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Environmental contaminants in Arctic human populations: Trends over 30 years

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ABSTRACT

Introduction: Arctic Monitoring and Assessment Programme (AMAP) monitors persistent organic pollutant (POP) levels in the Arctic populations and assesses health effects related to exposure to them. Many internationally regulated POPs persist in humans and biota, while new Emerging Contaminants of Arctic Concern (ECAC), many of which are unregulated, present additional challenges. Biomonitoring offers valuable insights into temporal trends within human matrices, revealing critical information not only about the efficacy of international regulations but also serving as an early warning system for exposure and risks for human health.

Methods: Data analyzed in this study is aggregated data presented in the AMAP Human Health in the Arctic assessments, which provide data on contaminant concentrations measured in human matrices from adults, and children across various population studies conducted in the Arctic since the 1980 s. Linear regression analyses were used to assess trends of various POPs including organochlorine (OCPs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs) and per- and polyfluoroalkyl substances (PFAS), measured over time from the Arctic populations in Finland, Norway, Sweden, Denmark, Iceland, Canada and Alaska (USA).

Results: Overall, decreasing trends were observed for PCBs and OCPs. Regulated PFAS showed decreasing trends, but increasing trends were observed for unregulated PFAS in certain populations. PBDEs showed decreasing or inconsistent trends in certain Arctic populations.

Conclusions: Decreasing trends are observed for legacy POPs, but the trends for new emerging contaminants are inconsistent. More focus is needed on biomonitoring the new emerging contaminants of concern in the Arctic and their implications on human health.

Abbreviations: AMAP, Arctic Monitoring & Assessment Programme; CI, Confidence interval; p,p'-DDE, Dichloro-diphenyl-dichloroethylene; p,p'-DDT, Dichloro-diphenyl-trichloroethane; ECAC, Emerging Chemicals of Arctic Concern; HCB, Hexachlorobenzene; β-HCH, beta-Hexachlorocyclohexane; OCs, Organochlorines; OCPs, Organochlorine pesticides; P-P, Predicted Probability; PBDEs, Polybrominated diphenyl ethers; PCBs, Polychlorinated biphenyls; PFAS, Per- and polyfluoroalkyl substances, PFDA, Perfluorodecanoic acid; PFHxS, Perfluorohexanesulfonic acid; PFNA, Perfluorononanoic acid; PFOA, Perfluorooctanoic acid; PFOS, Perfluorooctanesulfonic acid; PFUnDA, Perfluoroundecanoic acid; POPs, Persistent Organic Pollutants; UNEP, United Nations Environment Programme.

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1. Introduction

Persistent Organic Pollutants (POPs) are man-made chemical substances that were used in agriculture and industry or produced unintentionally as industrial by-products (Li et al., 2023). Due to their harmful effects on both the environment and living organisms several of the polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs) were restricted by National or European regulations already in the 1970′s. Later, as a global response to the problem, the United Nations Environment Programme (UNEP) Stockholm Convention on POPs was adopted in 2001 with the main goal to reduce and prohibit the release of these chemicals into the environment (Carpenter, 2011; UNEP, 2019). The Arctic region contributes negligibly to global pollution, yet research shows that POP concentrations in the Arctic regions are higher compared to non-Arctic areas (AMAP, 2021b,2022). This is attributed to the transportation of these contaminants from the lower latitudes to the Arctic via ocean currents, rivers, and air transport. Furthermore, these chemicals bioaccumulate in fatty tissues of several fish and mammals which are part of the Arctic peoplés traditional and local diet, serving as the primary route of exposure to POPs in these populations (Gibson et al., 2016). Previous research has found that the Arctic populations have ten-fold higher POP concentrations than the general population in non-Arctic regions (Barr et al., 2006; Hjermitslev et al., 2020; Long et al., 2021; Muckle et al., 2001).

Research has shown that POP exposure is associated with adverse effects in humans such as neurobehavioral, immunological, reproductive, cardiovascular, endocrine, and carcinogenic effects (AMAP, 2021b,2022; Carpenter, 2013; Guo et al., 2019). The Arctic Monitoring and Assessment Programme (AMAP) is responsible for biomonitoring environmental pollutants, including routes, trends, and levels, as well as examining the consequences of climate change and pollution on humans and ecosystems in the Arctic. In the Arctic regions, there are currently over 30 years of biomonitoring data available for assessing pollutant concentration trends over time. Assessing time trends of POPs aids in monitoring the stability of these chemicals in humans and the ecosystem, evaluating the impact of international restrictions, and discover new, potentially harmful global pollutants emerging in the Arctic (Guillotin and Delcourt, 2022; Li et al., 2024). The primary objective of this study is to 1) analyze the temporal trends of contaminants in the Arctic, leveraging over three decades of biomonitoring data compiled by the AMAP reports (AMAP, 2021b,2022); 2) examine the variations in contaminant decline rates in the Arctic and to synthesize current understandings with previous biomonitoring findings; 3) highlight the presence of emerging contaminants in the Arctic regions; 4) evaluate the effectiveness of existing regulations in mitigating contaminant levels over time., and need for future regulations.

To meet the objectives of this study, we evaluated contaminant concentrations across diverse populations within the Arctic, as delineated by the AMAP (AMAP, 1998). This evaluation included data from nations that fall under AMAP’s geographical coverage – Norway, Finland, Sweden, Iceland, the USA (Alaska), Canada, and Denmark (including the Faroe Islands and Greenland) (The Arctic Council, 2024). It should be noted that not all populations in these nations are situated within the Arctic Circle. The definition of the Arctic varies, blending physical-geographical criteria with political and administrative boundaries as seen in various countries. AMAP’s defined boundary provides a framework for evaluating source-related environmental issues both within and external to the Arctic. Conversely, the Conservation of Arctic Flora and Fauna (CAFF), another working group of the Arctic Council, employs boundaries influenced equally by political and ecological factors. As highlighted by Grid-Arendal, the Arctic region’s boundaries are not fixed but vary according to the context – environmental, biological, economic, jurisdictional, or social (GRID-Arendal, 2024).

