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Time trend analysis of environmental contaminants in human Arctic populations

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Master's thesis in Public Health

HEL-3950, Spring 2022

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Abstract

Background:

Arctic Monitoring and Assessment Programme (AMAP) monitors persistent organic pollutant (POP) levels in the Arctic and assesses health effects related to them. Many of the POPs are regulated internationally, but still found in humans and biota. There are also new emerging contaminants, of which many are unregulated. Arctic populations present high contaminant concentrations compared to non-Arctic populations, with traditional food being the main source of exposure. Time trend analyses give information of effectiveness of international regulations, but also of warning of new emerging contaminants.

Objectives:

The objective of this study is to analyze time trends of 24 contaminants or their combination in Arctic populations including USA, Canada, Iceland, Faroe Islands, Greenland, Sweden, Norway, and Finland. Legacy POPs analyzed in this study include organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs), whereas per- and polyfluoroalkyl substances (PFAS) and polybrominated biphenyl ethers (PBDEs) are new emerging contaminants included in this study.

Methods:

Data included in this study is aggregated data presented in the AMAP Human Health in the Arctic 2021 assessment. AMAP assessments provide contaminant concentrations measured in maternal, adult and child blood and breast milk samples from different epidemiological studies conducted in the Arctic since 1980s. For some populations, where no new data was presented or it was presented as figures in AMAP 2021, AMAP 2009 and AMAP 2015 were used to collect data. Linear regression was used to assess time trends of the different POPs within different Arctic populations.

Results:

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

Conclusions:

Declining trends are observed for legacy POPs, but the trends for new emerging contaminant are inconsistent. More focus is needed on biomonitoring the new emerging contaminants in the Arctic and their health effects.

Acknowledgments

First and foremost, I would like to express my sincere gratitude to my supervisor Dolley Charles and my co-supervisors Khaled Abass and Saranya Palaniswamy for your advice, support, and encouragement during this Master´s thesis project. The level of your expertise and knowledge is truly inspiring and I´m grateful to have learned so much from you. This thesis would not have become complete without your guidance.

Secondly, I would like to thank Arja Rautio and Paula Pesonen for your help and support during this project. I would also like to thank Irina Gyllenhammar for providing data for this thesis. It has been a great experience to work with such an international group of people, and I´m feeling eager and inspired to learn more in the future.

I would like to thank my fellow MPH students Johanna and Mikaela. Your friendship during the studies, both on and off the school, has been invaluable. I´m so happy that we ended up in the same classroom before the pandemic moved our studies online. Our small but strong Finnish team in northern Norway made it through. I would also like to thank the Arctic University of Norway for providing the MPH studies in an international environment.

Finally, I would like to thank my family and friends. My parents and siblings for always being there for me. My partner, Elias, your support and patience has been irreplaceable during this process. I would also like to give special thanks to our dogs Neon and Snø, for providing as many furry hugs as needed and making sure I got enough fresh air in between the writing process.

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List of abbreviations:

ACCEPT	Adaption to Climate Change, Environmental Pollution and dietary Transition
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
GMP	Global Monitoring Plan
HCB	Hexachlorobenzene
β-HCH	beta-Hexachlorocyclohexane
MOMS	Maternal Organics Monitoring Study
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
POPUP	Persistent Organic Pollutants in Uppsala Primiparas
TEQ	Toxic Equivalency
UNEP	United Nations Environmental Programme
WHO	World Health Organization

