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The role of the Arctic Monitoring and Assessment Programme (AMAP) in reducing pollution of the Arctic and around the globe

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ABSTRACT

This article presents the initiation and implementation of a systematic scientific and political cooperation in the Arctic related to environmental pollution and climate change, with a special focus on the role of the Arctic Monitoring and Assessment Programme (AMAP). The AMAP initiative has coordinated monitoring and assessments of environmental pollution across countries and parameters for the entire Arctic region. Starting from a first scientific assessment in 1998, AMAP's work has been fundamental in recognizing, understanding and addressing environmental and human health issues in the Arctic, including those of persistent organic pollutants (POPs), mercury, radioactivity, oil, acidification and climate change. These scientific results have contributed at local and international levels to define and take measures towards reducing the pollution not only in the Arctic, but of the whole globe, especially the contaminant exposure of indigenous and local communities with a traditional lifestyle. The results related to climate change have documented the rapid changes in the Arctic and the strong feedback between the Arctic and the rest of the world. The lessons learned from the work in the Arctic can be beneficial for other regions where contaminants may accumulate and affect local and indigenous peoples living in a traditional way, e.g. in the Himalayas. Global cooperation is indispensable in reducing the long-range transported pollution in the Arctic.

1. Introduction

For a long time, the Arctic was seen as one of the last pristine areas of the globe. However, monitoring, research and assessments performed over the last 30 years have documented that the Arctic area (Fig. 1) is not as pristine as earlier believed. Long-range transported pollutants reach the Arctic, as well as other remote areas all over the world.

Historically, sources of pollutants within the Arctic had especially been linked to industrial sites and military installations. Some of the highest emissions of sulfur dioxide (SO_2) and heavy metals have occurred from the large smelters at Norilsk on Taimyr Peninsula and on Kola Peninsula since the 1930s (Fig. 1). These smelters did not use filters to reduce the emissions, resulting in significant pollution of forests and freshwater ecosystems, both in the immediate surrounding of the smelters and far away [1] (Fig. 2). The Arctic also held sources of radioactive substances, mainly the nuclear weapon test site at Novaya Zemlja, the storage of radioactive fuel and waste on the Kola Peninsula and disposal of materials (containers and nuclear submarines) in the Barents and Kara Sea [1].

However, the main pollution issues of the circumpolar Arctic include the long-range transport of persistent organics pollutants (POPs) and mercury, primarily carried to the Arctic by air, rivers and ocean currents from Asia, North America, and Europe [1,2]. The bioaccumulation of these chemicals in ecosystems and their ability to biomagnify in the food chain has led to the exposure of Arctic coastal peoples to harmful chemicals through the consumption of traditional Arctic food, including marine mammals that are high in

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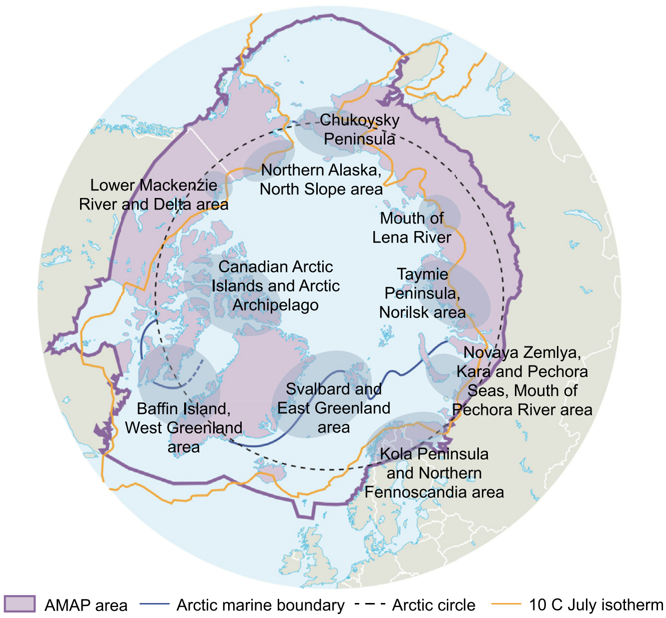

Fig. 1. The Arctic area as defined by the Arctic Monitoring and Assessment Programme (AMAP). The figure is modified from Ref. [2].

the food chain. Fish and sea mammals have been a significant part of the traditional diet of the Northern and Arctic indigenous and local peoples living along the coasts of North America, Northern Europe, Greenland, and Chukotka, providing nutrients and energy.

The objective of this paper is to describe and discuss the historical development leading to the Arctic Monitoring and Assessment Programme (AMAP). It addresses AMAP's impact on pollution control, both in the Arctic and around the world, the impact of global pollution control on pollutant levels in the Arctic, as well as current and future challenges.

2. From cold war to Arctic collaboration: the Arctic Environmental Protection Strategy (AEPS)

After the end of World War II the two military alliances, the North Atlantic Treaty Organization (NATO) and the Warsaw Pact, constructed military bases and radar installations in the Arctic, nuclear submarines were operating under the sea ice, and military airplanes crossed the Arctic area armed with nuclear weapons (Fig. 3). The cold war was also taking place in the Arctic. It lasted until the mid-1980s when US President Ronald Reagan and Soviet Secretary General Michael Gorbachev started to communicate and agreed to reduce the nuclear arsenal and thereby the global nuclear threat. In 1987, Gorbachev held a speech in Murmansk to honor the citizens for their fight during World War II. In this speech, he called for a change in the Arctic, to reduce the military activities and to turn the Arctic Ocean into an ocean of peace, science and prosperity [3]. He also called for a science cooperation in the Arctic and an environmental program focusing on Arctic pollution. Prior to his speech, there had been some negotiations between the East and West about the possibility to initiate an Arctic science cooperation, and in 1990, the International Arctic Science Cooperation (IASC) was established [4]. East and West were also represented in the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP), which began operations under the United Nations Economic Commission for Europe (UN-ECE) in 1977 and initially focused on acid rain [5]. It became a cornerstone of the Convention on Long-range