2. Materials and methods

2.1. Study population

The data analyzed in this study is aggregated data presented in the AMAP Human Health in the Arctic 2021 assessment (AMAP, 2021b,2022). The AMAP 2021 assessment included concentrations of POPs measured in from adults, children, and maternal participants in human matrices (whole blood, serum, plasma, breast milk) across various epidemiological studies conducted in the Arctic since the 1980 s (AMAP, 1998). In addition, monitoring data for Finland and Alaska were included from AMAP, 2015 report. (AMAP, 2015). AMAP, 2009 assessment was used to collect data from Greenland, which was only presented as figures in the AMAP 2021 assessment (AMAP, 2009) (**Supplementary File 1**). All data has been published in separate scientific papers or reports, and this study included only data for POPs measured at three or more time points. Therefore, there was no requirement to obtain ethical approval.

Environmental contaminants: This study investigated the time trends of 24 environmental contaminants or their combinations, data presented in **Supplementary File 1**. Seven polychlorinated biphenyls (PCB) congeners: PCB-28, 118, 138, 153, 156, 170 and 180 and sum of PCBs 2x(PCB-138 + 153 + 180); seven organochlorine pesticides (OCPs): oxychlordane, *trans*-nonachlor, 1,1,1-trichloro-2,2-bis-(4-chlorophenyl) ethane (*p,ṕ*-DDT), 1,1-bis-(4-chlorophenyl)-2,2-dichloroethene (*p,ṕ*-DDE), hexachlorobenzene (HCB), beta-hexachlorocyclohexane (*β*-HCH), mirex; two polybrominated dipheyl ethers (PBDE) congeners: PBDE-47 and 153 and the sum of PBDEs (PBDE-47 + 99 + 100 + 153 + 209) and 6 per- and polyfluoroalkyl substances (PFAS): perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA), perfluorohexanesulfonic acid (PFHxS), perfluorodecanoic acid (PFDA), perfluorononanoic acid (PFNA) and perfluoroundecanoic acid (PFUnDA) were included in this study. The data for organochlorines (PCBs and OCPs), and PBDEs are presented as lipid-normalized concentrations (μg/kg plasma lipid), and the data for POPs PFAS are expressed as wet-weight concentrations (μg/L plasma or serum).

2.2. Statistical analyses

The demographic characteristics of the study population extracted from the AMAP assessments are shown in **Supplementary file 1** and **Supplementary file 2 – Table S1**. Time trends of environmental contaminants were assessed using linear regression analyses. The geometric mean/median values of all POP concentrations were log-transformed to address right-skewed distributions observed in certain POPs. Measurement points in years were used as independent variables. When a single median/geometric mean of POP concentrations was reported for data collected over multiple years, the median year or the subsequent even year was utilized as a measurement point in the analyses and figures. Assumptions regarding linearity, homoscedasticity and normality were checked by predicted probability (P-P) plot and scatterplot of the residuals. The overall time-trends for the different POPs are presented as scatterplots with linear fit/regression line. The linear regression analyses are not adjusted for any covariates because of the limited data availability from the original studies included in the AMAP. The results from the linear regression analyses β-coefficients, 95 % confidence intervals (95 % CI) and p-values are presented in **Supplementary file 2 (Tables S2-S9)**. The results can be interpreted as changes in POPs concentrations per unit increase in time (measured time points/years). Findings with CIs that excluded zero were considered as consistent increasing or decreasing POP trends, while CIs including zero were considered as non-consistent trends. The analyses for data from Finnish children and Norwegian adults were sex stratified. Statistical analyses and figures were performed using IBM SPSS Statistics version 28.0 (IBM Corp, 2021).

3. Results

3.1. Study population

The study populations include Norway, Finland, Sweden, Iceland, USA (Alaska), Canada (Nunavik), and Denmark (Greenland and the Faroe Islands). The characteristics of the study populations based on country with measurement time points, human matrices used, age group and contaminants measured are provided in **Supplementary file 2 (Table S1)**. A brief description of the demographics of the study populations, mean age at measurement time points, and contaminant values is mentioned in **Supplementary file 1**. The linear regression results based on countries are presented in **Supplementary file 2 (Tables S2-S9)**.

3.2. Norway

Blood concentrations of POPs in Norwegian 30-year-old men and women have decreased over time (1986–2015/16) (Fig. 1, **Supplementary file 2**, **Table S2**). Most of the PCBs showed consistent decreasing trends with narrow CIs, except for PCB-118 and 156 in women which had wide CIs (Fig. 1**C and 1D)**. Among the pesticides, except for *p,ṕ*-DDE (men: β: −0.111, 95 %CI: −0.184, −0.037; women: β: −0.115, 95 %CI: −0.213, −0.016); oxychlordane in men (β: −0.089, 95 %CI: −0.115, −0.023), all other pesticides (*trans*-nonachlor, HCB and *β*-HCH) showed decreasing trends but with wide CIs (Fig. 1**A and 1B, Supplementary file 2**, **Table S2**).

3.3. Iceland

Among the available data from Iceland investigated in plasma from maternal blood, decreasing trends with narrow CIs were observed for all the PCB congeners and *trans*-nonachlor, *p,p’*-DDE, HCB, and *β*-HCH (Fig. 2**A, 2B, Supplementary file 2**, **Table S3**).