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. Several of these synthetic chemicals were introduced into commercial use. POPs include a wide range of 'legacy' contaminants like dioxins and dioxin-like compounds including polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs). PCBs were used widely in electrical equipment such as capacitors and transformers and in heat transfer fluids, lubricants, plasticizers, and hydraulic fluids. OCPs were used extensively as pesticides and insecticides, with only dichloro-diphenyl-trichloroethane (DDT) being allowed to use today under specific circumstances for disease-vector control (1). POPs also include chemicals of 'emerging' concern which do not fall under standard monitoring and regulatory programs but may be candidates for future regulation. In contrast to the legacy POPs which have been heavily studied upon and regulated, the new 'emerging' chemicals like polybrominated diphenyl ethers (PBDEs) and certain per- and polyfluoroalkyl substances (PFAS) have only recently gained the interest of scientific and regulatory communities (2). PBDEs are additive flame retardants widely used to reduce flammability in electronics, plastics, textiles, and furniture products (3) while PFAS are found in clothing, materials for food packaging, cooking utensils and firefighting foams (4).

Although several of these chemicals demonstrated to be beneficial in pest and disease control and in agriculture and industry, these same chemicals have unforeseen effects on the environment and human health. The chemical and physical properties of these substances make them resistant to degradation, persistent in the environment and toxic to humans and wildlife. They bioaccumulate in living organisms specifically in fatty tissues, and through biomagnification the species highest up in the food chain, such as humans, predatory fish and mammals, gather the highest concentrations. These substances are capable of long-range transport and can be found far away from their original sources, all over the world (5). In humans, the main route of POPs exposure is through diet (6). Other exposure routes include drinking contaminated water, contact with the chemicals, dust inhalation and skin absorption. POPs are also able to transfer through placenta and breast milk to offspring (1). Research has shown that POP exposure is associated with adverse effects in humans such as neurobehavioral, immunological, reproductive, cardiovascular, endocrine, and carcinogenic effects (6-8). The

global impact of POPs on human health and the biota, and the need to restrict or eliminate them have been a matter of interest for international agreements for several years.

1.1 International Regulations of POPs

The focus on environmental contaminants and their toxicity started in 1960s when the association between DDT and eggshell thinning among bird species was recognized. This discovery led to banning the use of DDT in many countries during the 1970s, but it took almost three decades before the first global restrictions on DDT and other POPs were launched (9).

In 1995 the United Nations Environmental Programme (UNEP) Governing Council requested an assessment of 12 initial POPs due to the increasing awareness globally on the threats of contaminants to human health and the environment. As a global response to the problem the UNEP Stockholm Convention on POPs was adopted in 2001 with the main goal to reduce and prohibit the release of the listed chemicals in the environment (10). The Stockholm Convention entered into force in 2004, with banning or restricting the production of several POPs including OCPs and PCBs. In the later years, several of the PFAS and PBDEs were also included in the list (9). Today the convention has extended to include 26 POPs and 184 nations, reaching nearly a universal coverage. Of the eight Arctic states (Canada, The United States, the Kingdom of Denmark, Iceland, Finland, Sweden, Norway and the Russian Federation), only United States is not a ratified party of the convention but acts an observer (11). A Global Monitoring Plan (GMP) for POPs was also launched to assess the effect of the convention (12). The third report from the GMP in 2021 for Western Europe and Others Group, including Scandinavian countries and North America, shows that most POPs listed before 2009 demonstrate a declining trend, describing efficient regulations and policies, but for newly listed POPs there is only baseline data available (13).

1.2 Biomonitoring of POPs in the Arctic

The Arctic region is responsible for insignificant amounts of pollution globally, but for some contaminants Arctic populations present the high end of concentrations measured in humans (8). For instance, Greenland has shown highest contaminant concentrations during the past decades (14, 15), with Nunavik in Canada and Faroe Islands having higher concentrations compared to non-Arctic areas as well (16, 17). The atmosphere, ocean currents and rivers transport the substances from lower latitudes into the Arctic, where many of the predatory fish and mammals are part of people´s traditional and local diets. Even though the diets in Arctic

are westernizing, the local foods, especially some marine mammals, are part of culture and act as the main source for POPs exposure to these populations (18).

