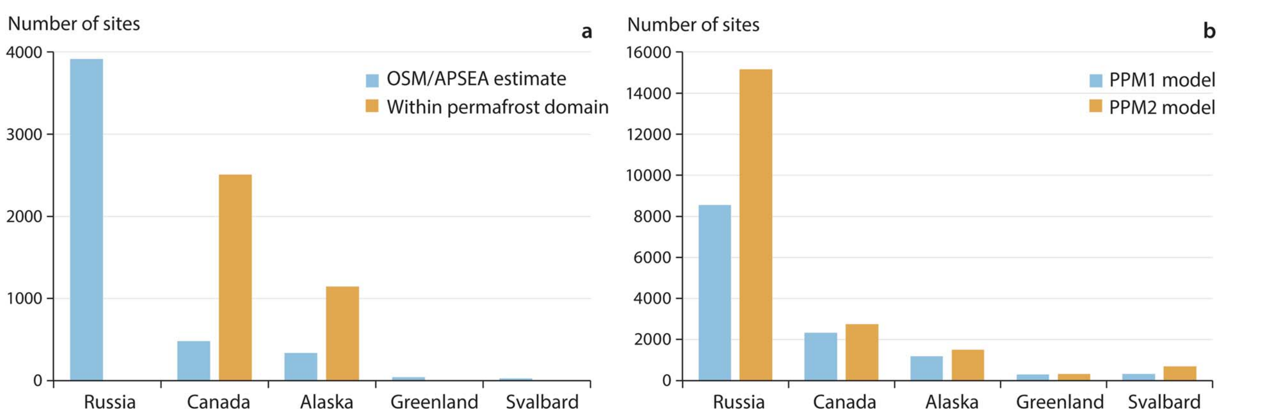

Fig. 12 The numbers of industrial and contaminated sites within the permafrost dominated region of the Arctic from Table 1 in Langer *et al.*[3] (a) Number of contaminated sites identified using OpenStreetMap (OSM) in combination with a spatial dataset on industrial facilities from the Atlas of Population, Society and Economy in the Arctic (APSEA), and (b) results from Poisson Point Models that represent the lower (PPM1) and upper (PPM2) bounds of the observed relationships between spatial densities of industrial sites and contaminated sites. Note that scales differ between (a) and (b).

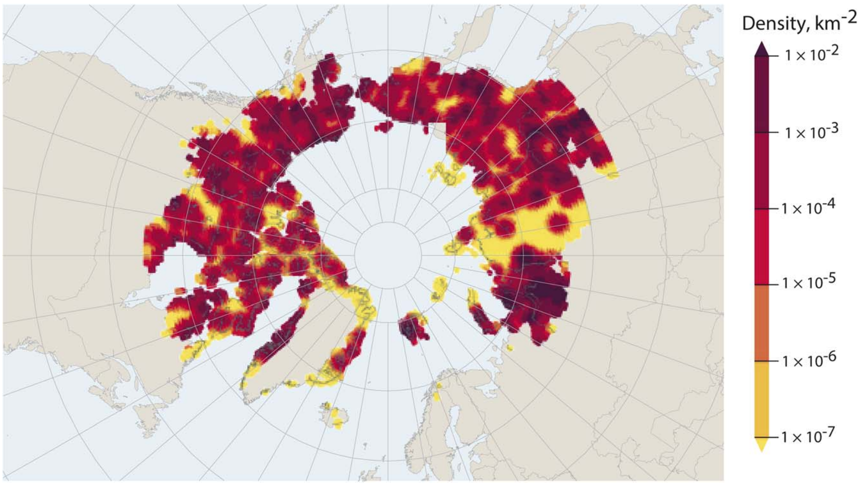

Fig. 13 Pan-Arctic map from Langer *et al.*[3] with estimated contaminated site density. Note that the speckled appearance results from the regional clustering of industrial sites combined with the chosen bandwidth (50 × 50 km) of the Gaussian density filter used for the Point Process Models. The Pan-Arctic section of the original figure is reprinted with copyright permission.

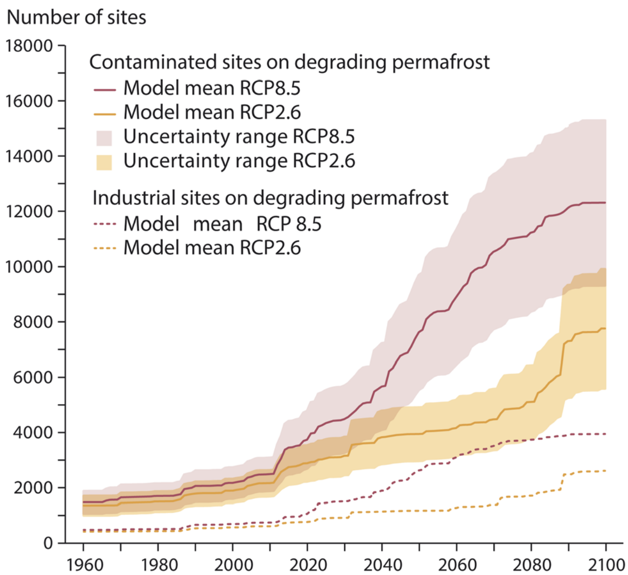

Fig. 14 The potentially growing number of industrial sites and the number of upscaled contaminated sites located in the permafrost-dominated region that could be affected by permafrost thaw based on RCP 2.6 and RCP 8.5 warming scenarios.[3] The shaded areas show the uncertainty range due to the spatial extrapolations used in the modelling. Reproduced from Langer *et al.*[3] with copyright permission.

and xylenes), trichloroethylene, TCE, and 1,3,5-trimethylbenzene.

Langer *et al.*[3] applied two climate change projections for the Arctic by CMIP5 models, *i.e.* the low (CCSM447) and high (HADGEM2-ES48) warming scenarios, run for low (RCP 2.6) and high (RCP 8.5) emission scenarios. They estimated the number of industrial and contaminated sites likely to be affected by climate-induced permafrost thaw before 2100 (Fig. 14). Approximately 220 of the current industrial sites and 440–960 (±4%) of the estimated ones are located in the areas with possible permafrost degradation (for the year 2020). For both of the above climate change scenarios, the number of industrial and contaminated sites in the permafrost degradation zone will be large (~50% until 2050 and ~100% until 2100 in the high greenhouse gas emission scenario, RCP 8.5, and ~50% until 2100 in the low emission scenario, RCP 2.6).

2.3.5.1 Conclusions on industrial sources from permafrost degradation. Although high uncertainty pertains to the number of industrial and contaminated sites, and also types of contaminants, the risk of destabilization of these sites on permafrozen ground is elevated. Langer *et al.*[3] indicate also that the impact of chemicals on permafrost thaw (*e.g.*, by introducing anti-freeze agents into the ground ice from contaminated sites) is under-appreciated. The co-occurrence of mechanical damage to infrastructure and intentional chemical waste storage sites enhances the risks of contaminant introduction into the environment, but also leads to a high uncertainty in predictions. To more fully assess the risks, a database is needed of polluted sites across the Arctic. Currently such databases are available only for Alaska and Canada, with more limited records for Greenland, Iceland, and Svalbard. Obtaining detailed information for the Russian Arctic is particularly challenging.

The risks related to the remobilization of POPs and CEACs from waste sites and other locations of deliberate storage of chemicals should also be included in climate-related risk management policies and strategies implemented in the Arctic. The remobilization hazard needs to be considered especially with respect to impacts on the aquatic environment, where instances of remobilization of legacy POPs have already been observed. The impacts of hydrologic changes on remobilization and bioavailability of POPs and CEACs in the future Arctic requires further insights.

2.4 Wildfires in the Arctic

Climate change has already increased the frequency of wildfires in the Arctic as it is warming faster than the rest of the globe.[1,143–145] McCarty *et al.*[143] concluded that climate change will enhance Arctic fires by increasing the frequency of extreme fire weather. A higher frequency of wildfires may also occur due to increased anthropogenic activities such as tourism, agriculture, forestry, and energy extraction in areas previously devoid of these activities.

During wildfires significant amounts of organic chemicals, such as PAHs, are released from burning vegetation and deposited into soil. The deposition flux of PAHs can vary depending on the vegetation and fire severity.[146] PAHs and volatile organic compounds (VOCs) such as BTEX and toxic compounds that occur naturally in soil and plants are released during fires. All are highly concentrated in the ash layer that remains following major wildfires.[146,147] The ash from burned vegetation can be infiltrated into groundwater especially during heavy rain and flooding, and smoke can be distributed over large distances and residues eventually enter the groundwater. Volatile compounds can be transported to other locations, including the Arctic, which can result in contamination of otherwise less impacted environments.[127]

Wildfire frequency within the region north of the Arctic Circle increased over the period 2012 to 2019.[148] Using a global atmospheric model for POPs, Song *et al.*[145] estimated that local (within the Arctic Circle) wildfire biomass emissions were the largest source of benzo[*a*]pyrene (BaP) in the Arctic, accounting for 65.7% of its air concentrations. Song *et al.*[145] also estimated that wildfires in the northern hemisphere had increased atmospheric inputs of BaP to the Arctic by eight-fold between 2011 and 2020. The greatest increases in wildfire frequency were in Russia, with lesser increases in Alaska, Canada, and Norway.[148] Proximity to roads increased active fire frequency, implying that most fires were caused by human activity. While increased frequency of wildfires has been documented in the Arctic as well as in boreal forests south of the Arctic,[143] the tundra biome has been historically characterized by a general lack of wildfire activity.[149] During the period 2002 to 2013, 0.48% of the Alaskan tundra burned, while the estimate for the circum-Arctic is 0.12% (Fig. 15). The majority of the burned tundra is in the Russian Arctic and is associated with areas of higher mean summer temperatures.[149] Including all areas above the Arctic Circle, about 13 M ha, consisting mainly of peatland tundra, burned over the period 1982 to 2020, with 71% of the fires in the Siberian Arctic.[150]

Gosden *et al.*[151] investigated tundra fires in western Greenland for the period 1995 to 2020 using satellite remote sensing and found 21 fires since 2008, whereas none before that time. Most fires occurred in July and August. Human activity was thought to be the ignition source for most of the fires. Two municipalities near Sisimiut, the second largest community in Greenland, experienced especially large wildfires in July 2017 and July 2019. These fires varied in fuels and burning behaviour from other high northern latitude fires due to unique flora in the area, specifically the lack of extensive grasses, shrubbery, or vascular vegetation, and presence of deep vertical beds of C-rich humus.[152]

Paul *et al.*[153] reviewed the literature on impacts on water quality from wildfires and found that nutrients, ions, organic chemicals (in particular PAHs), and metallic compounds increased in burned watersheds, sometimes by orders of magnitude over pre-fire conditions. Some exceeded guideline values for aquatic life criteria or drinking water regulations, for example benzene. However, the duration of effects were less than five years. Kieta *et al.*[146] reported that the most severe impact occurred one to three years after the fire, but little research has been undertaken to determine the long-term

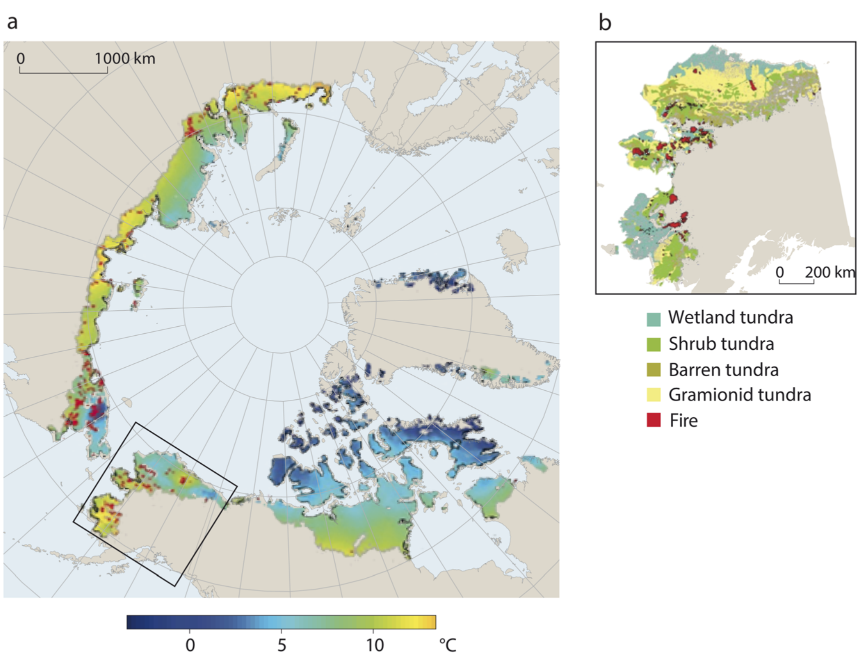

Fig. 15 Wildfires and climate in circumpolar Arctic tundra. (a) Mean summer average temperature and (b) spatial distribution of Alaskan tundra fires from 1950–2013. Red points in (a) and (b) represent burned-area estimates between 2002 and 2013 (reproduced from Hu *et al.*[149]).

persistence of PAHs in the aquatic environment after wildfires. Jones *et al.*[154] found that increased wildfire frequency in tundra zones contributed to enhancing thermokarst in permafrost areas in the seven years directly after a fire event (34% subsidence in the burned areas against 1% subsidence in similar areas not exposed to wildfire). While not directly connected to emissions of PAHs or other contaminants, the results from Jones *et al.*[154] highlight the feedback between two important sources of emissions related to climate change: permafrost thaw and wildfires.

While PAHs have been extensively investigated in relation to the increased frequency of wildfires impacting the Arctic,[70,145] it is possible that increased atmospheric emissions of chlorinated POPs could be co-occurring with the PAHs. PCBs, HCB, chlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), and pentachlorophenol have been shown to be produced during biomass combustion *via* "*de novo* synthesis" involving chlorination of carbon and oxidative degradation of the chlorinated carbon matrix.[155,156] In addition these POPs can be revolatilized from burning vegetation that they were previous absorbed to.[157] Elevated atmospheric concentrations of PCBs at Ny-Ålesund, in Svalbard, have been associated with smoke from wildfires.[158] HCB concentrations increased at Ny-Ålesund over the period 2005–2016 based on long term passive air sampling while PCBs did not show a significant trend in the same study.[159] Song *et al.*[160] concluded that global emissions of PCDD/Fs had remained relatively constant over the period 2010 to 2018 which they attributed to an increasing significance of wildfire contributions to the total annual emissions. However, the relative importance of wildfires, compared with other atmospheric sources for chlorinated POPs in the Arctic has yet to be determined.