3.4. Finland

Time trends in organochlorine concentrations and sum of PBDEs in breast milk from Finnish mothers are shown in Fig. 2**C & 2D**. For PCB-153, consistent decreasing concentrations were observed (Southern Finland: β: −0.079, 95 %CI: −0.111, −0.047; Central Finland: β: −0.080, 95 %CI: −0.103, −0.057) (Fig. 2**C, Supplementary file 2**, **Table S4**). The sum of PBDEs also showed decreasing trends but with narrow CIs only for Central Finland (Southern Finland: β: −0.080, 95 %CI: −0.329, 0.168; Central Finland: β: −0.066, 95 %CI: −0.084, −0.048) (Fig. 2**D**). Analyses of PFASs in Finnish children’s blood showed decreasing concentrations for most PFASs. Consistent decreasing linear trends were seen for PFOA (boys: β: −0.139, 95 %CI: −0.144, −0.135; girls: β: −0.181, 95 %CI: −0.286, −0.076) and PFNA, particularly in boys (boys: β: −0.069, 95 %CI: −0.108, −0.030) (**Supplementary file 2**, **Table S4**). PFHxS and PFDA concentrations showed decreasing trends, however with wide CIs (Fig. 2**E**).

3.5. Sweden

Time trends of POP concentrations in breast milk among Swedish mothers are shown in Fig. 3. Among the legacy POPs, consistent decreasing trends were observed for *p,ṕ*-DDE and HCB, PCB-28 (Fig. 3**A & 3B, Supplementary file 2**, **Table S5**). PCB-153 also showed consistent decreasing concentrations (β: −0.058, 95 %CI: −0.068, −0.049) (Fig. 3**B**). Among the PFASs, PFOS and PFOA concentrations declined consistently over time (PFOS: β: −0.089, 95 %CI: −0.103, −0.075;

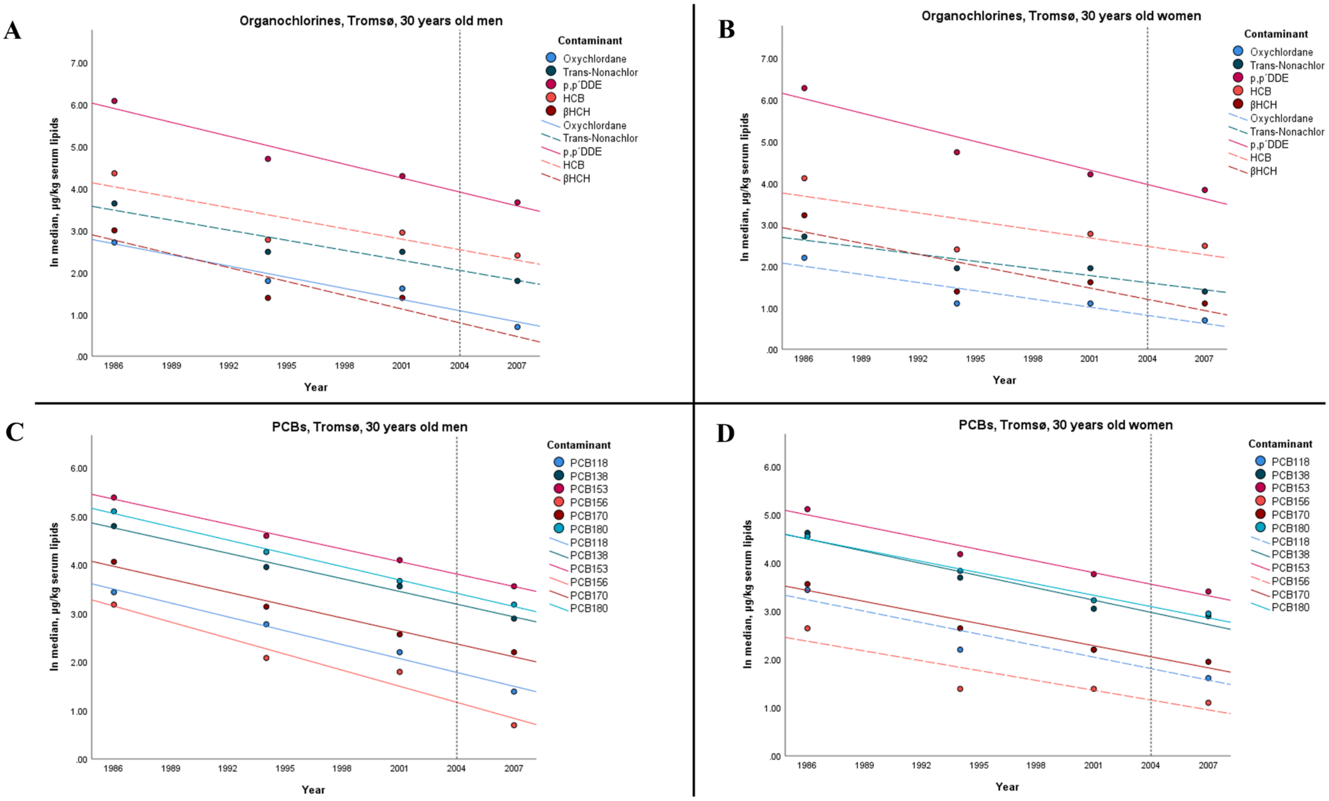

Fig. 1. Trends in POP blood concentrations in adults in Norway (A-D). Circles with different colors represent a specific POP measured over time. Solid lines describe consistent decreasing trends while the dotted lines represent inconsistent trends. The reference line on the X-axis denotes the year of implementation of the Stockholm Convention. Abbreviations: *p,p’*-DDE: dichlorodiphenyldichloroethylene; HCB: hexachlorobenzene; *β*-HCH: beta-hexachlorocyclohexane; PCB: polychlorinated biphenyls.