The Arctic Monitoring and Assessment Programme (AMAP) is responsible for the biomonitoring of environmental contaminants in the Arctic (19). It was initiated in 1991 as part of the Arctic Environmental Protection Strategy to monitor and assess climate change and pollution issues in the Arctic areas, and later became one of Arctic Council´s six working groups. The Arctic Council was officially established in 1996 by the Ottawa Declaration to strengthen cooperation, research and interaction between the eight Arctic countries with active involvement from six Indigenous People´s Organizations in the Arctic Areas who have the same consultation rights in the Arctic Council´s negotiations and decisions as the Arctic states (20).

The AMAP is mandated to investigate the effects of climate change and pollution on humans and ecosystems in the Arctic. The focus is to document pathways, trends and levels and monitor the status in the Arctic region. It also produces evidence-based assessments, policy-relevant information and action proposals for governments and policy decision-makers. In addition, AMAP supports the international environmental acts as the United Nations Environmental Programme (UNEP) Stockholm Convention on POPs. The first Human Health in the Arctic-assessment was published in 1998 with new assessments following in 2002, 2009, 2015 and 2021 (19).

The geographical coverage for AMAP assessments is presented in Figure 1. Generally, the Arctic is defined as the northern areas above the Arctic Circle, but since areas of permafrost, mountain ranges, large waters, vegetation, and temperatures vary, the boundary for AMAP area is defined considering these factors. Therefore, AMAP coverage includes both High Arctic and sub-Arctic regions based on a compromise between terrestrial, marine, and political boundaries. The relevance for the AMAP boundary can vary regarding issues addressed and extend across the boundaries when relevant. Some of issues relevant for crossing the boundaries are topics addressing climate change or long-range transport of environmental contaminants (21). This is relevant for this study, as some of the contaminant concentration data from Swedish and Finnish populations is geographically outside of the AMAP boundary.

Figure 1. The AMAP assessment area (22).

Despite international regulations, legacy POPs are still found in humans, animals and environment attributing to their long half-lives (18). There are also new emerging chemicals of Arctic concern (ECACs), which are chemicals that are unregulated or alternatives to banned substances with origin both inside and outside the Arctic areas. Some of the emerging PFAS compounds, such as perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) are already listed under the Stockholm Convention because of their properties and toxicity similar to OCPs and PCBs (9). Some other PFAS substances, such as perfluorohexanesulfonic acid (PFHxS), are under evaluation and proposition to be listed under the Stockholm Convention (23). PBDEs were listed for elimination in the Stockholm Convention in 2009 (9).

1.3 Rationale of the study

Assessing time trends of POPs helps in monitoring the stability of these chemicals in humans and the ecosystem, evaluate the effect of international regulations and to give warning of potentially harmful contaminants emerging in the Arctic (24). Assessments provided by AMAP have played a significant role when new contaminants have been added to the Stockholm

Convention, and they have provided important information for other international restrictions as well (25). Biomonitoring and the assessments provide information for policymakers regarding health outcomes related to contaminant exposure, public health advise and risk-management (8). As environmental contaminants are found in humans, animals and the environment, holistic One Health-approach is important for contaminant monitoring in the warming Arctic in the future as well (26). The Arctic is warming twice as fast as the global mean, and climate change can affect the behavior, transport and release of POPs in the Arctic (2). In addition to changing pathways of POPs, climate change can alter vegetation patterns and marine and terrestrial animal distribution and migrations patterns, affecting populations diets and lifestyles (26).

To date, several studies have examined time trends of POPs and their impact on human health. The earliest measurements of POPs in human matrices in the Arctic dates to frozen serum samples from 1979 that were analyzed later to look at time trends of POPs in northern Norway (27). Previous studies of time trends in POPs show decreasing trends for most of the regulated POPs in the Arctic populations (15, 27-33). However, several of these studies are either limited to a particular group of POPs, a particular study population or country, or POPs measured in different biological matrices. Long-term monitoring data over several years/decades is needed to observe significant effectiveness of an international convention on chemicals in the global environment.