Use of wildfire suppression chemicals could also be an increasing source of CEACs[161] as wildfire frequency in northern boreal and tundra increases. Although fire suppression chemicals mainly contain inorganic components (*e.g.* ammonium phosphate) some formulations also include surfactants, synthetic dyes and corrosion inhibitors.[162] The latter may be used on wildfires close to settlements and industrial installations, and if there is immediate danger to humans.[163]

Zooming in on the situation in Iceland, higher air temperatures and more intense precipitation are predicted in Iceland due to climate change, but also longer and more intense periods of drought. There are indications that the intensity of rainfall has increased and, despite the increase in total rainfall, the number of dry days may also increase.[164] Climate change is likely to increase temperatures in Iceland by 1.3–2.3 °C by 2050 and the warming is expected to be greater in winter than in summer.[165] The consequences are increased growth in vegetation, grass, shrubs, and trees. This leads to overgrowth that can fuel large fires during drought. The Icelandic Institute of Natural History has registered wildfires in Iceland since 2006, when the largest recorded wildfire in Iceland's history raged in 6700 ha of sedges and shrubs of a wetland.[166] Since 2006, 26 large wildfires have been registered and most of them occurred in the months of March to May.[167] Research on impacts from the 2006 wildfire on aquatic environments did not indicate significant long-lasting impacts on lakes in terms of water quality or effects on biota.[168]

A large wildfire took place in May 2021 within the primary water protection zone for the capital area of Iceland.[169] Results of analyses of samples taken one week after the fire showed that the main organic pollutants were PAHs and VOCs, mainly BTEX, which occurred in two- to fivefold higher concentrations than the median values during the previous two decades. Regular monitoring since 2002 had never previously detected PAHs in samples from the supply area. However, the detection limit was typically higher by an order of magnitude in the older samples (before May 2021) than it was after the fire. Of the eleven boreholes that were tested after the fire, PAHs were found in four boreholes in two areas (VK and G–J in Fig. 16). VOCs were also detected. The total sum of the five PAHs detected a week after the wildfire ranged from 1.1–7.3 ng L^{-1} (Fig. 16A). The three carcinogenic PAHs dibenz[*ah*]anthracene (DahA), benzo[*ghi*]perylene (BghiP) and indeno[1,2,3-*cd*]pyrene (Ind) were only detected in boreholes of the lower intake area (G–J). Naphthalene and phenanthrene were found at VK and G–J. In the samples taken five months later (19.10.2021), and then at all three water intake zones (VK, ML, G–J), only naphthalene was detected at VK, nearest to the fire (1.1 ng L^{-1}). After this wildfire incident, the water utility developed a wildfire emergency response plan including a post-fire sampling plan.[169]

2.4.1 Conclusions on wildfires. Wildfires are clearly important sources of organic contaminants to the Arctic, as also discussed in Hung *et al.*[70] With PAH emissions in circumpolar countries predicted to decline due to reduction in fossil fuel use, wildfires are likely to play a larger role in terms of Arctic PAH contamination due to increased frequency.[148] The extent to which wildfires may enhance emissions of other contaminants, *e.g.* PCBs, HCB and PCDD/Fs that may be formed as combustion byproducts or revolatilized from burning vegetation, has not been studied much. Faster warming within the Arctic compared to the neighboring forested sub-Arctic and north temperate regions may mean that more of these emissions could originate from within the Arctic rather than from long-range transport. In particular, the increased frequency of tundra fires within the Arctic is a growing concern for communities above the treeline.[149] For example, tundra fires may impact winter forage for caribou and reindeer (*Rangifer tarandus*), which are important traditional food sources for Arctic Indigenous Peoples. With fire frequency above the Arctic Circle being connected to human activity, it is apparent that future expansion of infrastructure could contribute to greater emissions of PAHs from fires within the Arctic as well as uses of fire suppression chemicals, which can contain surfactants and anticorrosion chemicals that may be used for fires close to human settlements or industrial infrastructure. There is also a concern about atmospheric deposition of soot particles and associated organic contaminants in surface waters that are drinking water supplies. While the fire event in Reykjavik's primary water protection zone did not permanently contaminate the aquifer, the incident has clearly shown that aquifers, not just surface waters, are also vulnerable to wildfires and to contamination by combustion byproducts such as PAHs.

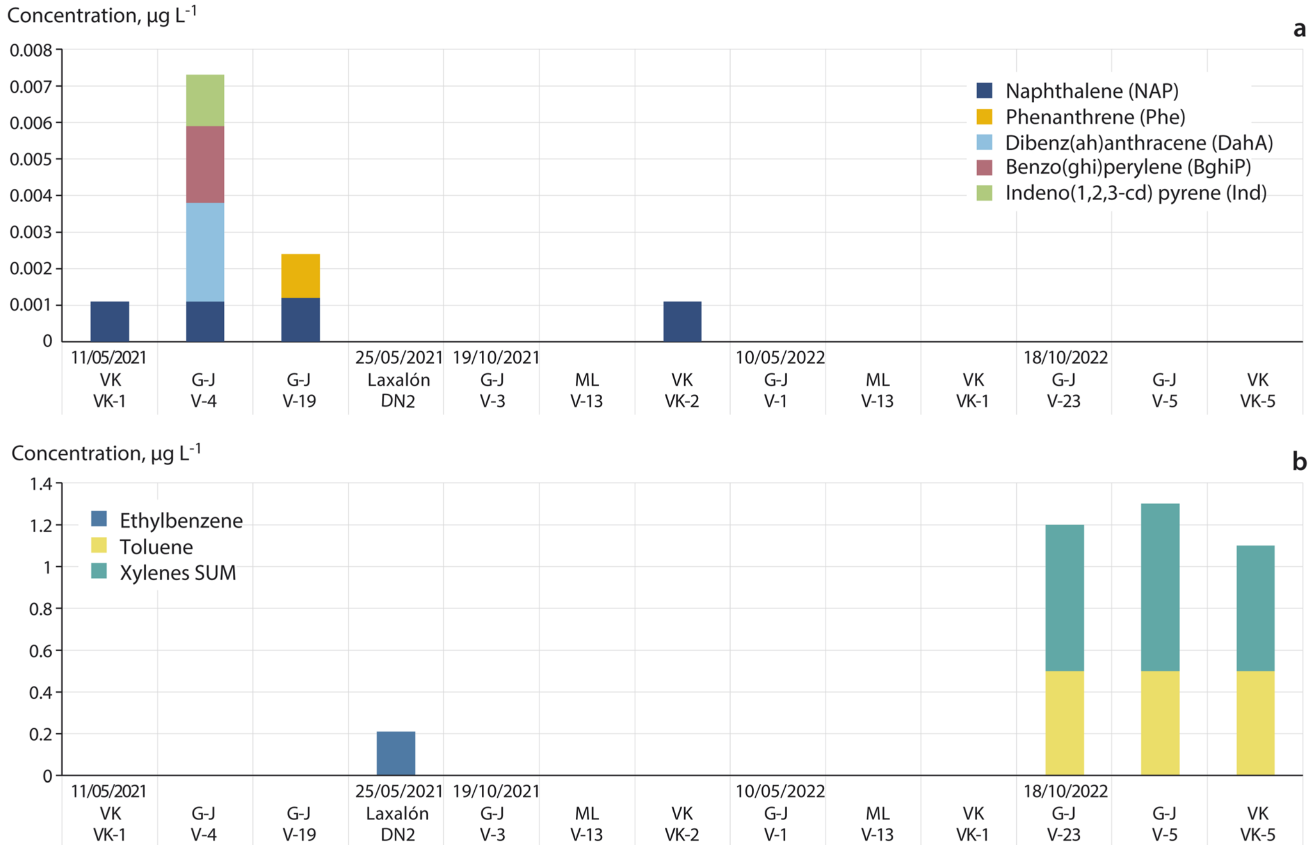

Fig. 16 (a) PAHs detected in samples (μg L^{-1}) from four boreholes at two water intake zones after a wildfire incident. (b) BTEX detected in water samples (μg L^{-1}) during 2021 and 2022 at multiple sampling times after a wildfire incident (DN = drinking water from the distribution network).[169]

2.5 Climate change, eutrophication, and drinking water contamination

Emerging concerns regarding water vulnerability in Arctic households include impacts of climate change on freshwater supplies, water systems, and infrastructure affecting water access,[170] as well as on contamination of water supplies by pathogens.[171] Drinking water quality for local communities is also a concern,[172,173] although not specifically focused on organic contaminants. Most chemical measurements in drinking waters of Arctic communities are for basic water quality parameters[174] and for toxic elements such as arsenic and lead.[175] Water treatment (such as with ultraviolet radiation, ozonation or chlorination) reacting with organic constituents could also generate byproduct chemicals of concern. Chemical contamination of drinking water due to mobilization of legacy contaminants from mining and former industrial sites has increased.[175,176]

An increase in temperature will lead to more frequent unusual weather patterns, such as more rainfall in some areas which increases water reserves, but more water shortages in others.[177,178] Most Arctic communities rely on nearby surface waters for their primary water supply, and thus climate warming is likely to have an impact on quality and quantity of the supply.[179] Surface waters account for 50% of drinking water sources in Alaska[170] while all communities in Nunavut,[180] Greenland,[181] and the Russian Arctic, as well as major communities in Norway and Finland,[182] rely on surface waters due to limitations of ground water access in permafrost terrain. Iceland relies almost entirely on groundwater for public supplies.[182] A report on drinking water infrastructure in the 205 Inuit communities of Alaska, Canada, and Greenland found that about 55% did not have piped water.[183] In the Eastern Russian Arctic, 50% of the settlements in Yakutia and 25% of settlements in Chukotka have no regular water supply.[184] The communities across the Arctic without piped water typically rely on untreated lake or river water in summer as well as storage tanks. Some communities rely on melted ice when storage is depleted.[175] These communities are particularly vulnerable to impacts on water quality and supply related to climate warming. Two examples are provided below.

Grise Fiord, Canada's most northern community, replenishes its two supply tanks annually with over 7×10^6 L of water from snow melt including melting snow from nearby glaciers.[174] The Grise Fiord watershed is 39 km^2 and contains four glaciers ranging from 0.12 km^2 to 5.69 km^2. The community is concerned about sustainability of the water supply due to glacier melting and impacts that increased freshwater inputs will have on the marine environment that they depend on for traditional foods.[185,186]

Similarly in Qaanaaq (Greenland) the drinking water is supplied by a river receiving glacial meltwater during the four summer months.[181] Two large water tanks are filled which provide a supply for another four months. In late winter and early spring months, iceberg ice collected near the village is crushed, melted and cleaned in a special facility connected to the distribution network to provide water to the community. The community is concerned about thinning of sea ice which has made collection of ice for drinking water more dangerous.[181]

More broadly, climate warming is impacting key ecosystem attributes and processes in Arctic freshwater environments. For a detailed overview of the impacts of climate change on Arctic terrestrial hydrology and lake ecosystems, readers are referred to other reviews.[80,81,187,188] Of relevance to POPs and CEACs in the waters and food webs of Arctic lakes and rivers are changes in primary productivity, altered biogeochemical cycles and chemical transport, altered seasonality, species gains and losses, and changes in trophic relationships. In addition to permafrost thaw, these changes are driven by declining lake ice cover, increased early and late season precipitation in the form of rain, and increasing average annual and summer air temperatures.

A general decline in the duration of ice cover has been observed in Arctic lakes with areas >1 km^2. Šmejkalová *et al.*[189] surveyed satellite imagery for 13 300 lakes across the circumpolar Arctic and found trends towards an earlier break-up ranging from −0.6 days per year in northern Alaska to −0.1 days per year in northern Scandinavia over the period 2000–2013. Lakes of this size generally have fish populations, with salmonids, especially Arctic char predominating in regions above the tree line.[190–192]

The extended open-water season and increased load and concentrations of nutrients and dissolved organic carbon (DOC) are elevating the productivity of Arctic and sub-Arctic lakes.[193–195] These changes could impact the concentrations of POPs and CEACs in surface waters and bioaccumulation in freshwater food webs. The possible effects on bioaccumulation of POPs and CEACs under these conditions have not been investigated in detail, but correlations have been found between air temperatures and levels of α-HCH as well as ΣPCB in land-locked Arctic char in Greenland.[196] However, Cabrerizo *et al.*[197] observed a negative correlation between POP levels in Arctic char in the Canadian Arctic and chlorophyll a levels, whereas Ahonen *et al.*[198] showed that age-adjusted mercury concentration in fishes was related to increasing lake productivity in a latitudinal gradient of sub-Arctic lakes in Finland.

2.5.1 Conclusions on drinking water contamination. The impacts of climate warming on sub-Arctic and Arctic surface waters are an important issue for most Arctic communities. Increases of parameters such as turbidity, toxic metals, chlorophyll, and DOC might be correlated with greater inputs of POPs and CEACs from secondary sources in river and lake catchments. Previous assessments[6,199,200] have mainly focused on contamination of freshwater environments by POPs and CEACs that are persistent and bioaccumulative. However, emerging concerns related to impacts of climate change on surface water quality suggest that there should be more focus on persistent mobile organic contaminants (PMOCs) in the Arctic. PMOCs are generally highly polar (mobile in water) substances that can pass through wastewater treatment plants and also through drinking water treatment processes.[201] Sühring *et al.*[202] suggested that models of long-range environmental transport potentially could be modified to include the pathways of PMOCs (*e.g.*, riverine transport). In addition, the secondary release of PMOCs from permafrost and glaciers needs to be included.

2.6 Extreme climate events and natural disasters

2.6.1 Overview of extreme climate events. Extreme events, which grow in frequency and severity with climate warming, pose unique hazards in the Arctic.[203,204] The loss of sea ice areal extent (40% in summer) and thickness is one of the key precursors that amplifies other impacts.[204] Until recently, sea ice retreat during the summer and fall was insufficient in timing and extent in much of the Arctic to create enough fetch for storm surges and consequent coastal erosion and flooding.[205] Coastlines that have been protected by sea ice and land-fast ice for thousands of years are now vulnerable to erosion, with significant impacts on communities, infrastructure, and contaminated sites. Permafrost thaw contributes to the problem, along with increasing rainfall and sea level rise.[205,206] Here we briefly review coastal erosion, landslides, and flooding, and the potential for release of POPs and other organic contaminants.

2.6.2 Coastal erosion. Coastal erosion has become pronounced throughout much of the Arctic, with considerable regional variability and increasing intensity.[124] Erosion is influenced by many factors including site characteristics, sedimentology and ice content of coastal terrain, and environmental variables such as temperature and storm intensity.[207] The Alaskan and Canadian Beaufort coasts show the greatest rates of erosion in the circumpolar region (Fig. 17A) mainly due to eroding permafrost bluffs. High erosion rates have also been observed in non-permafrost coasts of the Barents and Kara Seas as well as in the permafrost shoreline of the Laptev and East Siberian Seas (Fig. 17A). For example, the Beaufort Sea coastline of Alaska has eroded at a rate >1 m per year over a 60 years period at almost half of the examined locations, compared with approximately 10% of sampled locations along the Chukchi Sea, and short-term rates of erosion exceed long-term rates.[209] Coastal erosion rates are projected to increase and likely exceed the historical range of variability by 2100 (Fig. 17B).[124]

The U.S. Government Accountability Office found in 2003 that 184 of 213 Alaska Native villages were impacted by flooding and erosion.[210] In some cases, entire communities need to be relocated.[206,210,211] For example, a storm in October 1997 eroded over 10 meters of shoreline in Shishmaref, necessitating the relocation of homes and a National Guard armory.[212] In addition to yearly losses of 1–2 meters of shoreline, a 2013 storm eroded another 20 meters of shoreline in Shishmaref.[212] This community, along with others facing similar rates of loss of their coastline, voted to relocate to higher ground.[211]

The Arctic region of Alaska has thousands of local hotspots of pollution, including ∼400 Formerly Used Defense (FUD) and active military sites, ∼190 mines, ∼6000 oil and gas sites, and ∼500 other contaminated sites.[213] The impact of storms and