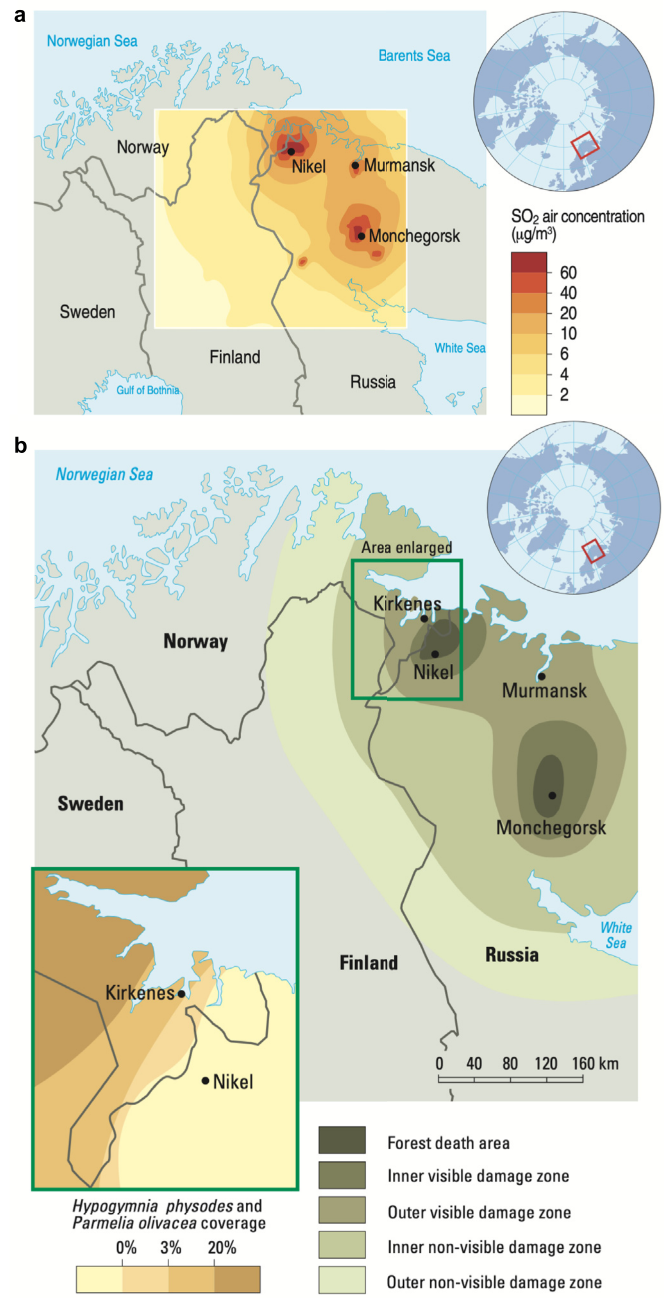

Fig. 2. Emissions of SO_2 at Pechenga and Norilsk (**a**) and effects on forests in Russia, Finland and Norway (**b**) [1,23].

Transboundary Air Pollution (CLRTAP), which was signed in 1979 and entered into force in 1983.

Based on Gorbachev's speech, the Finnish government initiated diplomatic activities among the Arctic countries and organized an Arctic environmental meeting in Rovaniemi, Finland, in September 1989. This process led to the establishment of the Arctic Environmental Protection Strategy (AEPS) signed in Rovaniemi in June 1991 by the Ministers of Environment of the eight Arctic Countries. As part of this declaration, AMAP was established, with the mandate to monitor and assess the pollution of the Arctic environment (ocean, land, rivers and air) and associated pollutant exposure of humans, especially of Arctic indigenous and local communities, and to provide policy recommendations based on scientific assessments. At

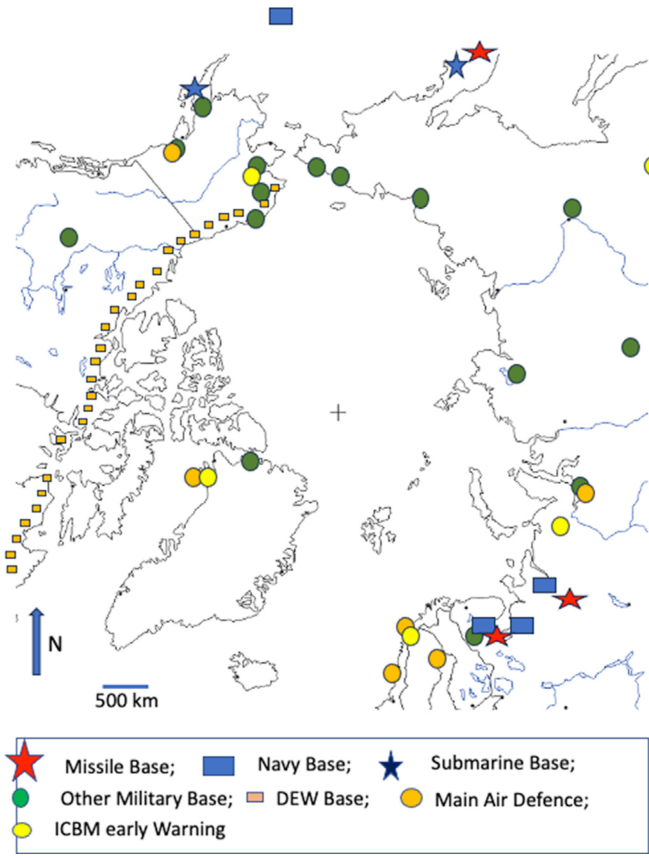

Fig. 3. Military installations reported after the cold war period. The figure is based on combined information from openly accessible reports [51–54].

this meeting, Norway offered to host the Secretariat for AMAP, where it was established in 1992 [6–8].

Originally, groups under the AEPS included AMAP, a group on Conservation of Arctic Fauna and Flora (CAFF), Emergency, Prevention, Preparedness and Response (EPPR) and the Protection of the Arctic Marine Environment (PAME). These were established as Task Forces and later renamed as Working Groups, a permanent structure, at the first AEPS ministerial meeting in Nuuk, Greenland in 1993 [9]. However, the Canadian government had reservations about the AEPS and worked towards an Arctic organization focussing more on the Arctic indigenous peoples' situation and security. In 1996, the Arctic Council was established in Ottawa, Canada, based on the AEPS structure and with the objective to continue the initiated work, with a stronger focus on the health and lifestyle of Arctic indigenous peoples, but not including security [10]. Thus, AMAP, CAFF, EPPR and PAME became Working Groups under the Arctic Council.

3. The development of the Arctic Monitoring and Assessment Programme (AMAP)

Prior to the ministerial meeting in Rovaniemi in June 1991, a consultation meeting regarding an Arctic monitoring programme had been held in Leningrad (today St. Petersburg) in March 1990 between Norwegian and Soviet Union experts. Thereafter, an international workshop was held in Oslo, Norway, in November 1990, where the draft program for AMAP was upgraded to secure linkages to ongoing research and monitoring programs, such as EMEP, the Oslo and Paris Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) and the International Council for the Exploration of the Seas (ICES). These synergies have led to greater international awareness of pollution issues and attempts to integrate different aspects of pollution across geographical regions. A significant part of the AMAP draft program is reflected in the ministerial declaration of the meeting in Rovaniemi [6,7].