Therefore, this thesis aims to give an update on the concentration levels of POPs and assess time trends of POPs in the different Arctic human populations.

1.4 Study aims and objectives

This thesis aims to give a holistic overview on the levels of POPs in Arctic human populations and provide recommendations for future studies assessing POP concentrations in the Arctic. The main objective of this study is to present analyses of time trends of PCB, OCP, PFAS and PBDE concentrations in blood samples and breast milk samples using study populations from 7 different Arctic countries including USA, Canada, Iceland, Norway, Sweden, Finland, Greenland, and the Faroe Islands.

2 Materials and methods

2.1 Study population

Data included in this study is aggregated data presented in the AMAP Human Health in the Arctic 2009, 2015 and 2021 assessments. AMAP (2021) included POP concentrations measured in maternal, adult and child blood and breast milk samples from different epidemiological studies conducted in the Arctic since 1980s. As no new data on concentrations of POPs in Finland and Alaska was included in 2021, we used AMAP 2015 assessment for these regions. AMAP 2009 was used to collect earlier data from Greenland that was presented as figures in AMAP 2021. The included study populations from AMAP (USA, Canada, Iceland, Norway, Sweden, Finland, Greenland, Faroe Islands) are described in detail below. An overview of the different study populations including the time points POPs were measured at, mean age of the study populations, study sample size, and reference to original studies when available, is provided in Appendix 1. Only concentrations of contaminants consisting of minimum three measurement points were included in this study.

2.1.1 Alaska/ USA

Maternal Organics Monitoring Study (MOMS) was developed by Alaska Native Tribal Health Consortium in 1998 to evaluate the possible health effects of bio-accumulative persistent chemicals and metals on Alaskan mothers and their children and to assess the risks and benefits of the population´s traditional diet. Three cohorts of pregnant women were recruited to participate during their first prenatal visit at the Yukon-Kuskokwim Delta Region Hospital in Bethel, Alaska, USA (34). As the hospital serves as a concentrated healthcare center, many of the women recruited represent rural Yupik communities in the Yukon-Kuskokwim Delta area (35). The first cohort was recruited between 1999-2003, second between 2004-2006 and third between 2009-2012 (36). Data in this study were extracted as geometric mean values of maternal blood concentrations (µg/kg plasma lipids) for oxychlordane, *trans*-nonachlor, *p,p´*-DDT, *p,p´*-DDE, HCB, *β*-HCH, Mirex, PCB-138 and 153 from the three cohorts presented in AMAP 2015 assessment (35).

2.1.2 Canada

Between 1992 and 2017, 13 different studies were conducted including total 559 pregnant Inuit women living in one of the 14 villages along Ungava Bay, Hudson Bay and Hudson Strait in Nunavik (29). A more detailed description of the studies is provided elsewhere (8, 37). In short, pregnant women were recruited during their first prenatal visit to the local health center, and

they provided blood samples for contaminant analyses (29). A more detailed description of methods and sampling has been described elsewhere for the measured OCPs and PCBs (29, 33) and PFAS (38) in these studies. Geometric means values of contaminant concentrations in µg/kg plasma lipids for OCPs and PCBs and in µg/L whole blood for PFAS in maternal blood samples from each study were included, as reported in AMAP 2021 assessment (8). POPs included from the above studies are oxychlordane, *trans*-nonachlor, *p,p´*-DDT, *p,p´*-DDE, HCB, *β*-HCH, Mirex, PCB-138, 153 and 180, PFOS, PFOA and PFHxS.