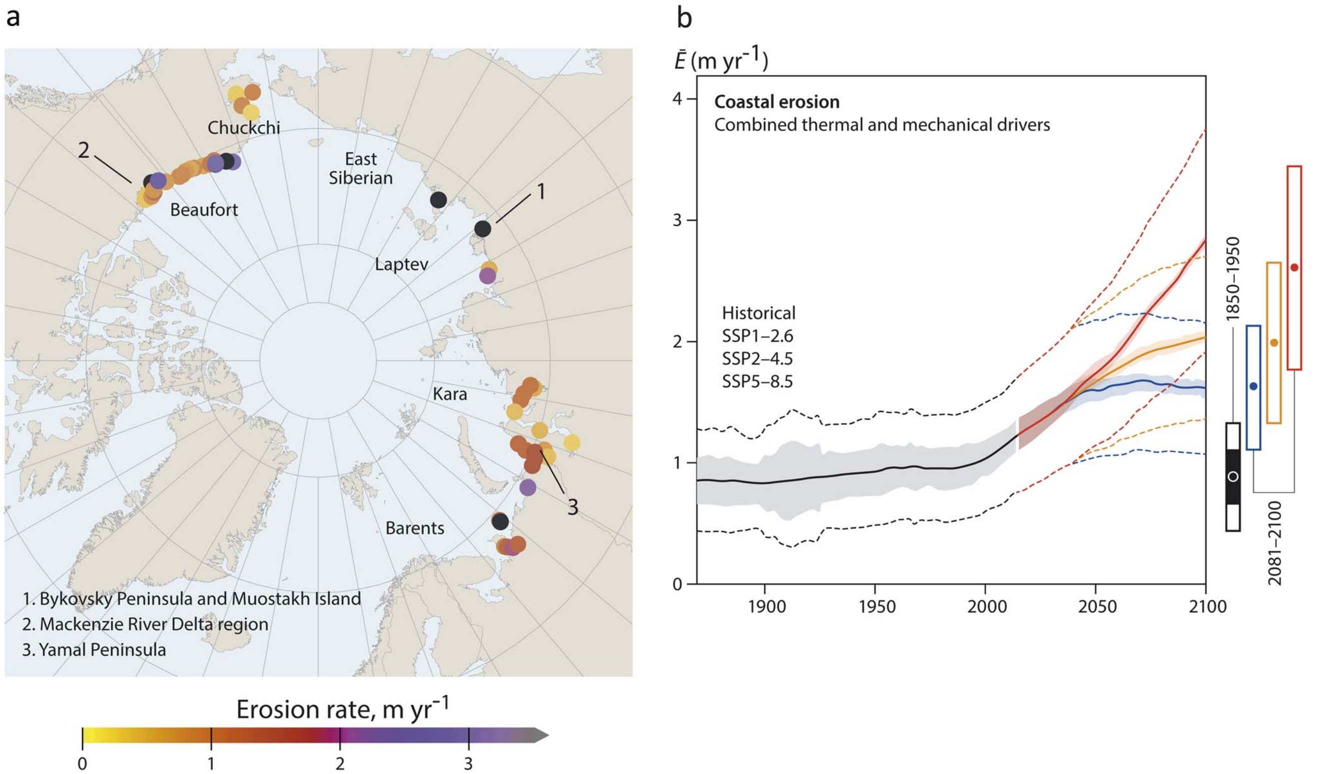

Fig. 17 Coastal erosion in the Arctic. (a) Mean rates of long-term coastal erosion from the Arctic Coastal Database of Lantuit *et al.*[208] (b) Historical and predicted trends of Arctic-mean coastal erosion rate, expressed as the combined effect of thermal and mechanical drivers. SSP1-2.6, SSP2-4.5 and SSP5-8.5 refer to the IPCC Shared Socioeconomic Pathway scenarios for global warming.[178] Dashed lines show a range of variability of erosion defined as 2σ from the modelled ensemble mean. Graphics are reproduced from Nielsen *et al.*[124]

coastal erosion on contaminated sites is exemplified by the Bering Strait coastline of Alaska (the Seward Peninsula and Norton Sound), which is dotted with FUD sites dating from the Cold War, as well as other hotspots of pollution[213] (Fig. 18). FUD sites in Alaska are important sources of POPs with characterized impacts on wildlife and potential health implications for residents of adjacent communities (*e.g.*, ref. 214). This region is also experiencing rapid coastal erosion with dramatic effects on the 16 Alaskan communities situated on its coast, as well as many other communities throughout Western Alaska.[212] For example, a November 2011 cyclone created a storm surge that damaged 37 coastal communities in the Bering Sea region.[212] Storm surges and coastal erosion undermine landfills and sewage lagoons, such as in the Indigenous communities of Shishmaref, St. Michael, Newtok, and Stebbins.[211,212] Erosion and flooding events often co-occur and amplify the damage to coastal communities, including potential release and spread of contaminants.

2.6.3 Landslides. Landslide frequency is closely related to climate change. Changing precipitation patterns and rapid snow/ice melt are associated with the frequency and magnitude of landslides, and the presence of permafrost adds an additional complexity.[215] While permafrost thaw results in shallow landslides in relatively flat terrain due to increasing thermokarst activity and retrogressive thaw slumps, it can also occur in talus slopes, which are rocky deposits at the base of mountain cliffs, as recently documented in Iceland.[216,217] Sæmundsson *et al.*[217] concluded that recent landslides in northern Iceland, in Torfufell Mountain and Árnesfjall Mountain, were due to ground-ice thaw. Patton *et al.*[215] identified research questions related to landslides in the Arctic but did not include the issue of remobilization of contaminants. However, they highlighted the potential of landsliding for carbon release which could be associated with POPs and CEACs, noting that its importance needed further study.

Landslides induced by permafrost thaw or glacial retreat have led to tsunami waves that have destroyed infrastructure in Karrat Isfjord in western Greenland[218] and altered the topography and coastal vegetation in Taan Inlet in Alaska.[219] Generally, these destructive events have occurred in fjords and inlets. A massive landslide to Karrat Isfjord in Greenland in June 2017 destroyed 48% of the infrastructure of the settlement of Nuugaatsiaq. Despite cleanup efforts, the remaining material and waste in the settlement area are still considered a serious hazard.[218] The inhabitants of Nuugaatsiaq were relocated and cannot return because of the risk of further landslides. Mapping in West Greenland revealed over 500 potential tsunamigenic landslide sites.[220] The landslide and tsunami in uninhabited Taan Inlet was related to glacier retreat. It did not result in any infrastructure destruction but illustrated the importance of identifying the potential for other such events.[219]

In Iceland, weather extremes have increased since 1950 resulting in increased frequency of floods and reductions of permafrost. This in turn increases the risk of landslides in

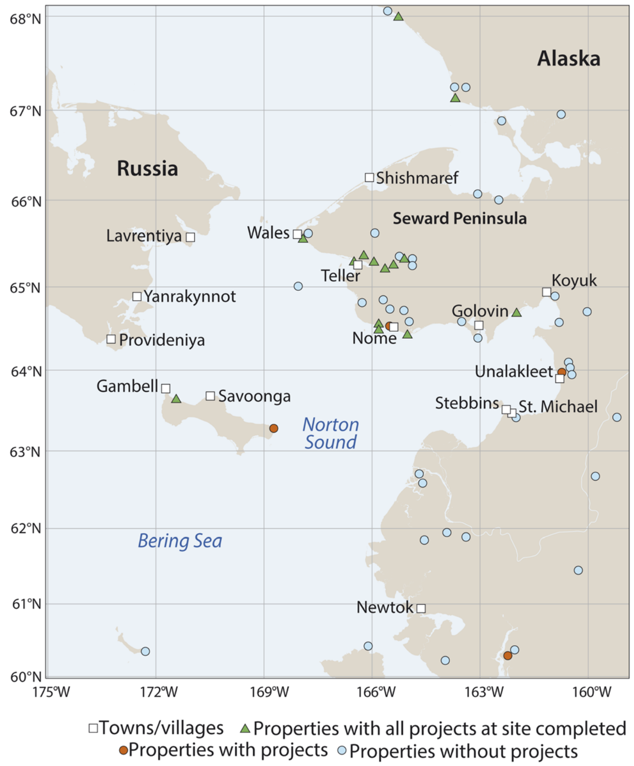

Fig. 18 Map of the Seward Peninsula and Norton Sound region of Western Alaska and its coastal communities. Sites with active, completed and yet to be completed projects at Formerly Used Defense Sites (FUDs) are shown as of April 2024 (U.S. Army Corps of Engineers Headquarters > Missions > Environmental > Formerly Used Defense Sites).

mountainous areas, which damages infrastructure such as water intakes.[221–223] In Norway, average precipitation has increased by 20% in the last 100 years, and intense rain showers and landslides have increased significantly.[224]

2.6.4 Flooding. Climate models predict not only warming temperatures in the Arctic, but also increased precipitation.[225] This can alter hydrological regimes of lakes and rivers by shifting runoff contributions from early season snowmelt to later season rainfall events. Warming is also altering subsurface water exchanges, and in some cases causing lake drainage as well through permafrost degradation. As discussed above, more frequent and more extreme storms can cause damage through erosion and floodings, with risks of contaminant releases and mobilization.

Communities throughout Alaska are facing threats to infrastructure imposed by erosion, flooding, and thawing permafrost, which often amplify one another to form a combined threat.[226,227] In Newtok, Alaska, the village became more susceptible to storm surges on the Ninglick River due to the loss of a land buffer between the village and the river. These changes increased the frequency and severity of flooding in Newtok.[228]

As discussed above, many coastal communities in Alaska are facing threats from erosion, which often co-occurs with flooding events.[210] In the storm surge in Alaska in November 2011, the storm surge flooded the sanitation system of Nome, the regional hub community, causing an influx of 660 000 L of untreated wastewater into the harbor.[212] The sewage lagoon in the Alaskan community Stebbins, as in other communities, was breached by flooding that spread waste in the village and across lands important for subsistence harvests.[212] In September 2022, typhoon Merbok flooded many Bering Strait communities and overwhelmed sewage lagoons, such as in Golovin, and resulted in fuel spills, such as in Koyuk.[229]

Pollution caused by storm surges is a priority community concern as flooding impacts not only sewage lagoons and fuel storage systems, but also legacy pollution sources such as FUD sites.[212] For example, the village of Unalakleet contains an FUD site that was active from shortly after World War II until 1963.[230] Initial characterization of contaminants at the site indicated high concentrations of fuel products, PCBs, chlorinated solvents, OC pesticides, and toxic metals.[230] Remediation efforts in 1993 and 1995 led to the burial of materials on site.[230] Thousands of barrels of uncharacterized contaminants were also scattered around the site due to flooding.[230] This illustrates that the uncontrolled spread of toxic chemicals has already occurred at some FUD sites, while climate change is increasing the risk of such events in the future.

Floods caused by glacial discharges are also a concern. For example, in 2015 and 2016, the outlet stream of Qaanaaq Glacier in Greenland destroyed a road linking the settlement of Qaanaaq to Qaanaaq Airport. Modelling of runoff from the Qaanaaq Glacier forecasted a threefold increase in total summer discharge owing to a 4 °C air temperature rise.[231] Extreme melting on the Greenland ice cap in July 2012 resulted in high flows in the Watson River, the outlet of the Kangerlussuaq sector of the ice sheet in central western Greenland, resulting in a washout and the destruction of the Watson River Bridge.[232] As discussed in Section 2.1, glacier melt may release previously deposited POPs and CEACs, leading to seasonal contaminant pulses in the surrounding environment.

Climate change in northern Finland is reducing snowfall, melting permafrost, and increasing floods in winter, which are predicted to reduce water quality in sensitive water bodies.[233] Heavy flooding and increased rain also affect water treatment efficiency. As a result of heavy floods, the potential increases for a surge of pollution such as POPs into nearby surface water aquifers used as water sources.

2.6.5 Conclusions on increasing frequency of extreme weather. Impacts of coastal erosion, landslides, and flooding on physical characteristics of coastlines and on infrastructure in the Arctic are relatively well documented. However, in terms of the release of contaminants, only the release of mercury due to permafrost impacted coastal and riverine erosion has been evaluated.[234] Little information is available on the release of organic contaminants such as POPs and CEACs[235] although there are clear possible contamination hotspots, such as FUD sites. There is an urgent need to assess such risks and identify communities vulnerable to such effects. This is also relevant to the broader scale of coastal erosion impacts on Indigenous Peoples and local communities, ecosystem services, and socioeconomic dynamics, which according to Fritz *et al.*[236] should be evaluated at the pan-Arctic scale.

3 Future developments and implications for POPs and CEACs

The recent AMAP assessment of the influence of climate change on POPs and CEACs in the Arctic included the assumption that Arctic warming would lead to increases in human activity.[6] Industrial and mining activities, fishing, tourism, and shipping are all expected to increase due to easier access, which in turn is likely to increase uses and emissions of chemicals. As Arctic settlements grow, they will require more construction and public infrastructure, with the associated emissions, as discussed by Kallenborn *et al.*[5] Furthermore, chemical emissions related to waste and wastewater are likely to increase as well, as discussed by Jensen *et al.*[237] and Kallenborn *et al.*[5] unless actions are taken to reduce these emission sources. The projections in AMAP[6] were mainly hypothetical. In this section, we compile and discuss the information available on future developments in human activity in the Arctic, which may have implications for future chemical use and emissions.

3.1 Population changes

The Arctic region is inhabited by approximately four million people according to the Arctic Human Development Report which follows the area identified by AMAP.[238] More recent assessments suggest that the Arctic population is about 7 million when several neighboring regions in Russia, Khanty-Mansi Autonomous Okrug, Sakha Republic, Magadan Oblast and Kamchatka Oblast, as well as parts of Nunavik and Northern Sweden are included[239] (Fig. 19). Recent analyses of population numbers indicate that the overall number of Arctic inhabitants is likely to remain relatively stable in the future, but with differences amongst regions and a general trend towards more urbanization.[240]

Since 2000, the population of Alaska, Arctic Canada and Iceland has grown substantially, with a moderate growth on the Faroe Islands (Fig. 20). Greenland and Northern Norway have remained stable, while Northern Sweden and Finland have shown moderate declines. The largest decline, accounting for the overall decrease in population number, has taken place in Arctic Russia.[238,240] Changes in population numbers are due to the ratio of birth to mortality rates, and a net migration into or out of the region. A net migration into the Arctic might also lead to natural increases as young adults are typically the main

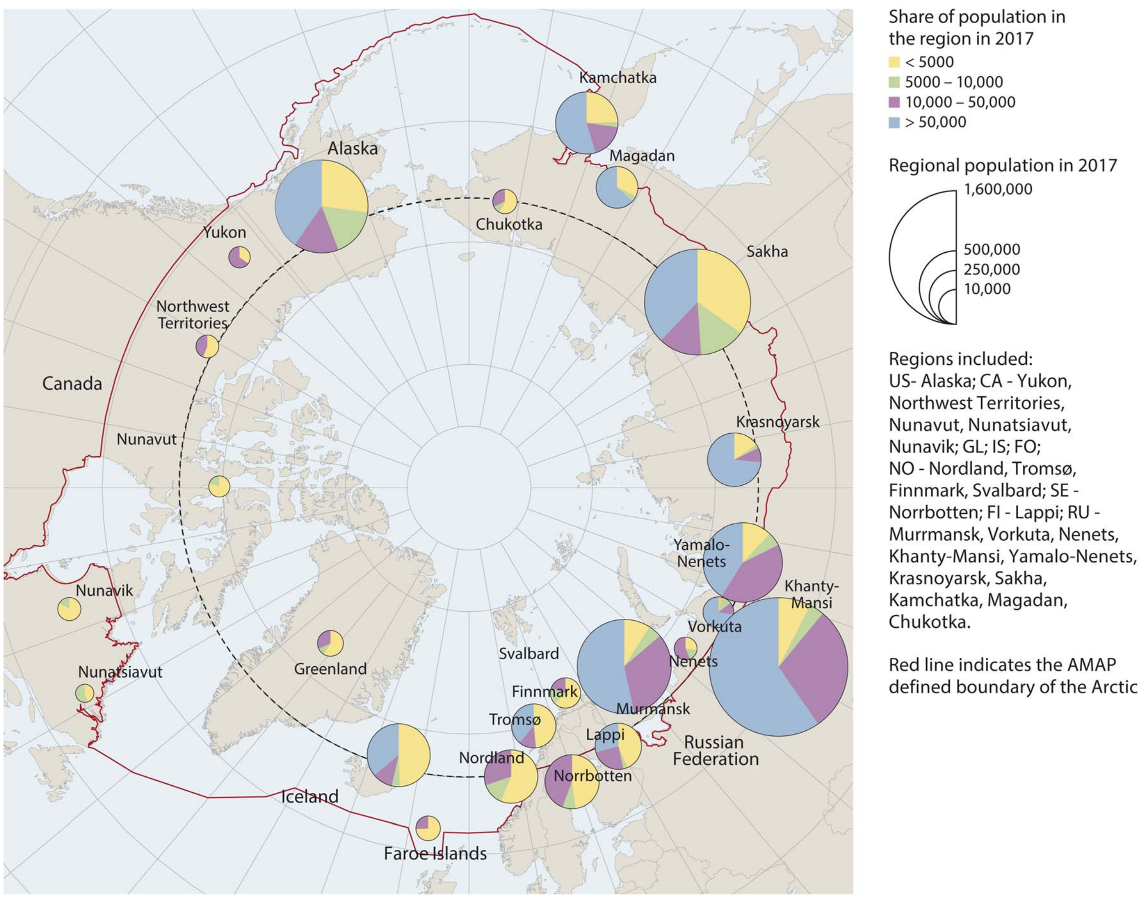

Fig. 19 Settlement structure in the Arctic and sub-Arctic as of 2017, showing the share of the population for various sizes of communities (Jungsberg *et al.*[239]). Note that Russian regions of Khanty-Mansi Autonomous Okrug, Sakha Republic, Magadan Oblast and Kamchatka Oblast, as well as parts of Nunavik and Northern Sweden, are included in the map but are not in the Arctic area defined by AMAP (red line).