In 1991, AMAP was given the mandate to monitor and assess the pollution of the Arctic from any sources. This wording was chosen to ensure that military sources were not excluded from the AMAP program (Fig. 3) and enabled the comprehensive and integrative assessment of various aspects of Arctic pollution (Table 1). The first AMAP meeting in Tromsø, Norway, in November 1991 was attended by two indigenous organizations involved in AEPS - the Nordic Saami Council and the Inuit Circumpolar Council (ICC). Observers were the United Nations Environmental Programme (UNEP), the UN-ECE, ICES, IASC, and three non-Arctic countries, the UK, Poland and Germany. One of the innovations in the AMAP concept was that indigenous peoples' organizations were included as equal partners and participants in the program, together with the Arctic states, and that assessments were based on integrations of scientific and local/indigenous knowledge.

During the discussions in Tromsø in 1991, the Scandinavian countries favored a mandatory pollution monitoring program in the Arctic, while the position of the USA was that all work should be based on voluntary contributions, which was the final decision. Later, the Senior Arctic Officials (SAOs), representatives of the Arctic countries' ministries of foreign affairs overseeing the work of the Arctic Council between ministerial meetings, decided that if two countries wanted to fund a project, it could be initiated even if other Arctic countries did not contribute to the project. This decision turned out to be a very efficient strategy for financing the monitoring and assessment work as priorities differed between the Arctic countries. For example, at the beginning of the AMAP work, Norway and Russia were eager to analyze and reduce all types of radionuclide sources in the Barents region, while Canada and Denmark were interested in clarifying the threats from pollutants to Arctic indigenous and local peoples. Canada and Sweden took the lead on POPs, and Finland was most concerned about the acidification of Northern lakes and forests, resulting from emissions from the Russian smelters.

Based on these national interests and following this collaborative approach, AMAP established six expert groups. Table 1 shows the priority areas for the first AMAP assessment performed between 1992 and 1997 and the leading countries for the work. The leading countries agreed to allocate the necessary funding and personnel to secure the assessment work. The organizations for the Arctic indigenous peoples were also invited to nominate experts, but due to insufficient national financial support, only a limited number of representatives pariticpated in the initial years. Over the years all countries have contributed to all assessment groups, securing a comprehensive circumpolar coverage for monitoring and assessing the pollutants in question. However, the ice-covered Arctic Ocean has always been a data gap as no permanent stations exist and sampling had to rely on icebreaking ships of opportunities. Costs related to AMAP contributions, e.g. for monitoring and research programs and time for assessment experts, were generally covered from national budgets.

4. Environmental monitoring and assessments performed by AMAP

After decisions on priority pollutants, a monitoring program was designed for different parameters to generate the necessary data from Arctic ecosystems and humans to perform a state-of-the-art scientific assessment. A detailed monitoring program including integrated quality assurance and control (QA/QC) protocols was designed [11,12] to ensure harmonization across the Arctic and with ongoing marine and atmospheric monitoring programs at lower latitudes. However, the primary responsibility for the implementation of monitoring activities was with the individual Arctic countries. The data obtained in the monitoring initiatives were assessed from a circumpolar perspective, following an assessment strategy developed by AMAP [13]. Over the years, both programs have been updated [13,14].

The AMAP assessments are produced by scientific experts from the eight Arctic countries, representatives of Permanent Participants, i.e. organizations of indigenous peoples, and experts from countries and organizations that are observers to AMAP. Assessments undergo national reviews to ensure completeness with regard to available data, and an international peer-review. While priority areas and assessment questions can be identified by policy makers, the scientific assessment process is conducted by independent scientific experts. The AMAP scientific assessment reports are signed off by the scientists involved, and all of them are listed as authors or contributors. The assessment reports, together with summaries for policy makers, are presented to Arctic ministers at the biannual ministerial meetings. Several assessments have also been published as scientific articles in the peer-reviewed scientific literature [15–17].

The first comprehensive AMAP assessment was presented at the AMAP conference in Tromsø in April 1997. With 440 participants, this was the largest Arctic science conference ever held by that time. A few weeks later, the key results and recommendations were presented to the AEPS ministerial meeting in Alta, Norway. The first scientific assessment report [1] was named the “brick stone” as it consisted of 871 pages addressing several aspects of Arctic pollution in a coherent manner. To make the results readable for politicians and the general public, a science writer was engaged to write the “layman” style report “Arctic Pollution Issues” [2]. In addition, a video was prepared to convey the observations and findings to the wider audience.

For most people, also scientists, some of the results were a surprise. The main source for the pollutants of the Arctic was not - as most people expected at that time – originating from the former Soviet Union (Fig. 4)!

The main results of the first assessment were as follows:

- **The POPs** observed in the Arctic ecosystems and humans, such as organochlorine pesticides and industrial chemicals, originated from all over the Northern hemisphere and were transported to the Arctic by the atmosphere, rivers and oceans. The atmospheric transport may only take a few days from the sources at mid-latitudes to the Arctic, while contaminant transport by the large rivers typically takes one to two years, and up to several years or even decades if contaminants are transported by ocean currents. Recent AMAP POP assessments have identified several new chemicals in Arctic ecosystems and documented that the changing climate influences the fate of contaminants in the Arctic [18,19].
- **Mercury** entering the Arctic was mainly carried by air in the gaseous phase, from all over the world, but the main sources were coal-fired power plants in Southeast Asia (SEA), which is still valid today. No filters or scrubbers exist that can remove mercury from the gas phase. A new process was identified that takes place in the Arctic during the spring when the sun returns to the North: Photochemical reactions involving reactive halogens on frost flowers on the ice surfaces lead to the rapid release of accumulated mercury into the Arctic environment (Fig. 5). Details on these processes can be found in the respective AMAP reports on mercury [1,20–22].
- **The acidification** of lakes and land in the North was mainly linked to the emissions from the smelters (Fig. 2). Although large areas of the North American Arctic were considered to be vulnerable to acidification the assessment did not corroborate this anticipation [1,23]. In recent years, the acidification of the oceans has gained increasing interest. It is related to increases in dissolved CO_2 in the oceans and has been the subject of recent AMAP reports [24].
- **The oil pollution** of the Arctic was low, except for some spill areas from corroded pipelines on the Russian tundra. Apart from these spills, the main source of oil pollution was linked to natural seeps, e.g., in the McKenzie River. However, if an oil spill happened near the sea ice edge, it could stay in the area for years due to slow natural degradation and the lack of adequate cleaning equipment deployed along the Arctic coasts that can operate under sea ice condition. This is still the situation in the Arctic area today [1,25].
- **The human health** assessment documented that the Arctic indigenous and local communities in Northern Canada, Greenland, Alaska and the Faroe Islands consuming traditional food such as sea mammals and fish, had higher levels of POPs and mercury in their bodies than people living further south and closer to sources. This situation is caused by the long-range transport of these chemicals, their biomagnification in the food chain and a very slow environmental degradation, especially under low temperature. In recent years, internal exposure levels have decreased, presumably as a consequence of decreasing levels in the environment and changes in dietary habits [26]. Several POPs found in breast milk and blood can have negative health effects, especially during pregnancy (Table 2). AMAP results confirmed that the traditional food that had secured the life of the Arctic indigenous and local peoples living along the coasts of Alaska, Northern Canada, Greenland and the Faroe Islands for generations was now contaminated with hazardous chemicals.
- Regarding the **radionuclide pollution of the Arctic**, AMAP documented that not all the radioactivity pollution of the Arctic originated from the former USSR, as had been previously assumed (Fig. 4). The main source of radionuclide exposure of people in the Arctic were tests of nuclear weapons performed at several locations of the world (Fig. 6).
- **Risk communication** was an important aspect in this first assessment that required careful consideration. The human exposure levels in particular were very sensitive information to be conveyed to people in the Arctic. Young women were faced with the question if contaminant exposure levels could lead to health risks for their children. In order to ensure easily understandable and balanced information for local communities, including study participants, elder indigenous women worked with the medical experts to communicate the findings and to give best advice.