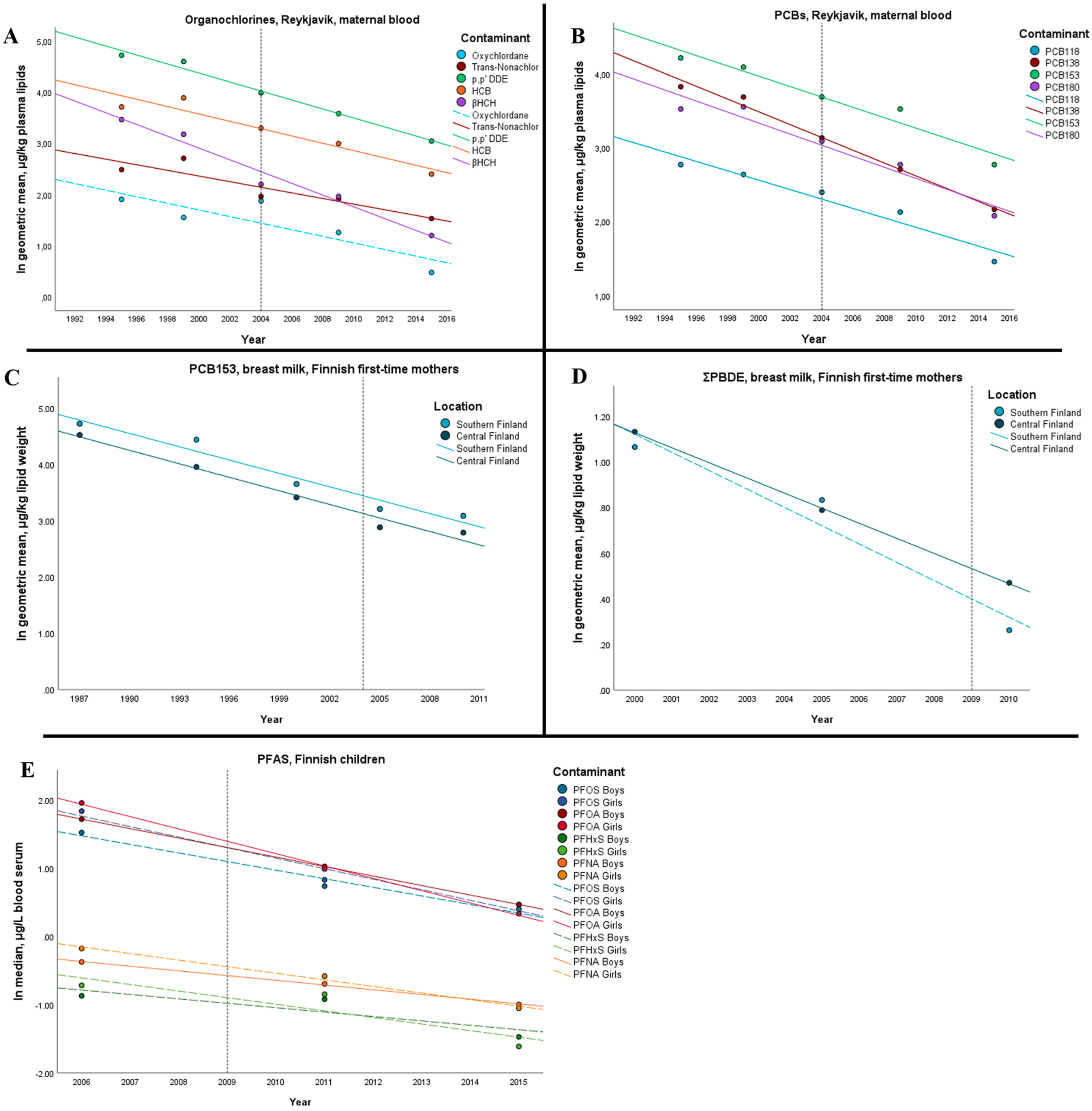

Fig. 2. Trends in POP concentrations in Iceland (A, B) and Finland (C-E). Circles with different colours represent a specific POP measured over time. Solid lines describe consistent decreasing trends while the dotted lines represent inconsistent trends. The reference line on the X-axis denotes the year of implementation of the Stockholm Convention. *p,p'*-DDE: dichlorodiphenyldichloroethylene; HCB: hexachlorobenzene; β-HCH: beta-hexachlorocyclohexane; PCB: polychlorinated biphenyls; PBDE: polybrominated diphenyl ethers; PFOS: perfluorooctanesulfonic acid; PFOA: perfluorooctanoic acid; PFHxS: perfluorohexanesulfonic acid; and PFNA: perfluorononanoic acid.

PFOA: β: −0.049, 95 %CI: −0.062, −0.036); while PFHxS, PFNA and PFDA increased over time, particularly, PFUnDA showed a consistent increasing linear trend with narrow CIs (β: 0.019, 95 %CI: 0.003, 0.034) (Fig. 3**C**, **Supplementary file 2**, **Table S5**). Among the PBDEs, decreasing trends were shown for BDE-47 in Sweden (β: −0.107, 95 % CI: −0.126, −0.087); while BDE-153 concentrations had an inconsistent trend (Fig. 3**D**).

3.6. Denmark

Among the Faroese children, although all organochlorine pesticides showed decreasing trends, only *p,p'*-DDE in cohort 3 showed CIs with narrow intervals (β: −0.179; CI: −0.258, −0.099) Fig. 4**A**, **Supplementary file 2**, **Table S6**). Among the investigated PCBs, PCB-118, 138, 180, ΣPCBs from cohort 3 and PCB-118 from cohort 5 showed consistent decreasing trends with narrow CIs (Fig. 4**B & 4C**). In cohort 3, PFOS, PFOA, PFHxS and PFDA decreased while PFNA increased, however, with wide CIs. In cohort 5, ΣPFOS and PFOA showed consistent decreasing trends with narrow CIs (Fig. 4**D, Suppl file 2,** **Table S6**).