2.1.3 Iceland

Maternal blood contaminant concentrations have been monitored in Iceland since 1995 approximately every five years. Samples were collected from pregnant women in their third trimester in Reykjavik in 1995, 2009 and 2015, and from other locations in Iceland in 1999 and 2004. The population of Iceland is considered to be socially and culturally homogenous and it´s determined that the location of the mother´s residence doesn´t influence measured contaminant levels (39). This allows contaminant concentration comparisons over time despite different data collection locations. Contaminant levels are presented in AMAP 2021 assessment (8). Geometric mean values in µg/kg plasma lipids of maternal blood concentrations for oxychlordane, *trans*-nonachlor, *p,p´*-DDE, HCB, *β*-HCH, PCB-118, 138, 153 and 180 were extracted and included in the data analyses.

2.1.4 Norway

Tromsø Study is a population-based study conducted in the Municipality of Tromsø in Northern Norway. It consists of seven surveys and includes over 40,000 participants (40). Blood serum samples of 30 years old, both men and women, who had participated in the Tromsø surveys conducted in 1986, 1994, 2001, 2007 were selected randomly and analyzed for POP concentrations. A more detailed description of methods and sampling has been described elsewhere (41). The median concentrations of POPs in µg/kg serum lipids at the different surveys are presented in AMAP 2021 assessment and were included in the present analyses (8). The OCPs and PCBs included from Tromsø, Norway are oxychlordane, *trans*-nonachlor, *p,p´*-DDE, HCB, *β*-HCH, PCB-118, 138, 153, 180, 156 and 170.

2.1.5 Sweden

Since 1996 the Swedish National Food Agency has monitored POP levels of first-time mothers living in Uppsala, Sweden. The objective of the Persistent Organic Pollutants in Uppsala Primiparas (POPUP) study is to estimate OCP, PCB, PBDE and PFAS levels among pregnant

and breastfeeding women to provide time trends and evaluate exposure of fetuses and infants (31, 42). Women who were Swedish by birth and gave birth at the Uppsala University Hospital were randomly recruited to participate in the study. The women provided breast milk samples or blood samples three weeks after delivery, depending on which part of the study they were recruited to. A more detailed description of recruitment, sampling and analyses has been described elsewhere for PCBs, OCPs and PBDEs (31) and PFAS (42) measured in these studies. PCB, OCP and PBDE concentrations were analyzed from breast milk samples and PFAS from blood serum samples (31, 42). PCB, OCP, PBDE and PFAS concentrations are presented as figures in AMAP 2021 (8). In addition, full data set including concentrations (2017-2019) for some contaminants was provided by Irina Gyllenhammar from the Swedish Food Agency through personal communications. The concentrations are provided in median values for *p,p´*-DDE, HCB, PCB-28, 153 and Total Toxic Equivalency (TEQ), PFHxS, PFOS, PFOA, PFDA, PFNA and PFUnDA, BDE-47 and 153. The concentrations are measured in µg/kg lipid weight for PCBs, OCPs and PBDEs in breast milk, pg/g lipid weight for total TEQ in breast milk and in ug/kg pooled blood serum for PFAS in blood samples.

2.1.6 Finland

Finland has taken part in WHO implemented study since 1987 that examines POP levels in breast milk (43). Two follow-up studies have been conducted in Southern and Eastern Finland, in 1987 and between 1993-1994. Women that were giving birth were recruited while visiting one of the maternity clinics in Helsinki and Kuopio. A more detailed description of recruitment, sampling and analyses have been provided elsewhere (44, 45). Measuring of contaminant levels continued in 2000, 2005 and 2010, with samples from Northern Finland included in the last two surveys. Data for this thesis is collected from AMAP 2015 assessment, but only data for Southern and Eastern Finland including five measure points (1987, 1993-1994, 2000, 2005, 2010) was included for the analyses. No newer data providing measurements after 2010 from Finnish mothers is available (35). Breast milk contaminant concentrations are provided in geometric means in µg/kg lipid for PCB-153 and for a sum of PBDEs (PBDE-47+ 99+100+153+209).