Table 1
Priority areas in the first AMAP assessment and associated lead Arctic countries 1992–1997 [1].

Priority area	Lead Arctic countries
Persistent organic pollutants	Canada and Sweden
Mercury	Canada and Denmark
Oil pollution	Norway and USA
Radionuclides	Norway and Russia
Human health	Canada and Denmark
Acidification of land and lakes	Finland

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Soviet, European pollution threatens health in Arctic

BY MATTHEW FISHER
The Globe and Mail

CHESTERFIELD INLET, NWT

Canadian scientists fear that the health of Canada's 22,000 Inuit has been put at risk by pollution from chemicals used primarily in agriculture and industry in the Soviet Union and Europe.

The chemicals, including PCBs and DDT, have entered the fragile Arctic ecosystem and are being found in the fish and animals that form the basis of the Inuit diet.

PCBs, polychlorinated biphenyls, have been linked to cancer in laboratory animals and to brain, liver and other defects in humans. The pesticide DDT was banned in the early 1970s in Canada and the United States.

Federally financed research conducted over the past four years in the Far North has found dozens of toxic substances in every part of the Arctic food chain, from bottom-feeding sea organisms to seals, polar bears and Inuit mothers' milk.

The potential magnitude of the problem is such that "the Inuit might have to go on a diet of chicken and beef," said Dennis Gregor of Environment Canada's water quality branch in Regina. He is in charge of a special study of toxic substances found in Arctic snow.

"That would require a huge diet and cultural change. It would not be good for them," Mr. Gregor said.

The chief medical officer for the Northwest Territories, David Kinloch, said: "We are finding a whole range of toxic substances. . . For the people of the Northwest Territories it is a very fundamental question — the contamination of their food supply."

The inter-departmental project to identify the contaminants and analyze the risk they pose to Inuit and Arctic wildlife "is our highest priority," said the program's co-ordinator, Grant Bangay, director of regional planning and resources for the Department of Indian Affairs and Northern Development.

While it is too early to draw categorical conclusions from the research, Hiram Beaubier, director-general of natural resources and economic development for the department, said: "We acknowledge the significance of the problem. We are now preparing a report on its magnitude. . . It is being looked at very, very carefully. We are taking it very seriously."

Once the situation and its effect on native northerners is better understood, the department will use "a reasoned and sensible approach" to advise those affected, Mr. Bangay said.

Both Mr. Bangay and Mr. Beaubier said they were concerned that the problem

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Fig. 4. Newspaper article presenting the view at the time of Arctic pollution originating from the Soviet Union.

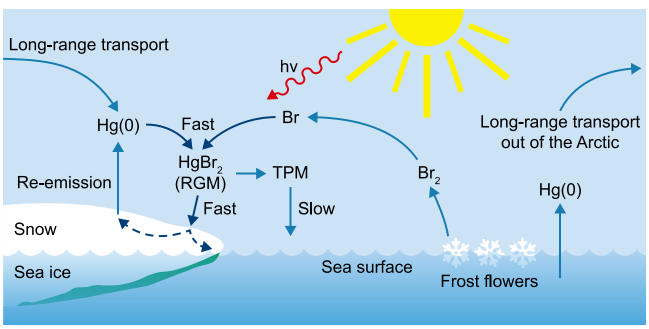

Fig. 5. Formation of reactive gaseous mercury (RGM) in the Arctic, in the presence of sunlight and bromine. The figure was reproduced from ref. [55], with permission from the Arctic Monitoring and Assessment Programme (AMAP).

New organic chemicals are produced and used on the global market, and some might have properties similar to the POPs of the first assessment. Over the last few years, AMAP has had a special focus on newly detected chemicals found in Arctic ecosystems and humans, due to long-range transport and/or from local emission sources [18,19]. These have been categorized as **Chemicals of Emerging Arctic Concern (CEACs)**. The detection of new chemicals in the Arctic, particularly in food items, is a health concern for the peoples of the Arctic. Information on persistence, long-range transport and bioaccumulation of unregulated chemicals is important for risk assessments, among others for prioritization of contaminants and reviews of their POP characteristics for global regulations under the UNEP Stockholm Convention on POPs.

While the first assessment focused on mercury in the Arctic environment, mercury was also identified as a human health concern in the AMAP 2002 human health assessment [27]. This and subsequent assessments documented significant human exposure to mercury for indigenous and local people with high consumption of sea mammals, exceeding the mercury exposure of people mainly consuming terrestrial food (Fig. 7). A long-term study from the Faeroe Islands documented that if mothers had an intake of whale meat more than twice a week, their newborn children had an increased risk of irreversible neurobehavioral effects, as shown in repetition studies performed at the age of 7 and 14. Table 2 shows observed effects in humans due to mercury exposure [22,27–29].

In contrast to the exposure to POPs and mercury which mainly occurs from the consumption of high trophic-level marine species, the exposure to radionuclides is mainly related to a terrestrial diet. Following the nuclear testing (Fig. 6), radioactive emissions from these tests were transported with the atmosphere and deposited with precipitation. This led to a situation that those Arctic inhabitants mainly living off terrestrial food, especially reindeer meat, e.g., the reindeer herders and their families, were exposed to a higher radioactive dose than other Arctic indigenous and local groups. On the other hand, their exposure to POPs and mercury was lower due to their limited intake of marine food. The flow and bioaccumulation of radionuclides in the terrestrial food chain are shown in Fig. 8. The radioactive fallout accumulates in mushrooms and lichen that are eaten by grazing reindeers, eventually finding their way into humans consuming reindeer meat. This holistic approach to exposure to different types of harmful substances was a new concept developed through the AMAP work.