Among the organochlorines investigated in maternal blood plasma in Greenland, oxychlordane and *trans*-nonachlor showed decreasing trends in Disko Bay and Nuuk, however, the CIs were narrow only for Disko Bay

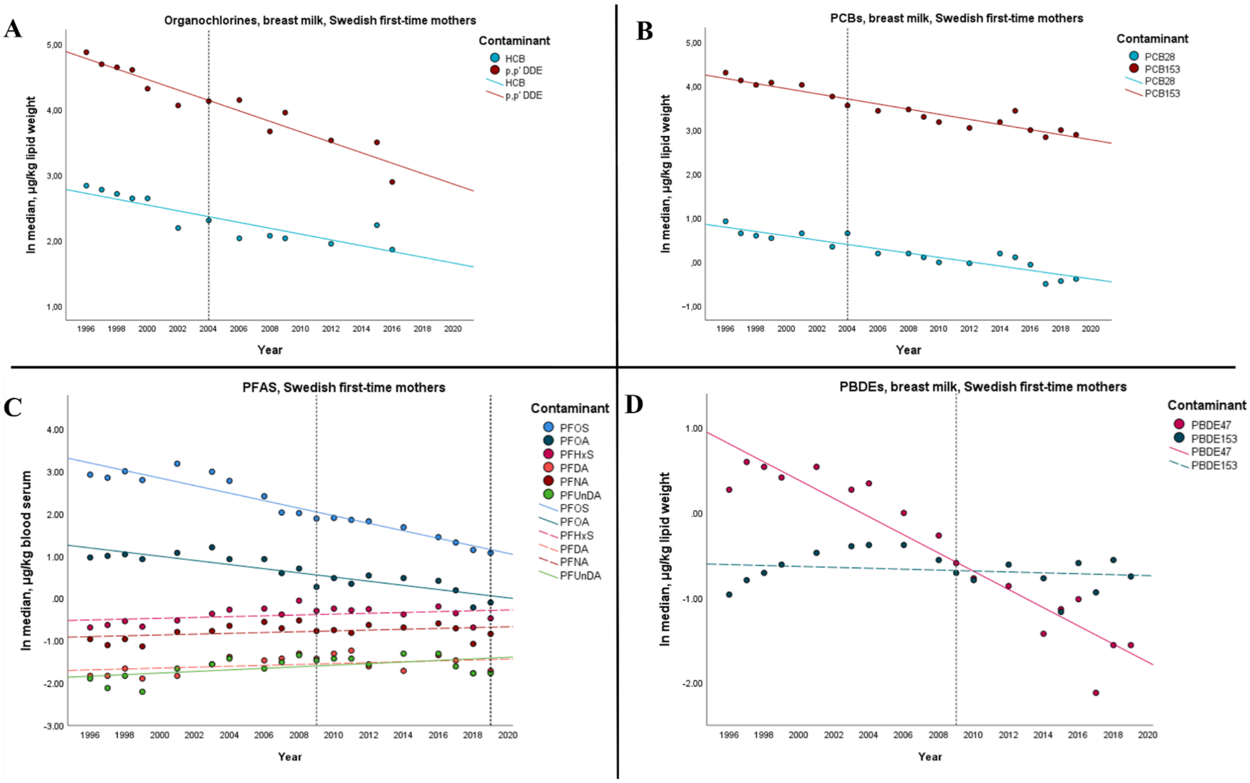

Fig. 3. Trends in POPs (A, B, D) and PFAS (C) concentrations in breast milk from Swedish mothers. Circles with different colors represent a specific POP measured over time. Solid lines describe consistent decreasing trends while the dotted lines represent inconsistent trends. The reference line on the X-axis denotes the year of implementation of the Stockholm Convention. *p,p'*-DDE: dichlorodiphenyldichloroethylene; HCB: hexachlorobenzene; *β*-HCH: beta-hexachlorocyclohexane; PCB: polychlorinated biphenyls; PBDE: polybri\ominated diphenyl ethers; PFOS: perfluorooctanesulfonic acid; PFOA: perfluorooctanoic acid; PFHxS: perfluorohexanesulfonic acid; PFDA: perfluorodecanoic acid; PFNA: perfluorononanoic acid; and PFUnDA: perfluoroundecanoic acid.

(β: −0.064, 95 %CI: −0.095, −0.033), while p,p'-DDE and PCB-153 showed consistently decreasing trends in both places (Fig. 4**E**, **4F**, **Supplementary file 2**, **Table S7**).

3.7. Alaska (USA)

In Yupik, Alaska, all the organochlorines (oxychlordane, *trans*-nonachlor, *p,p'*-DDT, *p,p'*-DDE, HCB, *b*-HCH, mirex) and PCBs (PCB-138, 153) showed decreasing concentrations, however with wide CIs (Fig. 5**A**, **5B**, **Supplementary file 2**, **Table S8**).

3.8. Canada

In Nunavik (Canada) several of the OCPs (oxychlordane, *trans*-nonachlor, HCB, mirex, *p,p'*-DDT, *p,p'*-DDE) showed consistently decreasing linear trends with narrow CIs (Fig. 5**C**, **Supplementary file 2**, **Table S9**). Consistent decreasing trends were also observed for several of the PCB congeners (Fig. 5**D**). Decreasing trends with narrow CIs were also observed for PFOA (β: −0.045, 95 %CI: −0.049, −0.040), and PFHxS (β: −0.053, 95 %CI: −0.103, −0.002) (Fig. 5**D**, **Supplementary file 2**, **Table S9**).

4. Discussion

This study examines time trends of POPs from different Arctic human populations. Overall, decreasing time trends were observed for all PCBs and most OCPs in USA (Alaska), Canada (Nunavik), Iceland, Norway, Sweden, Finland, Denmark (Greenland and Faroe Islands). Regulated PFAS showed decreasing trends while increasing trends were observed for unregulated PFAS. PBDEs showed either decreasing or inconsistent trends in Sweden and Finland. Of all the contaminants, greatest declines over time were observed for *p,ṕ*-DDE and PCBs across the Arctic region.