Also included in the thesis are median serum concentrations of PFAS from children included in a birth cohort study conducted in Eastern Finland between 2005 and 2015. The mothers were recruited during visit at the Kuopio University Hospital, and blood samples of the children were collected at ages 1, 6 and 10,5 years. Both girls and boys were included. A more detailed

description of sampling and analyses is provided elsewhere (46). Median concentrations in μg/L serum are provided for PFOS, PFOA, PFHxS and PFNA in AMAP 2021 assessment (8).

2.1.7 Greenland

As a part of circumpolar mother-infant health study maternal blood contaminant monitoring has been conducted among pregnant Inuit women living in Disko Bay and Nuuk, since 1994 and 1999 respectively (39). Between 1994-2006 blood samples were collected from 223 pregnant women in Disko Bay area and between 1999-2005 from 209 pregnant women in Nuuk area (39, 47). The samples were taken during a visit at the local district hospital or health care clinic. A more detailed description of sampling, methods, and analyses is provided elsewhere (47-49). Between 2010-2015, The Adaption to Climate Change, Environmental Pollution and dietary Transition (ACCEPT)-study was conducted in Greenland including pregnant women from Disko Bay and Nuuk. A detailed description of sampling and methods is provided elsewhere (14). The above mentioned studies provide concentrations over time for both Disko Bay and Nuuk, presented as figures in AMAP 2021 assessment (8). For this thesis, the data for Nuuk between 1999-2005 is collected from AMAP 2009 assessment and for Disko Bay between 1994-2006 from AMAP 2015 assessment as it included corrections to the earlier published data (35, 39). Data from the ACCEPT-study is collected from AMAP 2021 assessment (8). Geometric means of POP concentrations in μg/kg plasma lipid for oxychlordane, *p,p´*-DDE and PCB-153 were extracted for this thesis.

2.1.8 Faroe Islands

Several biomonitoring child cohort studies have been conducted in the Faroe Islands during the past 25 years to examine contaminant exposure and health effects in children (8). In this thesis data from cohorts 1, 3 and 5 is included. More detailed description of the cohorts is provided elsewhere (50).

The Faroe Island Cohort 1 was established in 1986-1987 including 1022 newborns. Blood samples were taken from cord blood at birth, and the children were followed-up at the age of 7, 12, 22 and 28 years old. The latest follow-up was conducted between 2013-2016 when the participants were 28 years old. The objective of the cohort was to assess methylmercury exposure and health outcomes in children, but concentrations of OCPs and PCBs were also measured (35). Regarding PCBs, it is reported that three main congeners (PCB-138, 153,180) represent approximately 50% of the total PCB concentrations measured in Faroese mothers, therefore duplicated sum of these congeners is used as a surrogate to present total ∑PCB

concentration in Faroese children (51). Data for the whole cohort is presented in AMAP 2021 assessment with geometric mean values of contaminant concentrations (µg/kg plasma lipids) for *p,p´*-DDE, HCB, PCB-138, 153 and 180 and ∑PCB [2x(PCB-138+153+180)] (8).

The Faroe Island Cohort 3 was established in 1998-2000 including 656 newborns. The aim of the cohort was to assess health effects of PCBs and other lipophilic contaminant exposure. Blood samples were taken at the age of 1.5, 5, 7.5 and 13 years. At the age of 1.5 year concentrations were measured only for *p,p´*DDE and ∑PCB [2x(PCB-138+153+180)] (35). Geometric mean values of OCP and PCB concentrations in µg/kg plasma lipids are collected from AMAP 2015 assessment and PFAS in µg/L serum from AMAP 2021 assessment (8, 35). Data was available for *p,p´*-DDT, *p,p´*-DDE, HCB, *β*-HCH, PCB-118, 138, 153, 180, PFOS, PFOA, PFHxS, PFNA and PFDA.