Surprisingly for most experts, the main source for ^{137}Cs (Cesium) observed in the Barents/Kara Seas was not related to Russian rivers and upstream Russian nuclear facilities, but originated from the UK reprocessing plant at Sellafield in the Irish Sea (Fig. 9). For ^{99}I (Iodine) the main source was the Cap La Hague plant in France. The accident at Chernobyl in Ukraine/USSR in 1986 is the third largest source of radioactivity affecting the Arctic, in particular southern Arctic areas. Later assessments showed that the Fukushima accident in Japan in 2011 could be traced in the Arctic, but at a very low level. The distribution by air is faster and more dangerous for humans than a leakage to and subsequent transport by the sea [30].

5. AMAP-related research and monitoring in Russia

Due to the situation in the Soviet Union in the 1990s, financial resources were made available by the other Arctic countries and the Nordic Council of Ministers to support AMAP work in Russia.

Table 2
Health effects of persistent organic pollutants (POPs) and mercury observed in Arctic populations [22,26–29].

Persistent organic pollutants (POPs)	Mercury
Immune system	Neurobehavioral effects
- Infectious diseases	- on attention, memory and language
- Reduced effects of childhood vaccines	- on visuospatial and motor functions
Endocrine system	- No evidence that selenium was a significant protective factor against methylmercury neurotoxicity.
- PFAS affects thyroid homeostasis during pregnancy	Cardiovascular effects, increased blood pressure
- Interference with steroid hormone receptor functions	More toxic if exposure occurs prenatally than postnatally
- Low sperm concentrations	Results at ages 7, 14, and 22 suggest that effects are permanent
- Reproductive hormone levels indicated lower Leydig cell capacity for testosterone production	
Type 2 diabetes associated with some POPs	
Potential neurobehavioral effects, also related to effects on Vitamin D	
Carcinogenicity	

Fig. 6. Sites with atmospheric testing of nuclear weapons since 1945 ([1] and references therein).

Specifically, the monitoring activities in Siberia (Tixi at the Lena River estuary) and Northwest Russia (Amderma) were upgraded, including monitoring stations for POPs and mercury in the atmosphere. The Typhoon laboratory at Obninsk was upgraded to deliver high quality analyses of POPs and mercury based on internationally accepted protocols and QA/QC standards including annual participation in international laboratory intercalibrations.

In addition to funds from most of the Arctic countries, the AMAP Secretariat succeeded in rising financial support in 2000 from the Global Environment Facility Programme (GEF), supported by UNEP and the World Bank, to perform a significant pollution assessment of Russian Arctic indigenous communities on the Kola Peninsula, the Nenets area, Taimyr Peninsula and in Chukotka (Fig. 1). These studies were co-led by RAIPON and the AMAP Secretariat. This project on “Persistent Toxic Substances, Food security and Indigenous peoples of the Russian North” [31] was the most significant environmental and health study ever conducted in Russia at the time. The study documented for indigenous communities in Russia what AMAP had already observed in North America and Greenland, i.e. that indigenous people mainly consuming sea mammals and fish had higher levels of POPs and mercury than people with a different diet.

Fact sheets were produced to inform local communities on how to avoid these chemicals, together with local governments and the Indigenous Peoples Secretariat, an organization established to coordinate Indigenous peoples’ work under the AEPS, now part of the Arctic Council Secretariat. The study also documented that in addition to the long-range transport of contaminants, local emission sources existed that led to the contamination of drinking water and ecosystems at large. These were mainly connected to old military installations, e.g., old rusty and leaking barrels and technical installations or abandoned radar stations leaking polychlorinated biphenyls (PCBs) and fuels into the environment (Fig. 3; Fig. 10).

The results were presented to the Russian government in 2004 and were followed by local actions to clean up contaminated sites and thereby reduce the exposure to the most potent contaminants in these regions, e.g., PCBs and the insecticide DDT. Approximately six years later a study was performed to clarify if the information campaign and the local actions had been effective, generally showing decreased levels, but also indications of continuous emissions from local sources.

In May 1995, a study organized by the AMAP Secretariat in cooperation with the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet), with experts from Russia (mostly from the Navy) and from Norway, Sweden and Finland (only civilians) documented the significant nuclear sources in Northwest Russia and their potential threats for health and environment e.g., old nuclear submarines, nuclear waste (fluid and hard materials), power plants, etc. A report presenting these “hot spots”, also including options for cleanup and a rough cost estimate, was produced and presented to the Barents Environmental Ministerial meeting in Rovaniemi, Finland in December 1995 [32]. In

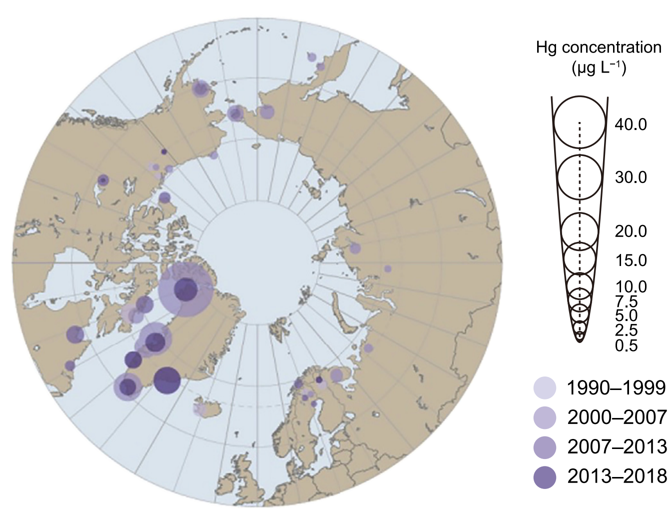

Fig. 7. Mercury concentrations in blood of mothers and women of child-bearing age. The figure was reproduced from Ref. [22]; with permission from the Arctic Monitoring and Assessment Programme (AMAP).