The findings on decreasing trends in restricted and/or banned OCPs and PCBs are consistent for most countries included in the present study with trends documented in earlier studies done among Arctic populations (Abass et al., 2018; Adamou et al., 2020; Long et al., 2021; Nøst et al., 2013; Xu et al., 2021) as well as from general populations outside the Arctic region (Fång et al., 2015; Gascon et al., 2015; Henríquez-Hernández et al., 2021; Li et al., 2022; Link et al., 2005; Ma et al., 2014; Mannetje et al., 2013; Seo et al., 2022; Thomas et al., 2017). The only exception was, we observed increasing trends for HCB in Alaska and Faroe Islands (cohort 3), and for *trans*-nonachlor in Alaska. Many factors can explain the increasing trends, one being that for each population only three measurement points were available from about 10 years. The biomonitoring data, limited to three time points over a decade, are indeed sparse. Therefore, more data points are essential for a reliable assessment of trends. Further, there is no information on exposures that could be very specific for Alaska thus resulting in increasing concentrations (although with wide CIs in the regression). Decreasing trends of legacy POPs in Arctic human populations started already before the global regulations were implemented, attributed mainly because of previously implemented national regulations, decreasing intake of traditional foods, and decreasing contaminant levels in Arctic biota (Donaldson et al., 2010; Mosites et al., 2020; Weihe et al., 2016). All Arctic countries are experiencing a shift to more imported foods rather than native hunting, fishing, and gathering, which has both adverse and beneficial effects on the health and well-being of Arctic communities. In the present study, Greenland had the highest concentrations for all measured OCPs at the different measurement points, except for *β*-HCH in Iceland. Fish is an essential element of food for all Arctic populations, as are marine animals for Indigenous populations in Greenland, Alaska, and Canada, as well as terrestrial mammals (mainly moose and reindeer) in Norway, Finland, and Sweden (AMAP, 2021b,2022). Species highest up on the

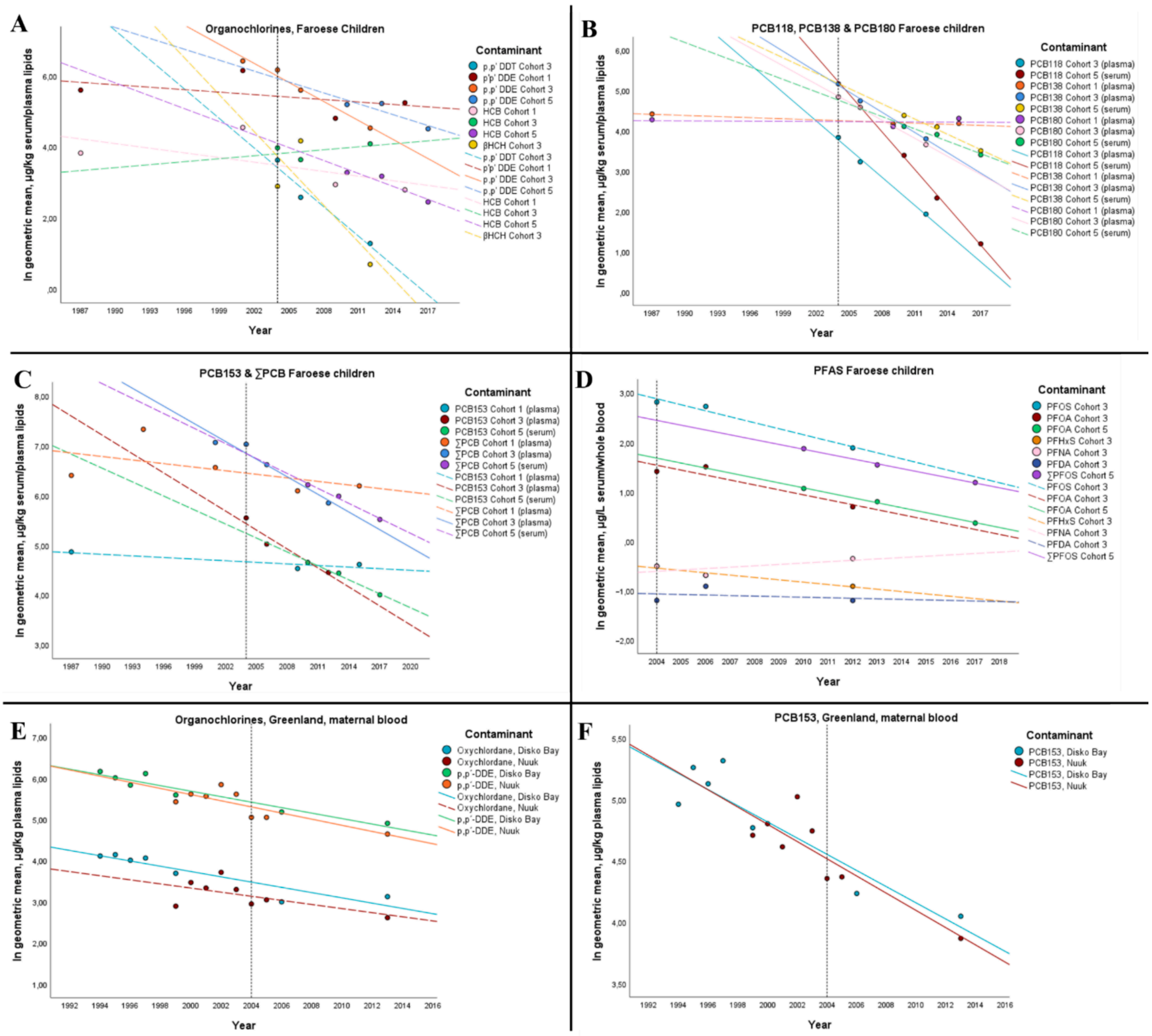

Fig. 4. Trends in POP blood concentrations from children in Faroe Islands (A-D) and from Greenland (E, F). Circles with different colors represent a specific POP measured over time. Solid lines describe consistent decreasing trends while the dotted lines represent inconsistent trends. The reference line on the X-axis denotes the year of implementation of the Stockholm Convention. Abbreviations: *p,p'*-DDT: 1,1,1-trichloro-2,2-bis(4- chlorophenyl) ethane; *p,p'*-DDE: dichlorodiphenyldichloroethylene; HCB: hexachlorobenzene; *β*-HCH: beta-hexachlorocyclohexane; PCB: polychlorinated biphenyls; PBDE: polybrominated diphenyl ethers; PFOS: perfluorooctanesulfonic acid; PFOA: perfluorooctanoic acid; PFHxS: perfluorohexanesulfonic acid; PFDA: perfluorodecanoic acid; PFNA: perfluorononanoic acid; and PFUnDA: perfluoroundecanoic acid.

marine food web have generally higher contaminant levels than terrestrial animals (Donaldson et al., 2010), which can partly explain the higher POP concentrations observed in Canadian and Greenlandic populations in this study.