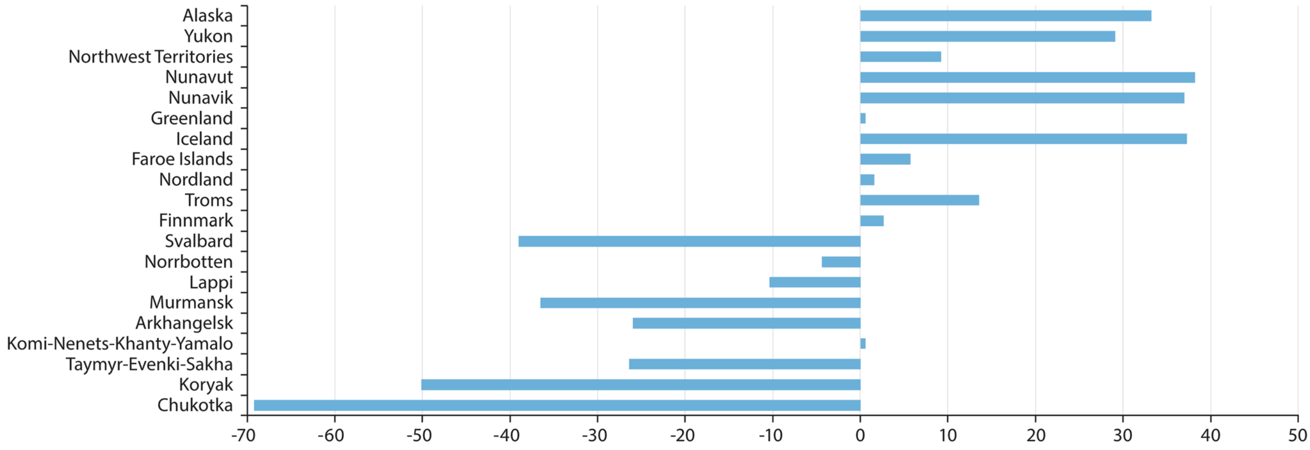

Fig. 20 Population changes in the Arctic states, territories and regions from 1990 to about 2018 (modified from Heleniak[240]). Data for Nunavik are for 2001 to 2016 from Lévesque and Duhaime.[241]

migrants. The combination of these factors differs between regions. Iceland experienced an increase in both births and migration, while population increases in Alaska and Nunavut were mainly driven by increased birth rates.[240] Nunavut was the fastest growing region in the Arctic, with a population increase of nearly 34% since 2001.[240] Greenland has been affected by out-migration, but this has been counterbalanced by increased births.[240] The demographics tipped towards a population decline in the Russian Arctic, with the exception of the Yamal-Nenets Okrug.[240]

The Arctic is characterized by a large number of small settlements with less than 5000 inhabitants.[239] The share of the population living in small or larger settlements varies across regions (Fig. 19). The majority of the population in Alaska, the Yukon and Northwest Territories, Greenland, Iceland, Faroe Islands, and in Arctic regions of Norway, Sweden and Finland lives in larger towns and cities. Exceptions are Nunavut and Nunavik in Canada, and Chukotka in Russia. Since 2000, a trend is evident of migration towards the urban centers in the Arctic, resulting in population losses in rural areas. Out-migration from small communities is a major concern in all the above regions.[242,243] In addition, migrants from outside the Arctic tend to settle in the main centers of the region.[239] This trend towards urbanization is visible throughout the Arctic, although at different population scales. Exceptions exist for areas of oil and gas exploitation which attract incomers due to better employment opportunities, for example in the Komi–Nenets–Khanti–Yamalo regions in Russia, where population has increased from 1990 to 2018 (Fig. 20).[239,240]

The populations of Alaska and the three territories that make up the Canadian Arctic are projected to increase by roughly 20% over the period 2020 to 2030 [240,242] (Fig. 21). Alaska's population is projected to grow to roughly one million, depending on the scenario for migration, which would be an increase above the US average. Parts of Arctic Canada are expected to grow by roughly 20–40% with the largest increase in Nunavut, given its age structure. However, factors of uncertainty include migration to the Arctic due to resource exploitation and an expected out-migration from Nunavut. An increase of 36% by 2060 is projected for Iceland, while the population of Greenland is expected to remain at roughly 55 000 by 2040. About the same number is projected for the Faroe Islands under a scenario of high in-migration. While the populations of Norway, Sweden and Finland are projected to grow, their Arctic regions will either grow at a lower rate or even lose population (Sweden). The projections for Russia are based on limited data, but generally predict a continuing population decline, down to approximately 1.8 million. This is caused by lower birth rates and continuing out-migration, although some regions, such as Yamal-Nenets Okrug, may show a different development. However, it is not only the population development in the Arctic that will be of significance for human activity in the Arctic. The global population may pass 10 billion by the end of this century.[238,244]

The associated needs will also direct a view to the Arctic and its natural resources. Furthermore, all other things being equal, the global population growth will contribute to climate change, which impacts the Arctic more severely than other regions of the world.

3.2 Economic developments potentially leading to contaminant emissions

The states of the Arctic differ in their economic histories, but share similar characteristics related to the climate and remoteness. Huskey *et al.*[245] described three pillars of the Arctic economy: (1) large-scale natural resource production, often for an international market; (2) traditional activities and small-scale natural resource production; and (3) public sector and provisional services. The effect of climate change on Arctic economic development is difficult to predict.[246] Although climate change will facilitate access to the Arctic, mainly because of receding sea ice, some economic outlooks[246–248] generally do not foresee imminent growth in industrial and shipping activities because of high costs, logistic challenges, and environmental concerns. Climate warming is also likely to increase costs of development of terrestrial resources. However, many other assessments of impacts of climate change point to increases in shipping, mining, oil and gas exploration,

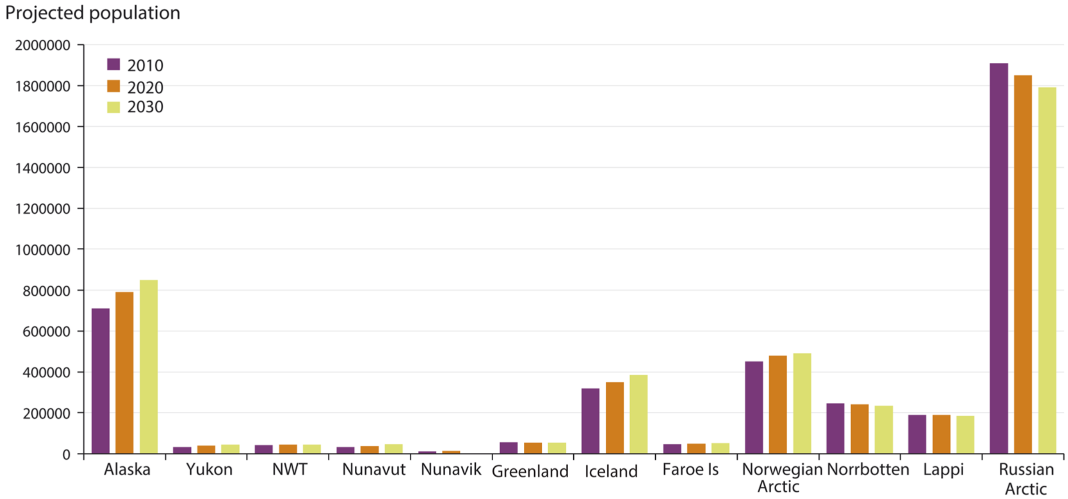

Fig. 21 Projected population development in the Arctic based on projections in Heleniak and Bogoyavlensky[238] for the Norwegian Arctic, Norrbotten and Lappi in Sweden and Finland and the Russian Arctic. Projections for Alaska, Yukon, Northwest Territories (NWT), Greenland, Iceland and the Faroe Islands are from Heleniak.[240] The population for Nunavik is from Lévesque and Duhaime.[241] The Russian Arctic regions are limited to Murmansk, Nenets, Yamalo-Nenets, Taimyr, Sakha, and Chukotka. The figure is redrawn from Fig. 2.18 in Heleniak and Bogoyavlensky.[238]

agriculture, marine fisheries, and related urbanization/industrialization development.[138,225,249–252] All these activities could influence emissions of POPs and CEACs.

3.2.1 Gross regional products in the Arctic. Gross Domestic Product (GDP) has been correlated with emissions of PCDD/Fs and PAHs globally.[253,254] Therefore it is of interest to compare GDPs among Arctic countries and sub-regions. The Gross Regional Products (GRP, regional equivalent to the GDP) of the Arctic States show that the Arctic economy is dominated by Russia (specifically the Khanty-Mansi and Yamal-Nenets regions), and to a lesser extent by Alaska, the Northwest Territories and Nunavut (Fig. 22), mainly due to natural resource exploitation (oil and gas, mining).[255] Disposable household income (DHI; per capita income adjusted for taxes and transfers) is more evenly distributed among Arctic states and territories (Fig. 22). It is important to note that the value of hunting, fishing and harvesting by individual households is not included in GRP nor DHI due to lack of data.[255]

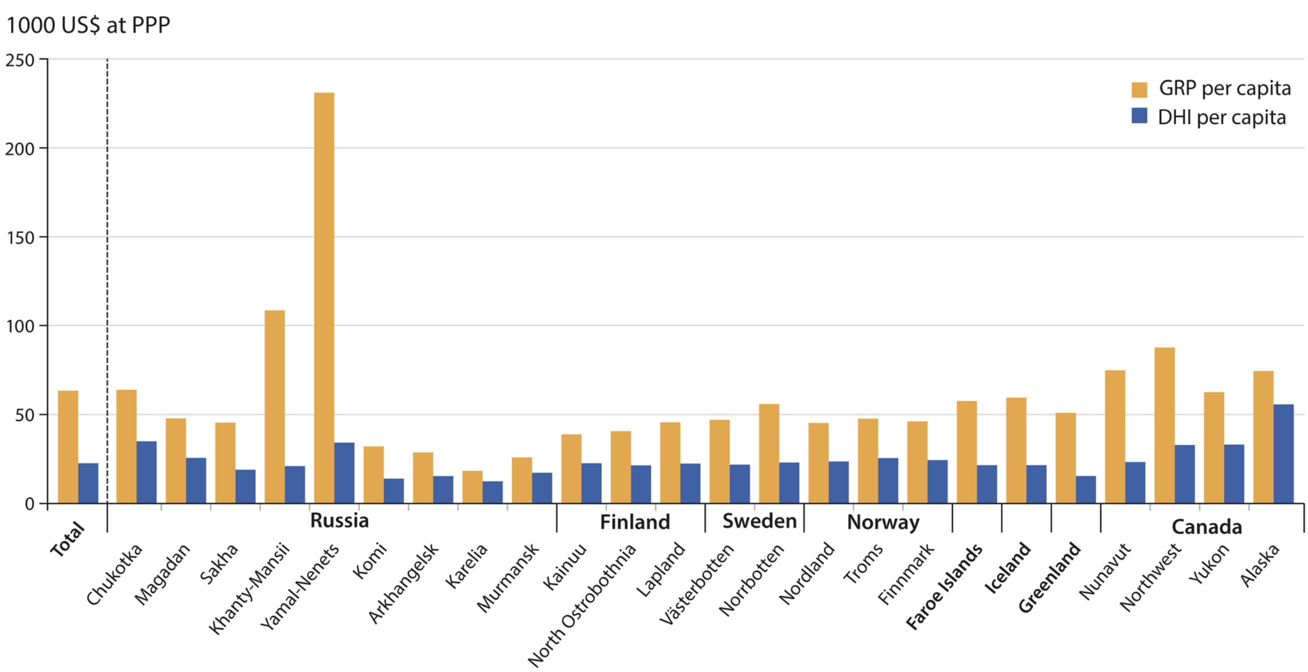

Fig. 22 Gross regional product (GRP) per capita and disposable household income (DHI) per capita, by Arctic sub-regions in 2018 expressed as $1000 US Dollar equivalents using Purchasing Power Parity to take into account price differences between countries (redrawn from Glomsrød and Wei[255]).

In Iceland, Norway, Sweden and Finland, and in Nunavut, developments towards strong economies have occurred in new sectors in addition to the traditional sectors of resource production and public administration and services. Huskey *et al.*[245] highlighted that the urbanization trend leads to critical masses that favour the growth of local businesses replacing imports. Another relevant development for the regional economy is a higher degree of local governance, including over resource exploration and exploitation. For example, in Greenland the power to negotiate agreements with mining companies was delegated to the municipal level in 2009 [256] and in 2024 the Federal Government of Canada handed control of decisions on mining and oil and gas development on Nunavut's public lands to the Government of Nunavut.[257]

3.2.2 Future oil and gas production. The energy sector was associated with a significant proportion of contamination of industrial sites in the permafrost dominated regions of the Arctic, particularly by diesel fuel and various aromatic and chlorinated solvents.[3] Thus it is of interest to consider the likelihood and impacts of future developments, especially considering that 10% of global oil production and 25% of global natural gas production is located in the Arctic, mainly in Russia and Alaska.[247,258] Lindholt and Glomsrød[259] developed two scenarios for future production. Their reference scenario assumed a required rate of return (RRR) on oil/gas development of 7% and an oil price ranging from 70 USD per barrel in 2025 to 90 USD in the period 2040–2050. A second scenario assumed an RRR of 20%. The higher RRR results in generally lower production (Fig. 23) except after 2047 when undeveloped reserves become more attractive to exploit. The market demand is the main driver of economic investments. For example, in the years following the report on the Arctic economy by Glomsrød *et al.*,[248] the embargo on Russian oil and gas imports in the European Union as of 2022 might have impacted the development. While oil and gas activity is already underway in the southern Barents Sea, development of the northern Barents and Kara Sea areas is regarded as too costly.[260] Offshore oil and gas exploration in the Canadian Arctic has been prohibited pending review every five years[261] and a similar ban exists for Beaufort Sea coastal waters of Alaska.[262] However, onshore development continues to expand in Russia and Alaska. The Willow project, a large oil and gas development near the community of Nuiqsut in northern Alaska was approved in 2023.[227]

3.2.3 Future mining development. Mining has been central to the economic development of Alaska, as well as northern territories and regions of Canada, Norway, Sweden, Finland and Russia.[256,263] As discussed in Kallenborn *et al.*[5] one of the primary concerns with mining operations in the Arctic is its potential to be a local pollution source. Langer *et al.*[3] concluded that the mining sector was a major contributor to the contaminated sites within the permafrost region. The Arctic region already produces a significant fraction of some of the world's critical metals and minerals, such as palladium (40% of world production), platinum (15%), and diamonds (25%). Mining takes place in all Arctic countries except Iceland and the Faroe Islands, with approximately half of the mines being located in Russia.[247,248] The growing demand for metals and minerals especially for "critical minerals" used for batteries, fuel cells and electronic devices has resulted in calls for increased mining development in the Arctic.[264–267] As of the early 2020s, planning is underway, particularly in Russia, Greenland, and Canada for new mines for different minerals from zinc to diamonds to gold. Possible emissions of organic contaminants from mining development, apart from PAH emissions from fossil fuel combustion, are related to flotation and flocculation chemicals,