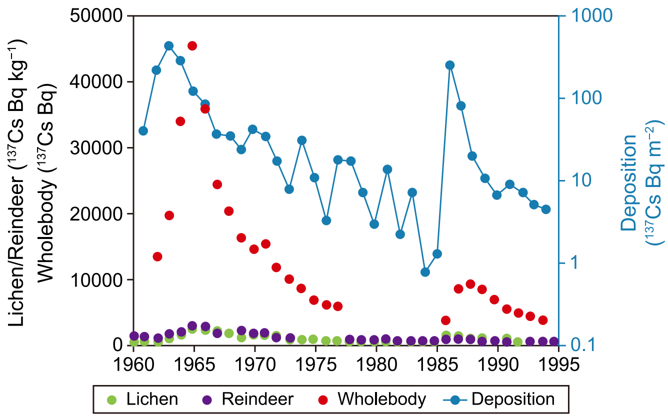

Fig. 8. Deposition of ^{137}Cs over time and accumulation in the lichen-reindeer-human food chain, for Northern Finland. "Reindeer" presents reindeer meat, "wholebody" refers to humans. The figure was reproduced from ref. [1], with permission from the Arctic Monitoring and Assessment Programme (AMAP).

January 1996, this report was presented to the International Atomic Energy Agency (IAEA) in Vienna, Austria. The report, with its documentation and recommendations was an important basis for planning the cleanup actions of radioactive sources in Northwest Russia, decommissioning of 198 nuclear submarines of which 122 were in Northwest Russia, upgrading the safety procedures at the Kola Nuclear Power Plant, handling of radioactive fluid and hard waste, etc. Approximately €250 million (by 2010), along with in-kind contributions from Russa were spent on these actions.

6. Actions to reduce the pollution of the Arctic and the globe

Prior to the development and adoption of the UN Stockholm Convention on POPs, the only international agreement to reduce long-range transported pollution was CLRTAP under the UN-ECE. Experts from Canada and Sweden brought drafts of the first

Fig. 9. Ocean transport of ^{137}Cs to the Arctic. The numbers in bold indicate the concentrations of ^{137}Cs, relatively to a maximum level of 1000 at the primary source. The years indicate the duration of transport, and the distance from the source (in km) is given.

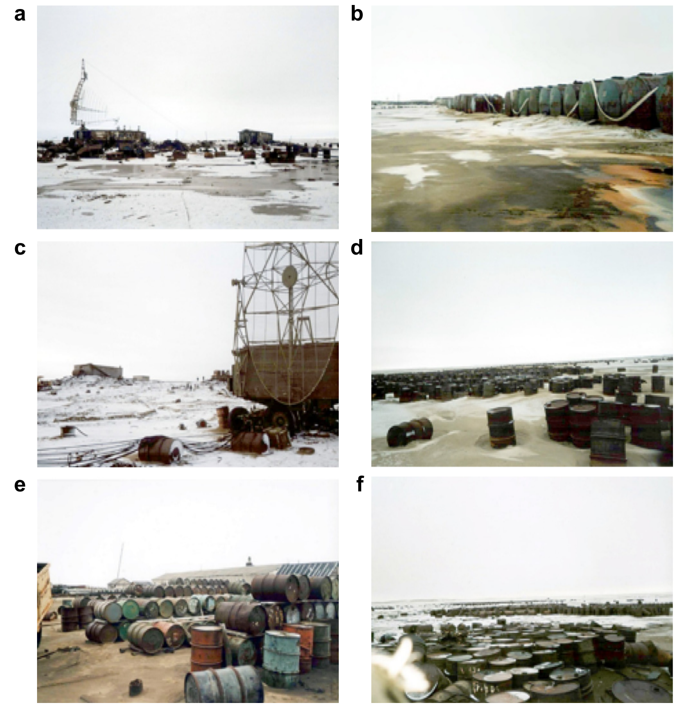

Fig. 10. Barrels and old radar equipment at Franz Josef Land in 2004, presenting potential sources of oil, lubricants, polychlorinated biphenyls (PCBs) and warfare chemicals. Photos: Yuri Sychev

AMAP assessment to CLRTAP to inform about the presence of contaminants in the Arctic and their effects on indigenous populations [8,33]. The scientific data from AMAP documented the global dimension of POP pollution and played a significant role in establishing the UN Stockholm Convention on POPs, which regulates chemicals on the basis of being persistent, transported over long distances, bioaccumulative and toxic. Arctic data were instrumental in recognizing POPs as a global problem, which was caused by various chemicals of different uses, but with similar physical-chemical properties favoring the transport to and accumulation in the Arctic environment. Data from the Arctic have provided evidence of persistence, long-range transport and bioaccumulation, if measured in biota, and have been a substantial contribution to the risk assessments of new chemicals under the Stockholm Convention. Furthermore, the long-term monitoring of POPs in the Arctic has generated time series that are used to evaluate the effectiveness of these global regulations (e.g., Ref. [34]. These data confirm that the regulations by the Stockholm Convention have had a significant effect in reducing the levels of POPs in the Arctic.

Similarly, the effects of long-range transported mercury on humans in the Arctic were conveyed to UNEP by experts from the Arctic countries and contributed to the UN Minamata treaty, signed in 2015 to reduce emissions of mercury [8,35]. Phasing out coal-fired power plants as a significant source of mercury as well as CO_2 to the atmosphere will have the positive side-effect of reducing global CO_2 emissions as well. These international agreements have reduced the environmental levels of POPs and mercury and the associated human exposure, not only in the Arctic, but all over the world.

In addition to these long-term global conventions, actions on the regional scale have reduced contaminant exposure. Food advice was provided to the indigenous and local communities in the Arctic to reduce potential exposure risks. Local health experts worked together with leaders from local indigenous groups to convey AMAP results and advise on their implications. The exact food advice was adjusted to the local situation and considered the importance of food security in the Arctic. Until one or two decades ago, it was challenging to provide alternative food sources to cover the need for energy and vitamins in the North. In addition, traditional local food has an important role in the cultural identity of many peoples, as well as a social function in the communities, which goes far beyond the role of food for energy and nutrition supply. Fig. 11 shows an example from the Faroe Islands where food advice has considerably reduced the population's exposure to mercury, although Hg levels in pilot whales, an important exposure source, had increased at the same time [22].

Fig. 12 shows decreasing levels of DDE (the persistent transformation product of the insecticide DDT) and mercury in the blood of people living in the Arctic. This decrease likely reflects a combination of results from food advice and generally decreasing levels in the environment, including Arctic animals [29]. Table 2 shows observed effects related to POP and mercury exposure.

7. Climate change

Climate and ozone/UV were part of the first AMAP assessment report in 1998 but covered only 50 pages of the 871-page report. In the 1990s the political focus was mainly on ozone and UV due to the ozone hole observed over Antarctica. The AMAP assessment did not find a similar ozone depletion over the Arctic [1]. Regarding climate change, the conclusions of the first AMAP assessment in 1998 were: There are three signals observed over the Arctic. Some areas are warming, part of the ocean is cooling and for some areas there is no clear signal.