Considering PBDEs, decreasing trends were observed for PBDE-47 in Sweden and PBDEs in Finland, but PBDE-153 showed an inconsistent trend in Sweden. The observed differences in trends between PBDEs and OCPs could be attributed to the influences of distinct cultures, traditional lifestyles, and dietary habits. In addition, the regulations for the hexa- BDEs (PBDE-153), were implemented much later than penta-BDEs (PBDE-47). Further, deca-BDEs (PBDE-209 the parent compound for BDE-153) was only included in the Stockholm convention in 2017, which could have contributed to inconsistent trends in PBDE-153 in Sweden (Arctic Pollution, 2009). Moreover, a recent study reported decreasing trends in the younger population but increasing trends in the older population which show the effectiveness of regulations in phasing out the production and use of PBDEs in consumer products (Sjödin et al., 2020). We observed decreasing trends of regulated PFAS (PFOS and PFOA) and increasing or inconsistent trends among unregulated PFAS (PFHxS, PFNA, PFDA and PFUnDA). These results are in line with the trends observed in other studies conducted in the Arctic areas (Abass et al., 2018; Berg et al., 2021; Wielsøe et al., 2022). Global production of PFOS declined drastically in the beginning of 2000 as the main manufacturer 3 M phased out their production (Paul et al., 2009), and shortly after decreasing concentrations were observed in human populations, mirroring the changes in global production (Nøst et al., 2014). The use of PFOS was restricted in many countries before it being listed in the Stockholm Convention in 2009 (Berg et al., 2021). Even though the

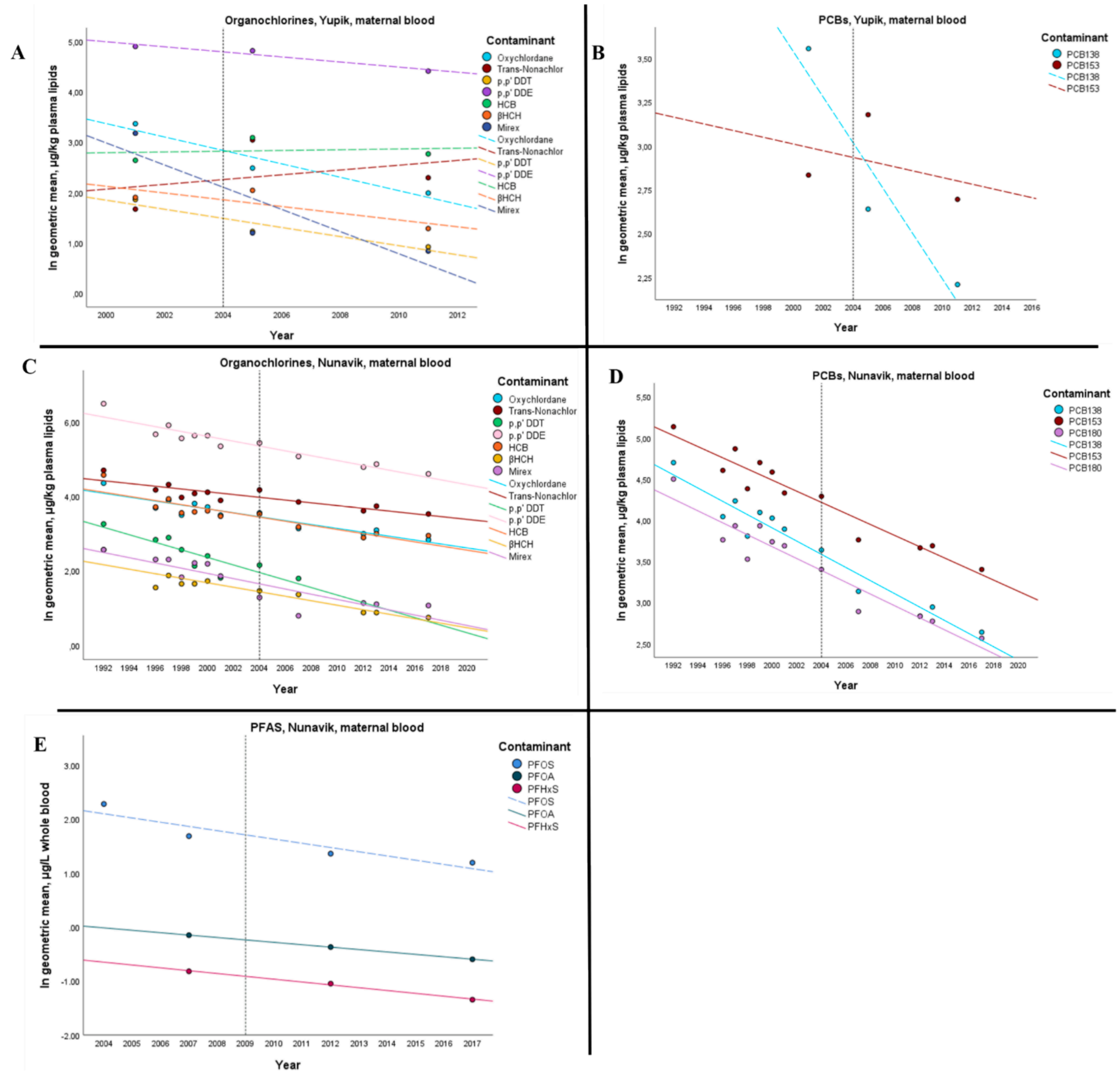

Fig. 5. Trends in POP blood concentrations from children in Alaska (A, B) and from Canada (C-E). Circles with different colors represent a specific POP measured over time. Solid lines describe consistent decreasing trends while the dotted lines represent inconsistent trends. The reference line on the X-axis denotes the year of implementation of the Stockholm Convention Abbreviations: *p,p'*-DDT: 1,1,1-trichloro-2,2-bis(4-chlorophenyl) ethane; *p,p'*-DDE: dichlorodiphenyldichloroethylene; HCB: hexachlorobenzene; *β*-HCH: beta-hexachlorocyclohexane; PCB: polychlorinated biphenyls; PFOS: perfluorooctanesulfonic acid; PFOA: perfluorooctanoic acid; and PFHxS: perfluorohexanesulfonic acid.