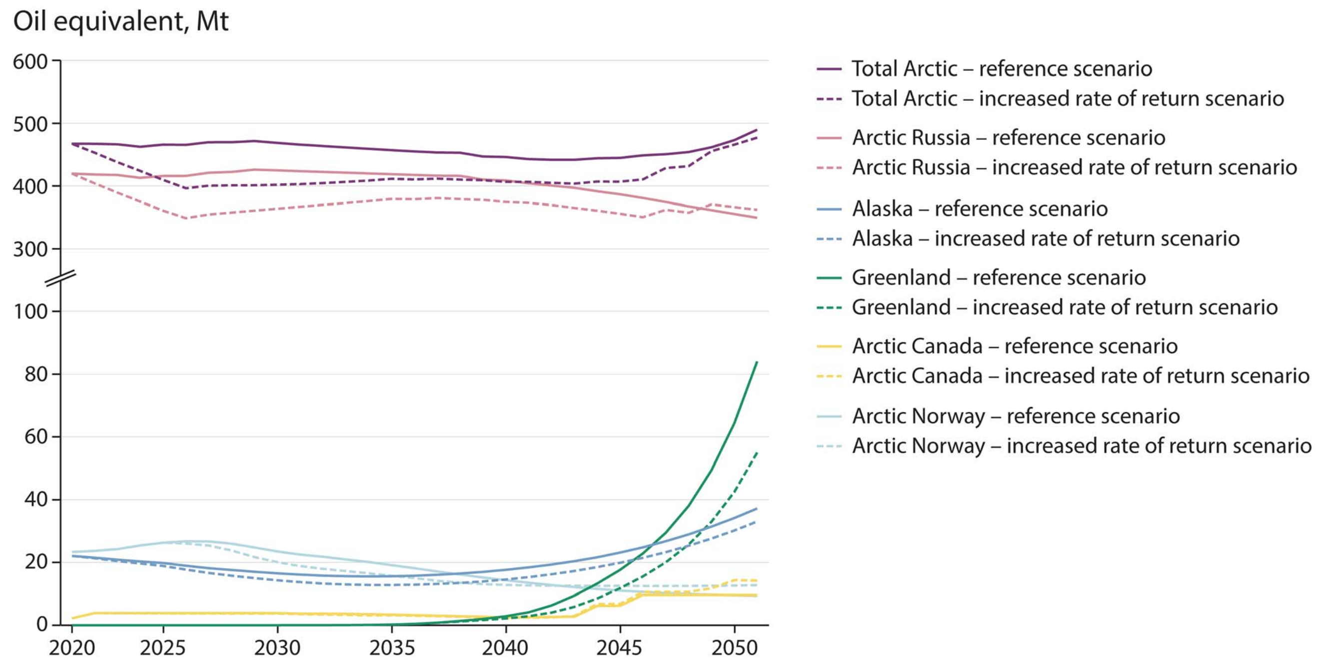

Fig. 23 Projected oil production in the Arctic under two production scenarios as discussed in Lindholt and Glomsrød.[259]

many of which are surfactants, that could be discharged into marine and freshwaters with the wastewater and tailings.[268]

Due to the high costs, mines in the Arctic are typically large-scale operations. There are many well-known mineral deposits that are unexploited due to their remote location and the challenging Arctic environment.[264] Environmental impacts are a major concern of Indigenous Peoples, and local communities and two recent major mining developments have been curtailed or halted: (1) the Nunavut Impact Review Board and the government of Canada denied a request for the expansion of the Mary River iron ore mine due to concerns about impacts on marine mammal, fish and terrestrial wildlife,[269] and (2) the US Environmental Protection Agency denied building and operating permits related to waste from the proposed Pebble gold and copper mine in southwestern Alaska, in order to protect the salmon fishery of Bristol Bay.[270]

3.2.4 Future shipping activity and associated contaminant emissions. The IPCC Special Report on the Ocean and Cryosphere[225] predicted that shipping activity will continue to rise across the Arctic as northern routes become increasingly accessible as the retreat of summer ice expands navigability. The area regarded as safe for shipping by open water vessels expanded by 35% during the period from 1979 to 2018.[271] The Northern Sea Route (or Northeast Passage) is expected to be more viable than other routes because of infrastructure already in place (Fig. 24). A survey of shipping companies conducted in 2008–2010 found an interest in expansion of destinational shipping, *i.e.* to and from destinations in the Arctic, while most companies were more reluctant about transit shipping, *i.e.*, larger container and bulk carriers crossing the Arctic Ocean.[273] Major factors affecting feasibility are the length of the period of open water, unpredictable weather conditions, lack of infrastructure, and insurance costs, and types of vessels required (*i.e.*, moderately ice-strengthened).[247,272] Nevertheless, the shipping in the Arctic has increased by 37% from 2013 to 2023 with the Northern Sea Route predominating in terms of total cargo volume.[274] Furthermore, the Russian government has issued a plan targeting an increase from 1.3 million tons of transit shipping in 2020 to 30 million tons in 2030.[275]

The volume of ship traffic in the Canadian Arctic, while very small compared to the European and Russian sectors, almost tripled between 1990 and 2015 (ref. 239 and references therein). Local shipping services are predicted to increase with longer navigable seasons.[273] Tourism is also expected to increase in the Arctic.[247,276] As a majority of tourists will enter the Arctic on self-sufficient cruise ships, the economic benefits to the region may

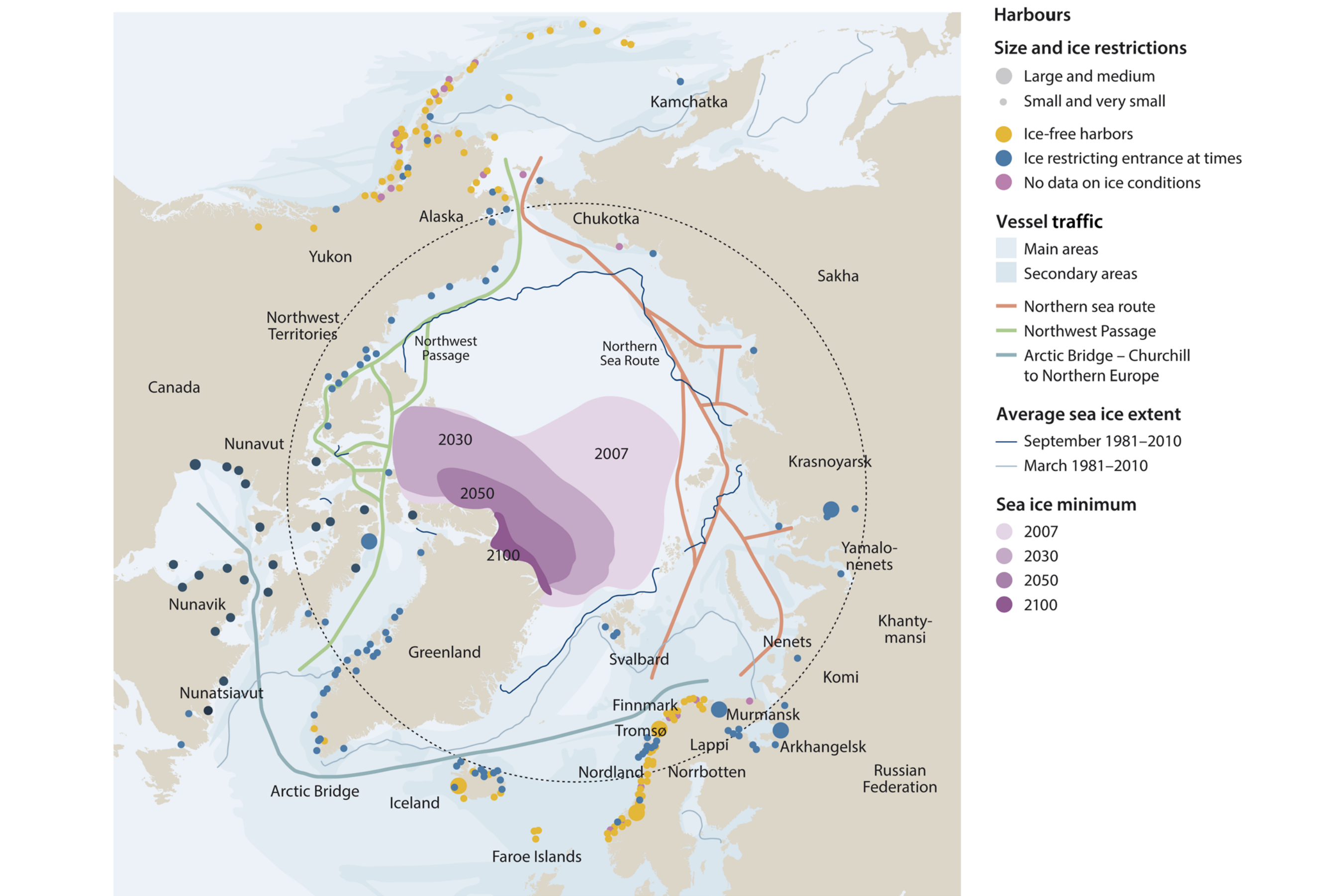

Fig. 24 Shipping routes and ports in the Arctic region based a map in Jungsberg *et al.*[239] modified with additional harbours in the Canadian Arctic. Sea ice minimums for 2007, and predictions for 2030, 2050, and 2100 are from Eliasson *et al.*[272] The average sea ice extent for September and March 1981–2010 is also illustrated.

be low, while environmental damage might be substantial.[247] Cruise ship activity in the Arctic increased significantly in the 2010s: Considering the area north of 60°N and including Greenland, but excluding Iceland, Northern Norway, Sweden and Finland, 65 cruise ships were registered in 2018 and 73 in 2019, with Svalbard and Greenland being the main destinations.[277,278] Even more pronounced than the number of cruise ships, their sailing distance in the Arctic increased by 75% between 2013 and 2019.[277,278] There has also been a great increase in cruise ships visiting Iceland, 152 in 2018 and 262 in 2023.[279]

How these projected increases in ship traffic will affect use and emissions of potentially hazardous chemicals has only scarcely been discussed in the scientific literature.[280] POPs as well as CEACs, including PAHs, could be associated with antifouling paints, oil and fuel spills, wastewater discharges, and atmospheric emissions from fossil fuel combustion. Emissions from ships of NO_x and black carbon are predicted to increase in scenarios of increased shipping.[281] Arctic expedition cruise ships are considered to be greater air pollution sources than cargo ships due to the need to provide power for onboard facilities for thousands of passengers.[277] In model calculations of climate change-related atmospheric transport of PAHs to the Arctic, Friedman *et al.*[282] included estimates of PAH emissions from future shipping scenarios, related to increased oil and gas exploration and transit shipping. Due to reduced global emissions, PAH concentrations are generally expected to decline. However, focusing on B(a)P, emissions are expected to increase due to increased shipping. Thus, a future shipping "penalty" of 21% was estimated for B(a)P, compared to simulations without increases in shipping.[282] Although oil and gas production remained stable in the model and emission factors decreased, locations were assumed to be more remote, requiring increased ship traffic.[249]

Expansion of shipping activity in Arctic waters will inevitably bring with it increased emissions of antifouling chemicals used on ships globally. Use of organotins as antifouling agents was restricted by the European Union (in 1991) and by the International Maritime Organization (in 2008) and concentrations in benthic biota in Arctic and sub-Arctic harbours have declined.[283] However, a wide range of substitutes are in use including diuron, Irgarol 1051, DCOIT (4,5-dichloro-2-*n*-octyl-4-isothiazolin-3-one), TCMTB ((1,3-benzothiazol-2-ylsulfanyl) methyl thiocyanate), dichlofluanid, chlorothalonil, pyrithiones (*e.g.* copper pyrithione (CuPT), zinc pyrithione (ZnPT)), ziram, and zineb.[284] As of early 2024 there has been no direct monitoring of these substitute antifoulants in Arctic sediments or biota. As the antifouling chemicals are often applied in polymer coatings, MPs from degradation of these coatings are a potential source of marine MP pollution as well as plastic additives in the marine environment.[285,286]

The Arctic Marine Shipping Assessment Report also noted that shipping of oil and gas in the Arctic is more vulnerable to oil spills than it is in other oil producing areas in the world.[287] There is also a lack of infrastructure and equipment to deal with a large oil or fuel spill or with ship cargo that includes hazardous chemicals, and oil dispersal surfactants are less efficient in cold water.[287,288] Increased shipping may have a direct adverse impact on Arctic fish stocks and on coastal aquatic ecosystems such as kelp forests, with subsequent indirect impacts on the provision of multiple ecosystem services.[289]

3.2.5 Future fisheries and aquaculture. The Arctic Marine Shipping Assessment Report foresaw an increase in fisheries, already notable by an extension of the commercial shrimp fishery in Greenland[287] and the expansion of the Greenland halibut (*Reinhardtius hippoglossoides*) fishery in Nunavut.[290,291] Most ships (41%) entering the Arctic as of 2019 were commercial fishing vessels.[274,288] A review of trawling activity in Arctic waters based on fishing activity data form 2013–2018 from Global Fishing Watch[292] found that commercial trawling was responding to reduced sea ice concentrations during this time period relative to a reference period (1982–2010) (Fig. 25A).[293] Trawling activity was predicted to increase in the Chukchi Sea, the Canadian Archipelago, Hudson Bay, Ungava Bay, coastal Labrador, west Greenland and the Kara Sea during 2040–2060 with climate warming and sea ice retreat (Fig. 25B). The predicted increase did not account for factors such as the fluctuations or range expansions of major fish stocks or changes in regulatory frameworks. The increased industrial fisheries could also have impacts on biodiversity, through bycatch and damage to the seabed, as well as generating potential conflicts between subsistence and industrial fisheries.[294] The increased fisheries activity in previously inaccessible areas is also likely to bring with it increased emissions of antifouling chemicals, as discussed for other forms of shipping, as well as an increase in plastic litter and MPs.[284] Plastic fishing gear can release additive chemicals into the water as the plastic weathers. For example, buoys have been found to contain part per million concentrations of antioxidants (280–91,000 ng g^{-1}; Irganox1010, Irganox 1076, Irgafos 168, and dibutyl hydroxy toluene) and benzotriazole UV filters including UV-328, while polyvinyl chloride rope used in aquaculture contained phthalate and bisphenol plasticizer additives.[295]

Aquaculture is an important fisheries-related activity in Arctic Norway (northern parts of Nordland and the northernmost counties of Troms and Finnmark). Nearly 500 fish farms were located in these northernmost counties as of 2020.[296] Arctic Norway's share of Norwegian production of farmed Atlantic salmon (*Salmo salar*) grew from 28% to 44% during 1997–2017.[297] Similar aquaculture operations, although on a much smaller scale, have been established in the Kola Peninsula of Russia, the Faroe Islands and Iceland. Fish farming is currently prohibited in Alaska although there is an active mariculture industry.[298]

Tripling of the production of salmon aquaculture in Norway by 2030 has been proposed but has been criticized due to concerns about diseases and parasites, pollution from waste and chemicals, and impacts on local ecosystems.[299] Expansion of salmon aquaculture in the Faroe Islands is limited by lack of suitable locations on the Faroese coastline. In Iceland, the salmon aquaculture industry has proposed expanding production by about 2-fold compared to the level in 2018–19.[300,301] In the Kola Peninsula, plans for doubling of salmon and trout aquaculture production from 2018–2019 to 2025 have been

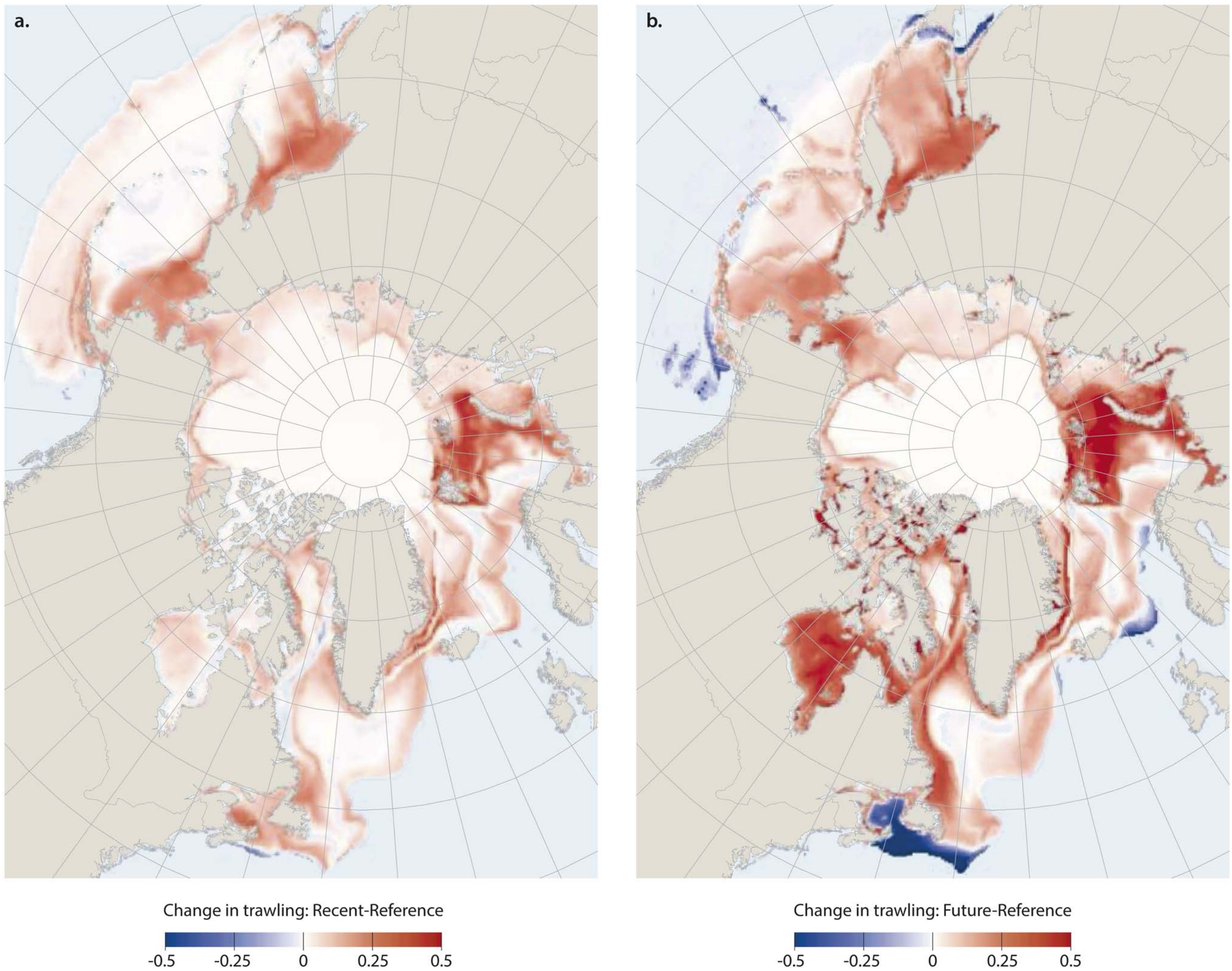

Fig. 25 Climate-impacted fisheries trawling activity in the Arctic. (a) Difference in predicted probability of activity between 2013–2018 and a reference period (1982–2011). (b) Difference between activity in a future climate scenario for 2040–2060 and the reference period[293] [redrawn from Fauchald *et al.*[293] with copyright permission].