Since 1998, climate change has gained importance in AMAP, also related to combined effects with pollutants in the Arctic [19]. At the 1997 AEPS ministerial meeting in Alta it was decided, based on a

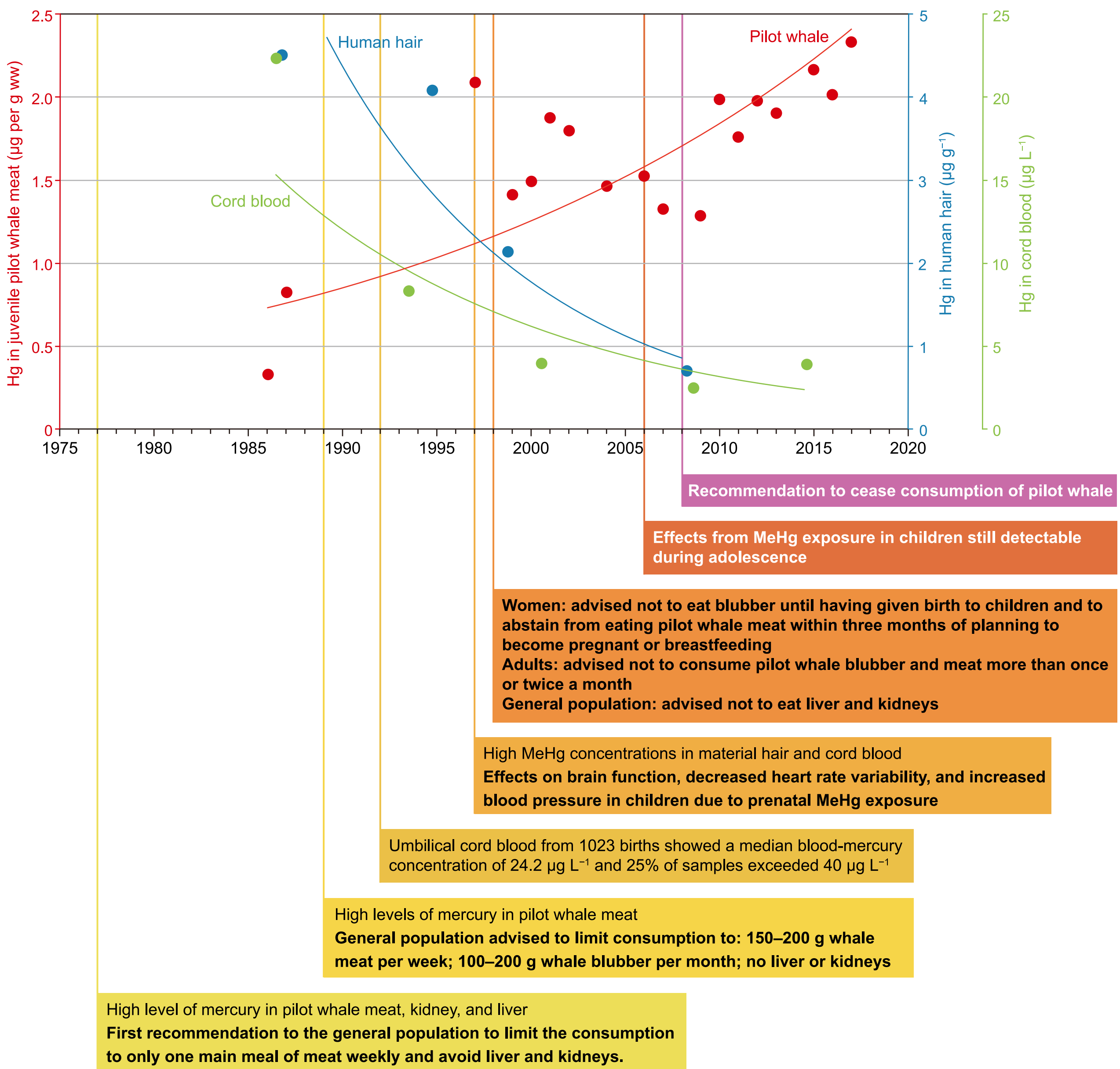

Fig. 11. Summary of dietary advice given to the population of the Faroe Islands, along with mercury levels in human hair and blood as well as mercury levels in pilot whales. The figure was reproduced from Ref. [22]; with permission from the Arctic Monitoring and Assessment Programme (AMAP).

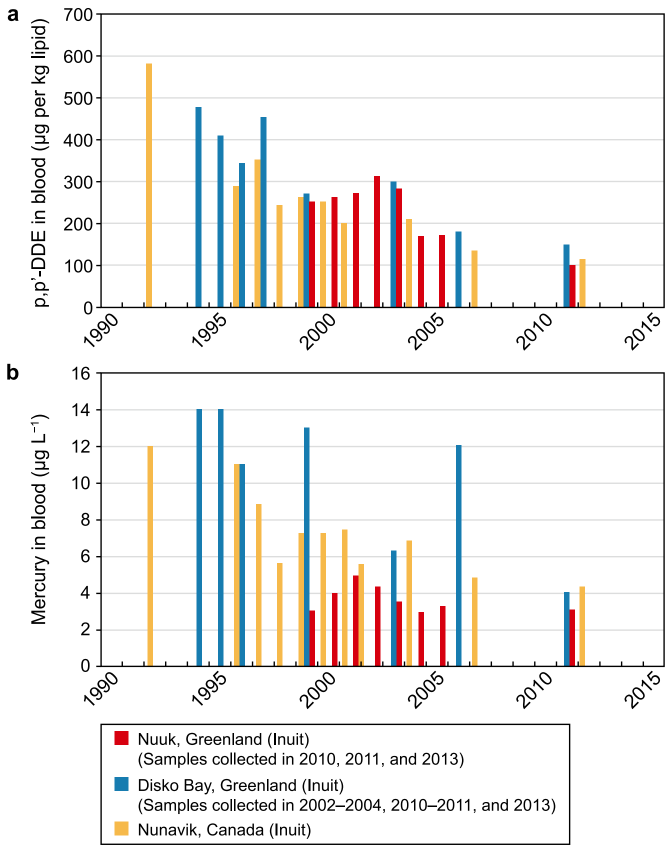

Fig. 12. Concentration development of p,p'-DDE (**a**) and mercury (**b**) in blood of Inuit from Greenland and Nunavik, Canada. The figure was reproduced from Ref. [29], with permission from the Arctic Monitoring and Assessment Programme (AMAP).

proposal by the USA, that AMAP should prepare a more comprehensive climate assessment report. The first meeting of the Assessment Steering Group for the climate assessment was held at the US National Oceanic and Atmospheric Administration (NOAA) center, Silver Spring Washington DC, in 1999. At this meeting a close cooperation started between AMAP, IASC and CAFF on an assessment related to climate change, the Arctic Climate Impact Assessment (ACIA) [36].