The Faroe Island Cohort 5 is the most recent cohort established in 2007-2009 including 500 mother-child pairs. The aim of the cohort was to evaluate dietary advice given to the Faroese population and to examine the effect of POPs exposure through breastfeeding (35). Blood samples were taken at the age of 1.5, 5 and 9 years of age. The geometric mean values for concentrations of *p,p´*-DDE, HCB, PCB-118, 138, 153, 180 and ∑PCB [2x(PCB-138+153+180)]; PFOA and PFOS (sum of linear and branched) are presented in AMAP 2021 assessment (8). OCP and PCB concentrations were measured in µg/kg serum lipids and PFAS in µg/L whole blood.

2.2 Selected environmental contaminants

Geometric mean or median concentrations (µg/kg or µg/L) of the different POPs were extracted from each of the studies included in the 2009, 2015 and 2021 AMAP assessments. The POPs included in this thesis, their primary sources and their global regulations are presented in Tables 1 and 2.

Table 1. OCPs and PCBs included in this study

Chemical/ Chemical group	Primary sources	Global restrictions
Oxychlordane	Chlordane constituent. Chlordane was used for termite control and as broad-spectrum insecticide in agriculture.	Chlordane is listed under Annex A (Elimination) in Stockholm Convention since 2004 (9).

***Trans*-Nonachlor**	Chlordane constituent. Chlordane was used for termite control and as broad-spectrum insecticide in agriculture.	Chlordane is listed under Annex A (Elimination) in Stockholm Convention since 2004 (9).
***p,p´*-DDT (Dichlorodiphenyl-trichloroethane)**	Insecticide used for malaria and other vector-borne disease control, used also in agriculture.	Listed under Annex B (Restriction) in the Stockholm Convention since 2004, with acceptable use for disease vector control. Banned in many countries since 1970s (9).
***p,p´*-DDE (Dichlorodiphenyl-dichloroethylene)**	Breakdown product of DDT, no commercial use.	Restricted through DDT restrictions (9).
HCB (Hexachlorobenzene)	Pesticide used in agriculture to kill fungi in food crops, also used as industrial chemical.	Listed under Annex A (Elimination) in Stockholm Convention since 2004 (9).
***β*-HCH (beta-Hexachlorocyclohexane)**	Used earlier as an insecticide, today produced only unintentionally as a by-product in lindane production. Releases also from contaminated sites.	Listed under Annex A (Elimination) in Stockholm Convention since 2009 (9).
Mirex	Insecticide mainly used for ants and termites. Also been used as fire retardant in rubber, plastic and electrical products.	Listed under Annex A (Elimination) in Stockholm Convention since 2004 (9).
PCBs (Polychlorinated biphenyls)	Compounds used in paint, electric capacitors and transformers and as heat exchange fluid in industry. Also produced unintentionally in industry.	Listed under Annex A (Elimination) in Stockholm Convention since 2004. Specific restrictions under Annex C (Unintentional production) (9).

Table 2. PFAS and PBDEs included in this study

Chemical	Primary sources	Global restrictions
PFOS (Perfluorooctanesulfonic acid)	Intentionally produced and widely used in firefighting foams, electronics, hydraulic fluids and textiles and in photo imaging. Unintentional product of degradation in similar chemicals.	Listed under Annex B (Restriction) in the Stockholm Convention since 2009, with acceptable use in agriculture to control specific ants. Exemption to be used in specific type of fires in firefighting foam (9).