reported.[302] Contaminants associated with the aquaculture industry include MPs and plastic additives[303] in nets and other gear, as well as antimicrobials (quinolones, tetracyclines, amphenicols, and sulfonamides) to protect fish health.[304] In addition, there is the use of pesticides for treatment of salmon lice (*Lepeophtheirus salmonis*); the chemicals are generally delivered in the feed or by using medicinal baths[305] and can cause contamination of the surrounding environment. Schar *et al.*[304] have predicted growth in the use of antimicrobials in aquaculture in Norway of about 30% by 2030. Increasing releases of MPs from fish farm infrastructure is likely to occur as aquaculture expands. Abihssira-García *et al.*[306] estimated mass losses of plastics *via* abrasion and degradation ranging from 0.39% to 1.02% mass loss/month from polymers in nets and ropes, which translated to over 1000 tons of MPs per year for salmon farms in Norway.

Land-based aquaculture has been proposed to reduce impacts on local marine environments in Norway and Iceland, but as of 2021 was not being conducted for production of market size Atlantic salmon.[301,307] Production on land using recirculating aquaculture systems may reduce use of pesticides and antimicrobials, however, there are environmental impacts related to water usage, wastewater discharge, and collection of solid wastes.[301,307,308]

3.3 Infrastructure development

Analysis of satellite imagery has indicated that the human-impacted area in the Arctic coastal region (within 100 km of coastlines) increased by 15% between 2000 and 2020. About 53% of the impacted area (661 km^2) was attributed to roads and 16% to buildings, with the remaining area including other infrastructure related to the oil/gas industry and mining.[309] Here we consider recent or potential future development of seaports, airports, roads and railways in the Arctic and possible contamination issues for POPs and CEACs that might occur.

3.3.1 Seaport expansion. Ports are expected to become more important hubs within and amongst Arctic communities in the future.[310] The World Port Index[311] lists about 225 ports within the region that includes the Northern North Atlantic, and Bering Sea as well as the coastal Arctic Ocean and Hudson Bay (Fig. 24). Of these about 50 are capable of handling vessels of 100 to 300 m length although only one, Murmansk, is ranked by the World Port Index, as a "large port". Coastal communities in Alaska, northern Canada, Greenland, Chukotka, Sakha, Yamalo-Nenets, and Taimyr, have small harbours that are mainly used for resupply shipping activity due to lack of roads to these communities.[310] Access to these harbours is restricted by ice conditions for most of the year; only ports in Iceland, Norway, Kola Peninsula and Southwestern Alaska are currently ice free in winter (Fig. 24), although this may gradually change over the next 50 years. Larger deep water ports are used for resource extraction (oil and gas (mineral) resources), transport, fishing, government research, and cruise ships. These larger harbours are limited to Iceland, Norway, southern Alaska, the Kola Peninsula and the White Sea (Fig. 24).

While roads are important for transport in Iceland, the European Arctic, and Western Russia, for coastal Western and Northern Alaska, Nunavut, Nunavik, and Greenland transport between towns or resupply of consumer goods and fuel usually occurs by sea. Expansion of harbour infrastructure may be prompted by shifts in accessibility of land-based industries (mines, oil and gas facilities) as well as remote coastal communities as land routes become impassable due to permafrost thaw.

Expansion of the harbour at Nome has been announced.[312] It would be the first deep water port in the Alaskan Arctic. Major expansion of port infrastructure in the Russian Arctic is planned as part of ambitious plans for use of the Northern Sea Route.[313,314] The Russian government Arctic strategy up to 2035[315] includes plans for year-round navigation throughout the Northern Sea Route that involve construction of one additional nuclear icebreaker, and the construction of ports-hubs for the transshipment of international container cargo over the period 2020 to 2035. Expansion of capacity for container shipping at the port of Murmansk as well as for liquid natural gas shipping at Petropavlovsk-Kamchatsky on the Kamchatka peninsula are underway.[275] The Russian government has set a goal of 30 million tons of transit shipments by 2030, against 1.3 million tons in 2020, implying an enormous expansion of shipping and port capacity.[275] A new harbour at Langanesbyggd in the Finnafjord area of eastern Iceland has been proposed, designed for *trans*-Arctic shipping.[316]

3.3.2 Airport expansion. There are 1300 civilian airports and heliports in the Arctic.[239] Of these, approximately 260 are large- and medium-size airports with regular passenger traffic. As discussed in Kallenborn *et al.*[5] several studies have shown significant sources of contamination by PFOS and other PFAS in and near airports in the Arctic. The contamination has occurred because of the requirement to regularly test aqueous fire-fighting foams (AFFFs) as part of fire safety protocols.[317] Many AFFFs commonly contain PFAS. Contamination of soils, water, and biota near airports in the Arctic by PFAS related to use of AFFF has been documented in Svalbard,[318] Greenland,[319] Canada[93,320] and Alaska.[321] Airports are also likely sources for other contaminants such as benzotriazole lubricant additives and anticorrosion additives in aircraft and airport pavement deicing fluids.[322,323] Aircraft lubricants are also major sources of OPEs (such as tri-*n*-butylphosphate, dibutyl phenyl phosphate, triphenyl phosphate and tricresyl phosphate) that have been detected in air and soils around mid-latitude airports.[324,325] OPEs have also been detected at elevated concentrations in air near the airport at Resolute Bay (Nunavut) and in air at Ny-Ålesund (Svalbard) relative to background sites implying local emissions.[326,327]

While PFOS containing AFFFs have been phased out, most airports are still using AFFFs with fluorotelomer based substances until fluorine-free replacements are certified.[317] Thus continued emissions of PFAS as a result of fire suppression and training at Arctic airports can be expected. As of the early 2020s, expansion of many airports in the Arctic is underway or planned, anticipating greater regional needs, *e.g.* for air cargo, as well as for increased tourism. In Greenland, the runways at Nuuk and Ilulissat airports are being lengthened to allow direct flights from Europe and North America.[328,329] In Canada, lengthening and upgrading of runways, terminals and air cargo facilities has been recently completed in Iqaluit and is planned for several other communities.[330] Upgrades are also ongoing in Alaska.[331] Upgrades of airports at Murmansk, Arkangelsk, and at three communities in Yakutkia are underway.[332–334] These upgrades will increase air traffic including larger aircraft, and are likely to result in increased emissions of lubricant and anticorrosion additives such as benzotriazoles and OPEs.

3.3.3 Road and railway expansion. Roads and railways have long been major types of infrastructure linking mid-latitude areas of circumpolar countries to sub-Arctic and Arctic regions, especially in Alaska, Canada, the Nordic countries and Russia.[335] However, roads and railways are sources of CEACs associated with vehicle exhausts, lubricant additives, as well as tire and brake wear, such as PAHs, OPEs, and rubber additives (*e.g.* 6PPD[336]). They are also sources of particles, including MPs[337] and can lead to pollution during accidents, *e.g.* fuel spills.

Recent proposals for road development include the "Ambler" road, a 300 km industrial corridor on the south side of the Brooks Range in Alaska that would allow mining development.[338] An environmental assessment by the US Parks Service noted potential issues with air quality (airborne particulates) and the potential for vehicle fluids or road deicers to enter surface waters through runoff. In Canada's Northwest Territories, planning and community consultation has taken place for a northern extension of the road along the Mackenzie River[339] and for a road running to Bathurst Inlet on the Arctic Ocean (Coronation Gulf).[340] In Nunavut, a railway to transport iron ore from the Mary's River mine in northern Baffin Island to a new port on Foxe Basin has been proposed.[341] In Norway, double tracking of the Ofoten Line between Sweden and Norway which carries iron ore from a mine at Kiruna in Sweden, has been announced in the Norwegian National Transport Plan.[342] The Russian government's Transport Strategy until 2030 envisions a Northern Latitudinal Passage (NLP), to ship cargo *via* railway to port facilities in the Yamal Peninsula on the Kara Sea, and at Sabetta on the Ob Gulf, facilitating access to the Arctic Ocean.[343]

3.3.4 Expansion of agricultural activity. Expansion of agricultural land northward especially in sub-Arctic regions of Alaska, Canada and Russia has been predicted based on climate projections using IPCC RCP scenarios. For example, under the RCP 4.5, the scenario which assumes stabilization of greenhouse gas emissions by 2050, global climate models predict that extensive areas of Alaska, Yukon, the Northwest Territories, the northwest of Russia (Yamalo-Nenets Autonomous Okrug, Nenets Autonomous Okrug), and Chukotka Autonomous Okrug will be potentially suitable for cold tolerant crops such as wheat (Fig. 26).[252] A roughly 2-fold larger area is predicted to have climatic conditions suitable for agriculture in the period 2060–2080, under the RCP 8.5, the pathway with the highest greenhouse gas emissions.[252] However, there is much debate about the sustainability of expansion of agriculture production into areas that are currently boreal forest, peatlands, or tundra or that may be changing rapidly due to permafrost degradation.[344–346] Several studies have pointed at the possibility that pesticide use will accompany any northward expansion of agriculture.[344,345,347] The predicted land area for expanded "commodity" production would bring pesticide use into river catchments draining directly into the Arctic Ocean and Bering Sea (Fig. 26). As noted by Balmer *et al.*[348] there has been relatively little study of the levels and trends of current use pesticides (CUPs) in the Arctic, with only a limited number of pesticides having been analysed compared to numbers registered globally as of 2018. The occurrence of pesticides in the Arctic has mainly been related to long-range transport. Recent studies have shown that a wide range of herbicides and insecticides, used in agriculture in temperate regions of Asia and North America, are detectable in summer surface waters of the Arctic Ocean.[349,350] The most prominent CUP detected in ocean water by Ding *et al.*[350] was cycloate, a widely used herbicide which is semi-volatile and thus likely undergoing long-range atmospheric transport from use regions. However, the direct use of CUPs in the Arctic region can be expected to substantially increase the exposure levels in the Arctic.

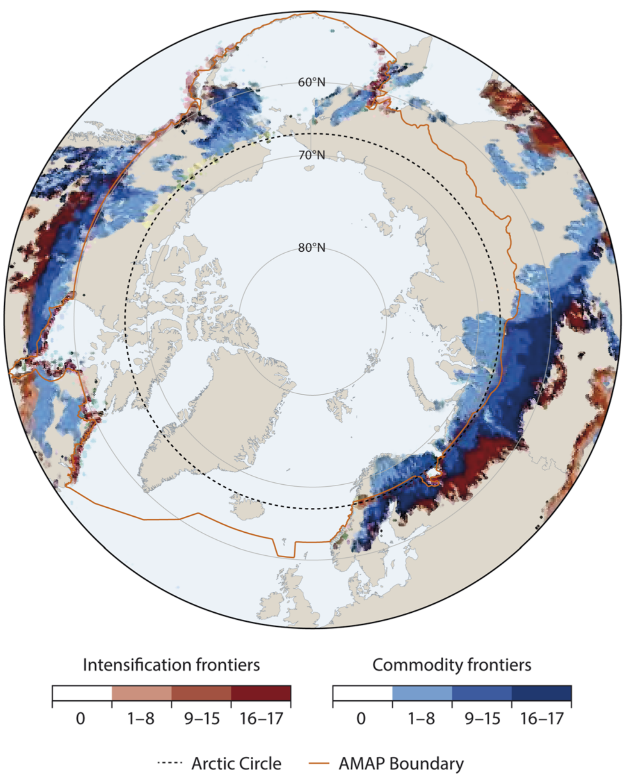

Fig. 26 Map of predicted expansion of agricultural areas in the Arctic and sub-Arctic with the RCP 4.5 scenario based on a map in Hannah *et al.*[252] "Commodity frontiers" refers to suitability for cold tolerant temperate crops such as potatoes, wheat, maize, and soybeans. "Intensification frontiers" refers to northward expansion of existing agricultural croplands. The red line shows the Arctic area as defined by AMAP.

3.3.5 Expansion of military facilities. Military facilities such as airfields and radar stations in the Arctic established during World War II and the Cold War era, had a long history of well documented contamination particularly with PCBs used in radar stations.[213,351] Most sites have undergone remediation and have been cleaned up to various extents[352,353] although others had relatively little cleanup.[354] In addition, there is potential for releases of buried waste soils that contain relatively low concentrations of PCBs (<50 mg kg^{-1}) with climate warming due to permafrost degradation and extreme weather as discussed in Sections 2.3 and 2.6. The abandoned ice sheet military base at Camp Century, on the Greenland ice cap east of Qaanaaq, is an unusual case of a facility that has not been remediated due to being buried by snow and ice following its abandonment in 1964. PCBs and other contaminants known to remain at this site could be remobilized during the present century.[355] Modelling predictions suggest that contaminants could be mobilized in glacial water flow decades before surface runoff is observed at the site.[355]

The ongoing expansion of military facilities such as airports and harbours in the Arctic has the potential to introduce new POPs and CEACs into Arctic environments. Renewed militarization of the Arctic has commenced reflecting increased interest in shipping through the Arctic Ocean and intensified competition for natural resources.[356,357] Competition among the Arctic nations for control of newly emerging shipping routes, natural resources, and territory has intensified.[356,358] Russia has been most assertive in its military upgrades to hundreds of old Arctic facilities and its construction of new ones to protect its Northern Sea Route and expand claims beyond its exclusive economic zone.[357] Over the period 2013–2022 Russia expanded and upgraded the number of military bases in the High Arctic.[359,360] New facilities have been built on Franz Josef Land (Nagurskoye airfield), Novaya Zemlya (Rogachevo airfield), Kotelny (New Siberian Islands), Srednyi Island (Severnaya Zemlya), and on Wrangel Island. The expansion includes new military vessels with ice-reinforced hulls capable of operating in spring and late fall conditions[359] as well as a new oceanographic vessel, the Severny Polyus, launched in 2020, which is designed to drift with the ice and conduct scientific and military related research.[361]

Expansion of military capacity has also occurred in North America. In Alaska this includes upgrading of the Fort Greely Air

Force and missile base in Eastern Alaska[362] as planning for new icebreakers to be used by the US Coast Guard and the Navy.[363] The Canadian navy is bringing ice capable (*i.e.* navigating in first year ice) Arctic Offshore Patrol Ships[364] into service, and planning for two polar class icebreakers is underway.[365] A small naval station has also been opened in Nanisivik Sound in northern Baffin Island on the site of a former mine shipping wharf.[366]

In April 2024, the Norwegian government announced a major expansion of military capabilities over the period 2024 to 2036, with acquisition of new frigates with anti-submarine helicopters, five new submarines, and other military vessels, much of which would be deployed in coastal and Barents Sea waters.[367,368] In Greenland, renovations of the US Thule base (now renamed Pituffik base) near Qaanaaq, are planned as permafrost degradation is impacting the buildings and airfield.[369] The Kingdom of Denmark has announced additional defence spending for its capabilities in the Arctic (Faroe Islands and Greenland), including long-range drones and radar facilities.[370]

In summary, there have been many announcements by circumpolar nations about expansion of military activities ranging from upgrading of existing airfields and marine ports to new naval vessels including icebreakers. The implications in terms of future emissions of POPs and CEACs are unclear but these developments add to the broader expansion of economic activity predicted with a warming Arctic. One major difference in terms of contamination issues is that environmental regulations are now in place and community consultation is required before major developments, unlike the case during the earlier military expansion in the 1950s.