In November 2004, the ACIA report was presented at a science conference in Reykjavik, Iceland, and the following week to the Arctic Council ministerial meeting. A key conclusion was that climate change was not a future scenario, but already ongoing “now”. Another important conclusion was that the melting of land and sea ice would make new resources accessible (e.g. minerals and marine species) and open a commercial shipping route between Northwest Europe and Northern Asia. This would reduce the traditional route via the Suez Canal by 40% [37,38].

This result triggered interest among many non-Arctic countries to call for an observer status at the Arctic Council e.g., China, Japan, South Korea, Singapore, the EU, etc. They wanted to learn more about the accessibility to the new resources such as minerals, oil and gas and fisheries, and not least about the general effects of a changing climate that would also affect lower latitudes.

Since 2004, AMAP has delivered several climate-related assessments, e.g., related to contaminants [19,39,40] as well as Short Lived Climate Forcers such as black carbon [41–44] and methane [45]. A report on Arctic Ocean acidification documented that the cold Arctic seas would become acidic faster than warmer oceans would because cold water can store more CO_2. Some of the Arctic Sea may become corrosive within the next decade [24]. The same process takes place in Antarctic oceans.

A bilateral agreement between the Intergovernmental Panel on Climate Change (IPCC) chair Robert Watson and the ACIA chair Robert Corell in October 2000 ensured collaboration between the organizations. The AMAP climate assessments have been made available to the work of the IPCC and several lead authors have contributed to the work by both organizations, but the Arctic content has not always found its way into their reports, due to some obstacles in the process, e.g. number of pages allocated to the polar areas.

8. Sustaining Arctic Observing Network (SAON)

During the AMAP assessments some obstacles were met, related to accessing geographical areas for observations and using data stored at private and governmental institutions. Some institutes requested payment for data to be used in assessments. These institutes view their data as their “family silver” that could be sold several times to different users. In addition, data sharing was not necessarily beneficial for a young researcher's career who was expected to be the first author of a publication. The willingness to share data was not credited. In an attempt to overcome some of these obstacles, AMAP and IASC took the initiative in the mid-1990s to improve the observation network and the access to data [46]. In 2011 the Arctic Council established the Sustaining Arctic Observing Network (SAON: https://www.arctic-council.org/projects/saon/).

In 2017, the existing collaboration on environmental research and monitoring in the Arctic was extended to other fields of research. An Arctic research agreement was negotiated under the Arctic Council umbrella and signed by Ministers of Science of the Arctic countries. The first Arctic Science Ministerial Meeting was held in the USA in 2016, two more ministerial meetings have been held subsequently, one in Berlin in 2018 (co-hosted by Finland, Germany and the EU) and a partly virtual meeting in 2021 (co-hosted by Iceland and Japan) [47]. Despite discussing observing networks and data sharing continuously, these issues have not been fully resolved yet.

9. Inspiration from the Arctic collaboration

9.1. Hindu Kush Himalaya (HKM) — International Centre for Integrated Mountain Development (ICIMOD)

A substantial part of the chemical pollutants transported to the Arctic is produced, used and released in SEA. Significant pollution and contaminant exposure also occurs locally in these emission areas. If actions can be taken in SEA to reduce/stop the pollution in the region, it will have positive effects for the Hindu Kush Himalaya (HKM) region and other areas of the world, including the Arctic.

The International Centre for Integrated Mountain Development (ICIMOD) is an intergovernmental knowledge and learning center that develops and shares research, information, and innovations to empower people in the eight regional member countries of the HKM — Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan. The head office is in Kathmandu, Nepal. The AMAP Secretariat was invited to inform about the Arctic Council and AMAP, the scientific and outreach work and AMAP's products. They also informed about the impacts these reports had on international agreements, such as the UN Stockholm and Minamata Conventions, and about regional actions, such as food advice to local and indigenous Arctic communities.

Several meetings and workshops have been held in Kathmandu, Nepal and Tromsø, Norway. Inspired by the AMAP work ICIMOD established HIMAP (Himalaya Monitoring and Assessment

Program), and a comprehensive climate and environmental report of 600 pages was delivered to the IPCC in 2019 [48].

9.2. Antarctica

Over the years there have been contacts between the AMAP Secretariat and scientists working in the Antarctic region to benefit from AMAP's expertise for a POP monitoring program in the Antarctic area [49]. Recently, an Antarctic Monitoring and Assessment Programme (AnMAP) has been proposed, and advice has been sought from the AMAP Secretariat and scientists involved in AMAP regarding the AMAP experience of harmonizing monitoring initiatives and implementing new technologies in contaminant monitoring. This is an ongoing process.

10. Reflections and recommendations

The development of AMAP happened on the positive political wave after the cold war and the speech held by Michael Gorbachev in 1987. This initiative systematized, expanded, coordinated and improved Arctic research and monitoring efforts. This process has provided important information for a better understanding of the pollution and climate change of the Arctic, its ecosystems and human inhabitants, in circumarctic assessments involving local and indigenous peoples. It has also provided the necessary scientific documentation for global actions to reduce the pollution and exposure of humans in the Arctic and worldwide. Regarding climate change, the Arctic assessments have documented that the Arctic is warming 3-4 times faster than the world [50]. This scientific work has been a significant peace process to keep the Arctic as a low-tension area where one could solve questions through dialogue and joint work.

There are still significant pollutant questions to be handled, especially how to incorporate risks for Arctic pollution in approval systems for use of new chemicals, with could have POP-like properties. This integration requires documentation related to the toxicity and persistence of these chemicals at low temperatures, the interactions between lower latitudes and the Arctic — and vice versa.

Since February 2022, with the conflict in Ukraine, the Arctic Council and its working groups have been on pause. The foreseeable future of the next five to ten years may not see the same positive cooperation as the situation between 1987 and early 2022. Given the rapid changes in the Arctic, a disruption in collaboration and science-based policy advice can have dramatic consequences for the Arctic environment.

Science cooperation is an important contributor to peace and prosperity, as Michael Gorbachev called for in 1987. While this article was in preparation, he passed away on the 30th of August 2022. The hope is that new leaders can stand up like him and continue the work initiated in 1987.

CRediT authorship contribution statement

Lars-Otto Reiersen: Conceptualization, Methodology, Data curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project Administration, Funding Acquisition. **Katrin Vorkamp:** Methodology, Validation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Roland Kallenborn:** Conceptualization, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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