persistence of PFAS in the environment has been known, and with over 4000 PFAS present, biomonitoring of the substances in Arctic populations mostly started after 2000. Studies from Arctic regions, for instance in Northern Norway (Berg et al., 2021; Nøst et al., 2014), Alaska (USA) (AMAP, 2021b,2022), Nunavik (Canada) and Greenland (Long et al., 2021) show decreasing trends for PFOS and PFOA, mainly after 2001, and increasing trends for other PFAS like PFNA, PFDA and PFUnDA (Berg et al., 2021; Nøst et al., 2014). The increasing trends of other PFASs (PFNA, PFDA and PFUnDA) could be due to continued production after 2001, longer elimination half-lives and their bioaccumulation ability compared to other shorter-chain PFCAs (Nøst et al., 2014). In contrary, studies from non-Arctic areas including Denmark, Australia, Germany, and USA show consistent decreasing trends for PFNA, PFDA and PFUnDA, in addition to PFOS and PFOA (Bjerregaard-Olesen et al., 2016; Eriksson et al., 2017; Göckener et al., 2020; Gribble et al., 2015; Olsen et al., 2017; Toms et al., 2014). These decreasing trends differ from the increasing trends reported in the Arctic areas. PFAS trends among Faroese and Finnish children show decreasing trends, except for PFNA in Faroe Island Cohort 3. There are few studies reporting time trends among children outside the Arctic areas, but trends reported in Swedish children show similar decreasing trends for PFOS and PFOA and increasing trend for PFUnDA. No consistent trend was observed for PFNA in Swedish children (Gyllenhammar I, 2016). The difference in PFHxS, PFNA, PFDA and PFUnDA trends between

Arctic populations and other non-Arctic population can possibly be explained by differences in diet and lifestyle (Nøst et al., 2014), and by long-range transport of PFAS into the Arctic areas (Butt et al., 2010).

Global regulations including national and international regulations, Stockholm Convention, are expected to reduce POP concentrations in humans in the future, but climate change effects, such as permafrost thaw, increased temperature, precipitation, and wind speeds, can influence POP transport and fate, as well as their release from primary and secondary sources (Nadal et al., 2015). Between 1971 and 2017, the yearly average temperature in the Arctic increased by 2.7 °C, which is 2.4 times the average temperature increases in the Northern Hemisphere (Box et al., 2019). Increased temperatures and rainfall can accelerate POP breakdown in the environment, whereas cold temperatures in Arctic regions can contribute to increased POP deposition in the biota (Nadal et al., 2015). Global climate change modelling studies analyzing POPs in the Arctic are inconsistent, and existing understanding suggests that climate change may increase or decrease POP concentrations in the Arctic (Nadal et al., 2015; Pacyna et al., 2015). PCB levels have been projected to fall further in the Arctic despite climate change, but indirect effects of climate change, such as altering nutrition, can affect pollutant concentrations in Arctic populations (Carlsson et al., 2018). This study thus highlights the necessity and effectiveness of international rules for regulated and banned contaminants, as well as the need to focus more on new developing contaminants in the Arctic, such as PFAS.

This study gives an overview of the time trends in POPs across the different Arctic countries over 30 years. The study used only data of at least three measurement points for each contaminant, providing a more reliable evaluation of the time trends. The laboratories providing contaminant data for the AMAP assessments participate in the AMAP Ring Test (Adlard et al., 2018), and all the participating laboratories are expected to participate in external quality assurance and quality control protocols. Because of these meticulous quality control measures, the data included in the present study is reliable and gives a good measure of the time trends. However, there are also some limitations that need to be considered. Several factors influence POP concentrations in humans, including age, diet, weight, seasonality, and geography. Because the purpose of this study was to give time trends in a broader context, no such factors were adjusted in the statistical analyses. There are also big variations between the sample sizes of the included study populations, varying from 9 to 1022 participants in the different countries. Also, the studies have measured POP concentrations in different biological matrices and presented the POPs in different units. Comparing median and geometric mean values is not possible, and for some contaminants comparing values measured from different biological matrices is impractical. This study excludes Russia from the analyses, due to lack of data from three time points. Considering that the Russian Arctic accounts for about half of the entire Arctic area and is home to two-thirds of the population (Emelyanova, 2017), excluding it might be viewed as a significant limitation. However, the other populations included in this study are representative of Arctic populations, and POP time trends presented in this study are consistent with expected trends. Therefore, we do not consider excluding Russia to have influenced the time trend results.

5. Conclusions

AMAP assessments have significantly influenced the inclusion of new contaminants in the Stockholm Convention and have informed additional international restrictions. The necessity of long-term monitoring data over several years/decades is needed to observe significant effectiveness of an international convention on chemicals in the global environment.

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CRediT authorship contribution statement

Saranya Palaniswamy: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Laura Nevala:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Paula Pesonen:** Writing – review & editing, Methodology. **Arja Rautio:** Writing – review & editing. **Marjo-Riitta Järvelin:** Writing – review & editing. **Khaled Abass:** Writing – review & editing, Validation, Supervision, Conceptualization, Data curation. **Dolley Charles:** Writing – review & editing, Writing – original draft, Supervision, Validation, Project administration, Methodology, Conceptualization, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108777.

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