3.3.6 Consultation and engagement of Arctic Indigenous Peoples in future infrastructure development. Historically there was little consultation with northern communities and Indigenous organizations about infrastructure development.[371] However, this situation has changed since the 1990s particularly in Greenland, Nunavut, the Northwest Territories and Yukon, due to greater self-governance.[372] Denmark has given Greenland control of natural resources and, as noted previously, the government of Greenland delegated the power to negotiate agreements with mining companies to the municipal level in 2009.[256] Greenland also complies with the European Union's protocol on Strategic Environmental Impact Assessments (EIAs) which requires the involvement of NGOs and citizens' groups in the assessment of proposals for economic development.[373] Consultation with Indigenous communities and stakeholders is also a legal requirement in Norway, Sweden and Finland[374] and the Nordic Saami Convention requires national governments to negotiate with the Saami Parliaments of each country before making any major economic decisions.[375]

The Federal Government of Canada handed control of decisions on mining and oil and gas development on Nunavut's public lands to the Government of Nunavut in 2024 [257] and signed similar agreements with Northwest Territories in 2014 [376] and the Yukon in 2003.[377] Similarly the province of Québec has included the requirement for consultation with the Inuit of Nunavik in proposed hydroelectric and mining developments.[378] In Canada, consultation with Indigenous groups is required for developments that may adversely affect Indigenous rights.

In Alaska, the Alaska Native Claims Settlement Act in 1971 created regional corporations which have been active in resource development. US Federal government agencies are required to consult Alaskan Native governments.[375] In Russia, the legal obligations for Indigenous participation and consultation in infrastructure and resource development are less clear as there is no general requirement for the Russian government to consult on development decisions. However, some regional governments have enacted more stringent Indigenous consultation mechanisms than those guaranteed by the federal government.[375] All the circumpolar Arctic nations have ratified the United Nations Declaration on the Rights of Indigenous Peoples which includes a number of provisions for consultation with Indigenous Peoples on decisions that affect them.[379]

The expansion of infrastructure in all circumpolar countries must undergo EIAs which generally requires consultation of local communities and Indigenous organizations. There is also a movement for "Indigenous-led" EIA which combines conventional EIA with Indigenous governance.[380] However, the degree to which Indigenous communities are consulted varies widely.[375] Mining and oil and gas development (including pipeline building) has faced the most opposition from local communities.[371] Yet numerous projects in Alaska, the Canadian territories, the Nordic countries and Russia have been approved by local communities and regional governments. In the context of new mining activity in the Arctic, Dale *et al.*[381] referred to this approval as "procedural legitimacy", where support is given locally and by impact assessment agencies because the community accepts the way the decision has been made "based on stakeholder engagement, deliberative processes, structured and open hearings, the accessibility of reports *etc.*". There is also the "instrumental legitimacy" of the expected economic development in terms of potential workplaces and economic growth.[381] While mining and oil and gas development have generally been controversial, the building of roads, expansion of airports, and port facilities seems to have had broader support possibly because of new opportunities for local communities related to travel, improved communication as well as new recreational and subsistence activity.[335,382] The latter infrastructure developments have also facilitated expansion of tourism in Arctic communities which is generally viewed as more sustainable, compared with natural resource development, if it is community controlled and supports traditional cultural values.[276,383] In summary, while there are many predictions of the future expansion of Arctic infrastructure with climate warming, the extent of expansion will depend on the support of Indigenous organizations and communities through various EIA and consultation processes.

3.4 Conclusions regarding expansion of human activity

Expansion of economic development (*e.g.* shipping, mining, fisheries, aquaculture, agriculture, tourism) and infrastructure (ports, airports, roads, urban areas) in the Arctic with climate warming is very likely to happen. Extrapolating CEAC emissions of current processes, this expansion will result in increased local emissions of CEACs and related organic contaminants. However, as of the mid-2020s, there is an uncertain trajectory for this extrapolation given the complex Arctic geopolitical landscape and the need to adhere to best practices in terms of environmental regulations and human rights, such as self-determination of Indigenous Peoples, when it comes to the rights to use and development of their homelands. Technological solutions might be able to reduce emissions and will be more likely to be implemented for developments of a certain size. Developments in the Russian Arctic (including the opening of Northern Sea Route) will be especially important due to the large area, the industry in the area and the relatively high urban population compared to other Arctic regions.

In terms of contamination of Arctic wildlife and fish with POPs and CEACs, the expansion of shipping might contribute to emissions of contaminants which could be persistent and bioaccumulative in the Arctic environment particularly antifouling chemicals. However, even non-bioaccumulative compounds could exhibit adverse effects on Arctic wildlife and fish, as known for PAHs and other compounds, for example with endocrine disrupting properties. Shipping related to fisheries and tourism is also likely to contribute to pollution with plastic litter and MPs, and associated plastics additives. These emissions will occur into the open ocean as fisheries expand north and transpolar shipping lanes open, as well as in harbours.

Similarly, the expansion of agricultural activities will likely result in pesticide use in river catchments draining directly into the coastal marine environments. There is already evidence for contamination by CUPs of open surface waters of the Arctic Ocean north of Russia although the sources and transport pathways are unclear. Aquaculture expansion may also increase pesticide use given the need for antimicrobials and insecticides. While use of pesticides is generally well regulated in circumpolar countries, there is nevertheless the potential for impacts on aquatic and terrestrial organisms. Here, it may also be important that pesticide authorization does not usually consider Arctic environmental conditions, for example low temperatures that may delay degradation processes.

Mining and oil and gas production are regarded as the largest sectors for future economic development in the Arctic, with most development impacting terrestrial environments.[263,309] The main concern is related to localized PAH emissions, which could be substantial given the use of fossil fuels in mining operations and emissions of produced water in oil and gas production.[384] The suite of chemical products used and emitted in mining (flotation/flocculation, hydraulic fluids, lubricant additives) and in oil and gas exploration (*e.g.* hydraulic fracturing fluids) and production (AFFFs, lubricants) is large and potentially includes many CEACs.

The potential increased emissions of POPs and CEACs are only one facet of many ecological and chemical impacts from expansion of Arctic infrastructure and economic development. Townhill *et al.*[289] reviewed the capacity for assessment of the cumulative impacts of multiple environmental stressors on the Arctic marine environment. They noted that there are no available models that allow integrating multiple pollution pressures (for example including nutrients and organic/inorganic contaminants). The literature indicates environmental concerns as a main consideration for economic development projects in the Arctic. Thus, it might be too simple to assume that emissions from current activities can be linearly extrapolated if these activities grow. Furthermore, the argument of critical masses may be important for future infrastructure projects in the Arctic, such as waste collection.

4 Local and secondary sources of POPs and CEACs in Antarctica and future impacts of climate change

Antarctica is increasingly exposed to human footprints including research stations, tourism, fishing operations, and ship incidents. The long-range transport of POPs and CEACs has been documented. Antarctica and the Southern Ocean are also affected by climate change and effects have been reported for the abiotic compartments of the ecosystems, such as ice loss and iceberg calving. In addition, the influence of climatic change on the structure and functioning of Antarctic ecosystems is an emerging issue, as are changes related to effects on the transport and distribution of anthropogenic chemicals from local and remote sources.[8]

4.1 Glacial releases of POPs in Antarctica

As described for Arctic glaciers in Section 2.1, melting glaciers have also been identified as a source of POPs to the surrounding environment in the Antarctic, for example increasing exposure to DDTs in local biota.[385] Although the global use of DDT had decreased by 90% since the late 1960s,[386] DDT concentrations in Adèlie penguin (Pygoscelis adeliae) eggs did not decrease, in contrast to the decrease observed in similar Arctic species, which was attributed to melting glaciers.[63] DDT has been used in the Southern Hemisphere without interruption, but DDT deposition in Antarctica has been low. However, Geisz *et al.*[385] estimated that 3.9 t of DDTs could be stored in the Antarctic Peninsula ice sheets and measurable levels of ΣDDTs (*p*,*p*′-DDT > *p*,*p*′-DDE) were detected in glacial runoff and in near-shore plankton around Palmer Station on the Antarctic Peninsula.[387] Geisz *et al.*[385] reported that other authors estimated that 1–4 kg per year of DDTs were released into the Antarctic marine environment due to glacier ablation.[388,389] While these findings highlight the importance of pollutant release from melting glaciers in the Antarctic region where enormous masses of ice may melt as a consequence of climate change,[390–392] the overall estimation of DDT storage in the Antarctic ice sheet is based on limited data.[393] Nevertheless, an increasing importance of climate change-driven ice melt as a secondary source of contamination is expected in the Antarctic as well as in the Arctic, with a potential impact on local ecosystems. In Antarctic seabirds, an uncertain time trend in concentrations of POPs was reported: after a little decrease in their concentrations, with a delay in respect to other areas,[394] an increasing trend of DDT was observed again in Antarctic penguins and migrating seabirds starting from the 1990s. The authors ascribed this trend to the increasing release due to global warming.[395]

Changes in vegetation cover particularly in the Antarctic Peninsula could also influence exchange of POPs with the terrestrial environment. Cabrerizo *et al.*[396] concluded that changes in vegetation cover can potentially exert a significant influence on POPs circulation and estimated that a 1 °C increase in Antarctic temperatures would increase the soil–vegetation organic carbon which would trap greater amounts of semi-volatile POPs.

Climate change-related effects in West Antarctica have been recorded for decades, but only recently in East Antarctica, *e.g.* the collapse of the Conger ice shelf in East Antarctica on 15–18 March 2022 after an intense heat wave arrived in Antarctica in March 2022.[397] Some processes responsible for ice melting have been discovered only recently, such as the melting of ice sheets and glacier tongues from their underwater base due to a combination of warm deep waters reaching the coastal areas and warming atmospheric conditions.[398] Despite this process being alarming, a major release of POPs in the Antarctic ecosystems may be ascribed to sea ice melting, which can release pollutants recently transported to the region and trapped in the seasonal sea ice (old deep ice layers might not be contaminated by POPs).

4.2 Releases of contaminants from permafrost in Antarctica

As discussed in Section 2.3, the thawing and degradation of Arctic permafrost can lead to release of POPs and CEACs, which has mainly been studied for PAHs. Releases of PAHs from thawing permafrost might also play a role in the Antarctic environment. Increasing PAH concentrations in fresh water in permafrost catchments during the austral summer were described by Szopińska *et al.*[399] and Potapowicz *et al.*,[400] based on a comparison of seasonal PAH concentrations in glaciated and non-glaciated catchments on King George Island in Antarctica. However, these authors concluded that PAHs were mostly associated with the activity of research stations with less input *via* long-range atmospheric transport from South America. An earlier study also identified atmospheric sources of PAHs from research stations in the South Shetland Islands and also found that the highest PAH concentrations related to a fuel spill in permafrost were in the upper soil horizons which acted as a barrier for downward PAH migration.[401]

4.3 Expansion of Antarctic infrastructure and human activity

Under the Antarctic Treaty System[402] economic development of renewable energy, hydrocarbons, and minerals, the exploitation of geographical areas on the continent and in the Southern Ocean extending from the Antarctic coast to 60° South latitude is not permitted. However, the Antarctic Treaty System is up for review in 2048 and some of its restrictions may be challenged.[403] The expansion of fisheries and exploitation of seabed mineral resources are regarded as possible economic activities that might expand later in this century[403] although any expansion would need to be approved by three-quarters of the 29 countries that are Antarctic Treaty Consultative Parties.[402]

The IPCC 5th Assessment[404] estimated an expansion of 17 000 km^2 of ice-free areas in the Antarctic by the end of the century, which corresponds to a 25% increase. However, based on satellite data from the past 40 years the overall trend has been for increased sea ice area.[405] The IPCC Report on the Ocean and Cryosphere[225] has noted that there is low confidence in projections of Antarctic sea ice because of challenges in modelling complicated processes involving the ocean, atmosphere, and adjacent ice sheet. Nevertheless, as global warming continues during the 21st century it seems reasonable to conclude that there will be greater ice-free areas and that this will drive ecological changes and the expansion of human activities and impacts, facilitated by accessibility and less extreme weather. Along with this increase in human activity, increasing release of contaminants from local sources can be expected, unless active measures are taken to reduce emissions, as discussed for the Arctic in Section 3.

Antarctic tourism, mainly on cruise ships, increased from 10 000 visitors per season in the early 2000s to more than 100 000 (on ships only or as landed visitors) in 2023.[406] Tourism is expected to expand further with increased accessibility due to ice loss. As discussed for Arctic tourism, the increased tourist ship traffic could bring with it emissions of POPs and CEACs to ocean waters related to antifouling paints and wastewater discharges, as well as atmospheric emissions from fossil fuel combustion.

The continent and the Southern Ocean have been impacted by human activity on a later timescale than the Arctic. Brooks *et al.*[407] highlighted that human impacts are concentrated in the rare deglaciated areas (~1% of lands), which are also some of the most sensitive ecosystems.[408] Recently, research has started to focus on management of human impacts on the continent and ocean, in particular regarding alien species, climate change, contaminants,[409–412] and expansion of infrastructure.[407,413,414] An important economic activity, historically, has been whaling and fisheries which led to overexploitation and near extirpation of whales, seals, and some finfish populations.[403] The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) of the Antarctic Treaty System, has successfully managed Southern Ocean marine fisheries since 1982.[402,415] With increasing accessibility of the Antarctic region and range shifting of commercially valuable marine species from mid to high latitudes with climate change, pressure for expanded fishing might increase.[415] As discussed for expansion of Arctic fisheries, this would potentially lead to losses of plastics litter, and releases of MPs and other contaminants. However, expansion of fisheries activity south of the 60° would need to be approved by CCAMLR.

Unlike the Arctic, the Antarctic continent and islands do not have permanent communities or Indigenous Peoples utilizing local fish and wildlife, but more than 80 scientific stations operate in the area seasonally or permanently (Fig. 27). These stations have an impact on the surrounding environment despite the strict environmental rules to operate following the

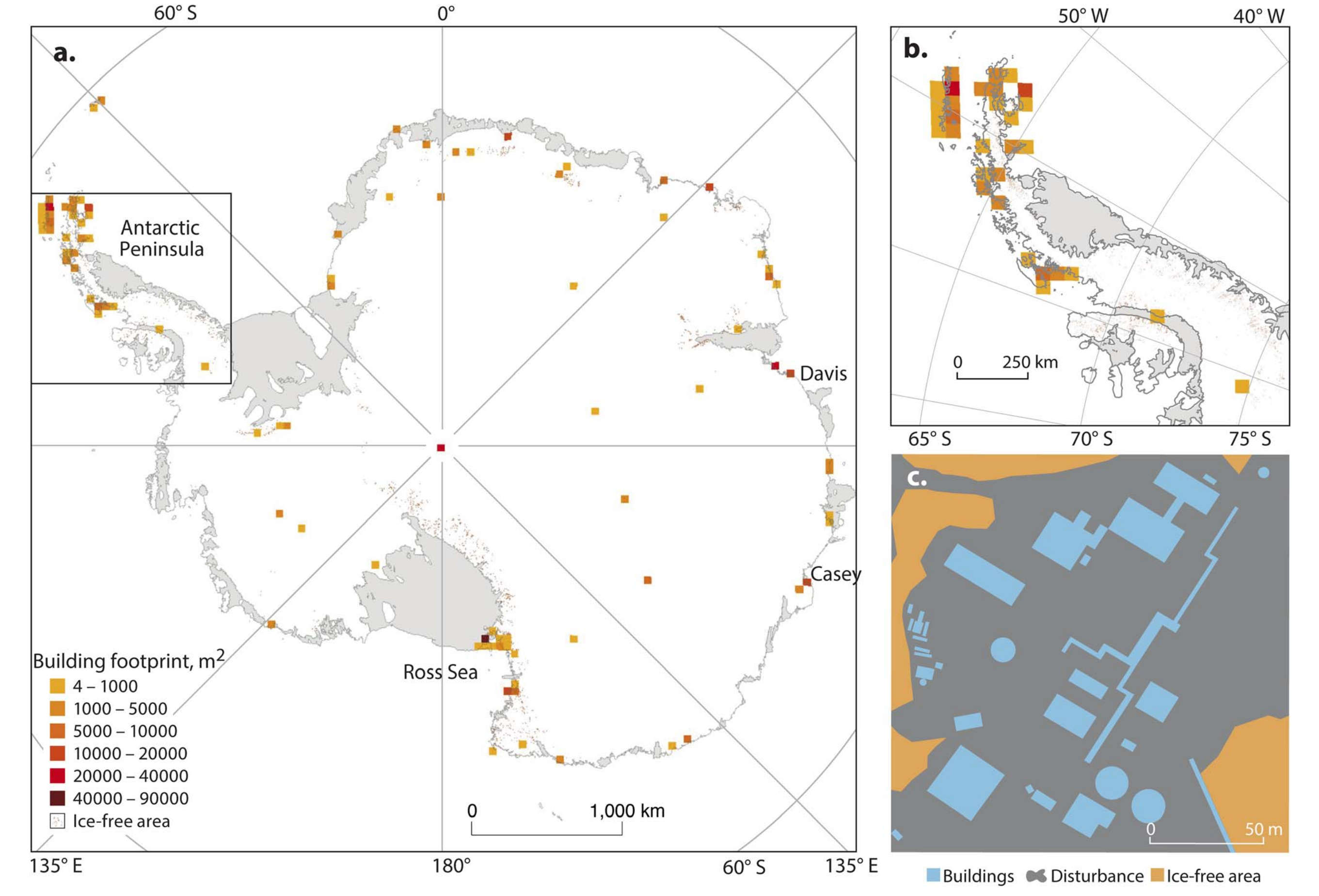

Fig. 27 Distribution of the building footprint in Antarctica: (a) distribution and density of the building footprint represented within 50 × 50 km^2 cells. These cells may include multiple stations. (b) Density of the building footprint within the Antarctic Peninsula—the area acknowledged as the most developed and vulnerable to threats from climate change and non-native species. (c) Example of the detail applied, showing the buildings and disturbance footprint mapped within Australia's Davis Station. Adapted from Brooks *et al.*[407]

Antarctic Treaty.[402] Scientific stations in Antarctica are local sources of MPs.[5,8] Fibers of technical clothing used by personnel operating at the nearest station (Mario Zucchelli Station, Ross Sea coastal area) matched with those detected in the Antarctic whelk (*Neobuccinum eatoni*), suggesting the wastewater outfalls as their local source.[416] The data reported for Antarctic whelks were comparable to those reported for Arctic marine whelks (Buccinidae),[417] suggesting comparable MP contamination in both polar regions. The same polymeric characteristics were reported for historic samples of surface seawaters from the Ross Sea area.[418] The abundance of lines/microfibers of polyethylene terephthalate (PET) in the region declined with increasing distance from the coast.[419] Similar matching MPs in the marine environment and organisms and technical clothes used by personnel was reported near McMurdo Station.[420] Climate change may impact plastic pollution fluxes and concentrations.[421] In the Arctic, sea ice has been shown to accumulate MPs, leading to higher concentrations than those in water.[422] Consequently, where seasonal and climate change-induced sea ice melting is high, the presence of MPs in the marine ecosystems is expected to increase due to the release of ice-trapped MPs, a process that can also take place in the Antarctic.

4.4 Conclusions on future impacts of development in Antarctica

Projections of future trends of POPs and CEACs in the Antarctic affected by climate change and, potentially, increasing human activity are difficult due to limited data in comparison to the Arctic environment and challenges in modelling trends, *e.g.* in sea ice extension. Future developments to be studied and monitored in Antarctica include the following questions:

(1) Are POPs accumulated in the Antarctic ecosystems and concentrations in biota at their peak? Recent findings are still ambiguous.[395,423]

(2) Will climate-driven Antarctic sea ice and glaciers melting, and thawing permafrost affect the bioaccumulation of POPs and CEACs in marine and terrestrial ecosystems?

(3) Will human activity in Antarctica, such as tourism and commercial fishing in the Southern Ocean, increase due to climate change and lead to increased local emissions of POPs and CEACs?

(4) Will climate-related changes in biogeochemical cycles affect contaminant releases from the scientific stations, for example from waste?

(5) How and to what extent will climate change affect ecosystem structure and functioning and thus bioaccumulation processes in Antarctic food webs?

Responses to these questions may come from internationally coordinated studies of the Antarctic region and from an integrated and bi-polar approach.

5 Conclusions and recommendations

This assessment has documented the emerging evidence for releases of POPs and CEACs as the Arctic climate warms and considered the impacts of increased infrastructure and economic development. We have also considered these issues for the Antarctic. We have focused on impacts on local and Indigenous Arctic communities in addition to their relative importance as local sources. The information on releases of POPs and CEACs in the Arctic in relation to different aspects of climate change is poor, with the exception of PAHs, for which emissions to the atmosphere from shipping and wildfires have been modelled and measurements from permafrost degradation are available. Deposition of POPs/CEACs to Arctic glaciers is also relatively well studied although studies of releases to waters of importance to local communities are more limited.

Recommendation: assessment is needed of how various types of contaminant sources in the Arctic (local primary anthropogenic and secondary) and sources outside the Arctic (primary anthropogenic and secondary) will contribute in future scenarios of climate change including economic development activity. While future PAH emissions have been modelled there is a need to measure and model other CEACs, particularly those related to increased economic activity in the Arctic (*e.g.* fishing, aquaculture, shipping, mining, oil and gas).

Arctic glaciers have been identified as reservoirs of both legacy POPs and CEACs and future climate scenarios point to accelerated melting. Some CEACs such as nonylphenol and OPEs are present at much higher concentrations in snow/firn or meltwaters than legacy POPs or PFAS. Releases from summer melting of glaciers could be an important issue for exposure of fish and wildlife in proglacial food webs as well as for water quality of local communities. The measurement of fragrances in glacial snows illustrates it is also likely that other widely used organic chemicals are present. The long-range atmospheric transport and deposition of MP particles on glaciers have been documented. Similarly, more rapidly melting sea ice can cause local pulses of released contaminants into marine waters.

Recommendation: there is a need to assess the relative and absolute contributions of increased remobilization from previously deposited (secondary) sources in the cryosphere and their impacts on the surrounding environment, including accumulation in food webs.

Recommendation: future research on POPs/CEACs in glaciers needs to focus on a broader array of substances. Releases of contaminants due to the changing glacial accumulation and melt regime would be best examined through a dedicated pollutant release model. Such a model would also help identify maxima in the remobilization of legacy POPs and CEACs already accumulated in glacial ice as well as potential cumulative release amounts. As recommended by Townhill *et al.*,[289] in addition to estimating the reservoir capacity of glaciers, modelling should take into account the release dynamics, fate, and exposure of vulnerable ecosystems/populations.

The measurements of MPs in northern flowing rivers in Russia illustrate the potential for contamination from urban environments south of the polar region to be sources for the Arctic coastal seas. Other contaminants (*e.g.*, PAHs, pharmaceuticals, pesticides, plastic additives) are likely travelling by the same routes and are likely to increase with future development. Rivers reflect both local inputs and long-range environmental transport from southern, sub-Arctic regions. Indeed, fluxes of HCHs into the Kara Sea from the Ob and Yenisey Rivers ranged from 116 to 130 kg per year in the early 2000s, and other POPs were also detected in the same study.[424] The relative importance of local emissions from Arctic communities near river mouths *versus* remote riverine sources further south is unclear, as are dynamics related to more precipitation and higher run-off.

Recommendation: given likely increased economic activity (agriculture, mining, oil and gas) in the catchments of Arctic rivers in the future, there is an obvious need for data on POPs, CEACs and MPs including plastic additives in north flowing rivers given the predictions of increased river inflows, the influence of freshwater inputs to the Arctic Ocean, and the fact that aquatic food webs that local communities rely on are likely to be impacted.

Recommendation: although the majority of the information on riverine contamination is from large rivers emissions of contaminants into smaller catchments could also be important.[73] Given that many Arctic communities are located on smaller rivers as well as the increased concerns with coastal erosion, there is a need to assess POPs and CEAC inputs from those rivers and coastal areas.

A substantial amount of information is available on PAHs in permafrost influenced peatlands and river and lake sediments but information on the presence or release of other organic contaminants is sparse, although the available information indicates releases of POPs as well. While the PAH burden is mainly from natural sources except for locations near industrial sites, a significant potential exists for releases due to deepening of the active layer and *via* thaw slump formation and coastal erosion, and thus sediment movement. All PAH constituents may become remobilized and transported out in globally significant amounts. The quantification of mobilization remains a challenge. Given the huge extent of the permafrost regions in the Arctic and limited measurements of PAH concentrations and fluxes, and few measurements of other POPs, major uncertainties persist with respect to the quality and quantity of pollutants in permafrost. Simple inventories of PAHs and other POPs in permafrost soils/peatlands can be made by analogy with estimates recently made for mercury.[425]

Recommendation: future research on permafrost degradation should address not only PAH and POPs/CEAC remobilization fluxes and the factors driving them, but also provide information on the potential harmful impacts of such fluxes on water and food resources for Arctic communities, including through the agricultural use of permafrost soils. The risks related to remobilization of POPs and CEACs from *e.g.* permafrost and ice should also be included in climate-related risk management policies and strategies implemented in the Arctic. The remobilization hazard needs to be considered especially with respect to impacts on aquatic environments of importance to local communities.

The recent report on the vast extent of industrial and contaminated sites on permafrozen ground in the Arctic and potential for releases with climate warming raises many concerns.[3,4] Knowledge is uncertain of the number of industrial and contaminated sites, and also types of contaminants in them, particularly for the Russian Arctic. Old infrastructure has the potential to fail leading to high uncertainty in the prediction of the total impact of permafrost degradation upon contaminant introduction.

Recommendation: there is a need for an expanded database of polluted sites across the Arctic (due to mining, oil and gas development, former and current military bases, and community solid waste landfills). This would build on contaminated sites databases for Alaska, Canada, and Svalbard.

Wildfires are clearly important sources for inputs of POPs to the Arctic *via* long-range transport with PAHs being the most studied example. More rapid warming within the Arctic region compared to the neighboring forested sub-Arctic and north temperate regions may mean that more of these emissions could be considered local sources rather than from long-range environmental transport. The increased frequency of tundra fires within the Arctic is a growing concern for communities above the tree line and may impact caribou and reindeer populations important to Indigenous communities. The effects of fire-suppression chemical use in Arctic wildfires are largely unknown and understudied.

Recommendation: while PAH emissions and deposition has been estimated, the extent to which other POPs/CEACs might be mobilized from the tundra and released due to wildfires needs to be investigated. Indeed, the relative importance of smaller local fires *versus* deposition from fires in forested zones south of the Arctic Circle needs to be better understood.

Recommendation: there is a need for further information on the use of fire-suppression products and on the chemical components in the formulations.

The impact of climate warming on sub-Arctic and Arctic surface waters is an important issue for most Arctic communities. Increases of parameters such as turbidity, chlorophyll and DOC are likely to be correlated with greater inputs of PAHs, legacy POPs and CEACs from secondary sources in river and lake catchments. The focus on contamination of freshwater environments by POPs and CEACs under previous AMAP assessments[6,199,426] has generally been on persistent and bioaccumulative contaminants. However, the emerging concerns related to impacts of climate change on surface water quality suggest that additional effort should focus on PMOCs in the Arctic and that the importance of clean drinking water should be considered at the same level as the importance of food security.

Recommendation: models of long-range environmental transport need to be modified to include the unique pathways of PMOCs (*e.g.*, riverine transport, percolation *via* the deepening active layer, and from glaciers).

Recommendation: measurements should include CEACs that are potential PMOCs, which might need other analytical methods than those typically used for hydrophobic compounds.

While impacts of coastal erosion, landslides, and flooding on physical characteristics of coastlines and on infrastructure in the Arctic have been relatively well documented, a major knowledge gap exists for release of organic contaminants such as POPs and CEACs. Contamination hotspots, such as FUD sites, are a particular concern, with regard to permafrost degradation, coastal erosion and flooding. However, coastal erosion and flooding pose a broader risk for local communities,[236] which also has implications for pollution of drinking water and aquatic ecosystems that have traditionally supplied fish and wildlife.

Recommendation: there is an urgent need to include consideration of release of, and exposure to, POPs and CEACs as part of risk assessments of impacts of coastal erosion and flooding and to identify communities vulnerable to such effects.

Activities related to shipping, mining, oil and gas exploration and exploitation, agriculture, marine fishing, and tourism are predicted to accelerate in the Arctic due to climate change. However, as of the mid-2020s, the rate of expansion is quite uncertain due to the complex state of affairs including the geopolitical landscape, the need to adhere to best practices in terms of environmental regulations, consultation with Indigenous Peoples, and the high costs still associated with commercial activities in remote regions. Nevertheless, the proposed or predicted expansion of infrastructure and economic activities is very likely to influence emissions of POPs and CEACs from local sources within the Arctic. However, linear extrapolation from current situations might be a simplification, given the complexity of socio-economic factors, technological developments and future governance priorities.

Recommendation: projections of economic developments in the Arctic should be updated and consolidated to reflect changes in geopolitics and socio-economics. These projections are currently rarely linked to the use and emissions of chemicals, which should be improved.

Modelling of PAH emissions within the Arctic region concluded that they would increase due to expansion of shipping even though emissions in the mid-latitudes would be declining.[282] PAHs represent the best studied organic contaminants in relation to impact of climate change in the Arctic. While industrial chemicals such as short chain chlorinated paraffins, Dechlorane Plus and UV-328 (recently added to the Stockholm Convention), will be somewhat less likely to enter the Arctic *via* products used for building new infrastructure and in various economic activities, their replacements are likely to do so. Uses of these replacements and, more broadly, of other CEACs in products such as vehicle tires, lubricants, and plastics that are imported into the Arctic (*e.g.* see ref. 427) is a major knowledge gap.

Pesticide use for aquaculture, crop productions, and in antifouling paints, is relatively well documented due to registration requirements in circumpolar countries. Thus it may be possible to model the emissions of pesticides used in expanding northern agriculture or in northern urban areas. Similarly, emissions of pharmaceuticals, *e.g.* antimicrobials from wastewater sources could be estimated based on current or projected future urban populations.

Recommendation: there is an urgent need for additional environmental measurements and modelling of emissions of CEACs associated with the expansion of economic activity in the Arctic. Pesticides and pharmaceuticals would appear to be "low hanging fruit" in this regard given knowledge of uses, methods of analysis, and generally well documented physical–chemical properties. Emissions of some industrial chemicals *e.g.* PFAS in AFFFs at airports may be another group that could be modelled given knowledge of airport contamination in the mid-latitudes.

Future expansion of Arctic infrastructure and economic activity with climate warming will depend on the support of Indigenous organizations and northern communities through various EIA and consultation processes. However, the degree to which Indigenous Peoples are consulted varies quite widely among circumpolar nations with Russia and the USA having less formal processes for Indigenous consultation than the six other circumpolar countries.[375]

Recommendation: thorough assessments of local sources of POPs and CEACs require much greater involvement of Indigenous Peoples to identify issues, monitor events and trends, and interpret and communicate findings than has historically been the case. Village or community-led environmental monitoring should be enhanced. The environmental contaminants data from community led projects can also be used for broader applications such as consultations on economic development.[428]

Data availability

This is a review article that draws on results and conclusions from peer reviewed studies of local sources of Persistent Organic Pollutants (POPs) and Chemicals of Emerging Arctic Concern (CEACs) published to May 2024. Two supplementary tables present summarized concentrations of POPs in glacier snow and meltwater and in permafrost soils. No original data are included.

Conflicts of interest

There are no conflicts to declare.

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