PFOA (Perfluorooctanoic acid)	Used as a surface treatment agent or surfactant in non-stick kitchen and food processing equipment, textiles, papers, paints, and firefighting foams. Unintentional release from inadequate waste incineration.	Listed under Annex A (Elimination) in Stockholm Convention since 2019 (9).
PFHxS (Perfluorohexanesulfonic acid)	Used in water-proofing agents, food contact papers, firefighting foams, surface protection agents in cleaning and polish products, also an industrial by-product.	Nominated to Stockholm Convention in 2017, listed as chemical under review (23, 52).
PFDA (Perfluorodecanoic acid)	Used as surface treatment agent or surfactant and in firefighting foams.	Not regulated. Listed as "Substance of very high concern" at European Chemical Agency (53).
PFNA (Perfluorononanoic acid)	Used as surface treatment agent or surfactant and in firefighting foams.	Not regulated. Listed as "Substance of very high concern" at European Chemical Agency (53).
PFUnDA (Perfluoroundecanoic acid)	Used as surface treatment agent or surfactant and in firefighting foams.	Not regulated. Listed as "Substance of very high concern" at European Chemical Agency (53).
PBDEs (Polybrominated diphenyl ethers)	Widely used as flame retardants in electronics, textiles, and plastic.	Listed under Annex A (Elimination) in Stockholm Convention since 2009 (9).

2.3 Statistical analysis

Linear regression was used to investigate the time trends of 24 environmental contaminants or their combinations, specifically, several PCB congeners (PCB-28, 118, 138, 153, 156, 170 and 180); sum of PCBs 2x(PCB-138+153+180); seven OCPs (oxychlordane, *trans*-nonachlor, *p,p´*-DDT, *p,p´*-DDE, HCB, *β*-HCH, Mirex); six PFAS (PFOS, PFOA, PFHxS, PFDA, PFNA and PFUnDA); two PBDE congeners (PBDE-47 and 153) and the sum of PBDEs (PBDE-47+99+100+153+209). Only time series consisting of at least three measurement points were included in the analyses. All dependent variables (POP concentrations in geometric mean/median values) were naturally log-transformed due to right skewed distribution for some of the POPs. Measurement points in years were used as independent variables. Assumptions regarding normality, homoscedasticity and linearity were checked by Predicted Probability (P-P) plot and scatterplot of the residuals. The overall time-trends for the different POPs are

presented as scatterplot with linear fit/regression line. The linear regression analyses are not adjusted for any covariates. The results from the linear regression analyses including β-coefficients, 95% confidence intervals (CI) and p-values are presented in Appendix 2. When a single median/geometric means of POP concentrations were reported for data collected over several years, the median year or the following even year was used in the analyses and figures as a measurement point. For the data from Norwegian adults and Finnish children, the analyses were conducted separately for males and females.

Analyses and visualizations were performed using IBM SPSS Statistics version 28.0 (54).

2.4 Ethical approval

All data included in this study is aggregated data from previously conducted and published studies. Identification of the participants is not possible. Therefore, there was no need to apply for ethical approval.

3 Results

3.1 Time trends of POPs in maternal blood

Time trends of POPs in maternal blood from different Arctic populations are shown in Figures 2-5. In most of the Arctic populations POPs decreased over time with differences in linear trends. For instance, in Nunavik (Canada) and Disko Bay (Greenland) oxychlordane had a consistently decreasing linear trend, whereas in Yupik (Alaska, USA), Iceland or Nuuk (Greenland) the trends were decreasing but not consistent (Nunavik: β: -0.052, 95%CI: -0.067, -0.038; Disko Bay: β: -0.064, 95%CI: -0.095, -0.033) (Table 52 & Figure 2A). Considering *trans*-nonachlor and HCB, there was a consistent decreasing linear trend for Nunavik and Iceland, while the same compounds showed increasing contaminant concentrations in Yupik (Tables 53 and 56 & Figures 2B and 3A). For *β*-HCH the trends were decreasing in Nunavik, Iceland, and Yupik (Table 57 & Figure 3B). A consistently decreasing linear trend was also observed for concentrations of Mirex and *p,p´*-DDT in Nunavik, whereas in Yupik the trends were decreasing but not consistent (Tables 54 and 58 & Figures 2C and 3C). A consistent decreasing linear trend was also observed for concentrations of *p,p´*-DDE and PCB congeners in Nunavik, Iceland, Disko Bay and Nuuk, except for Yupik (linear trends $p<0.05$) (Tables 55 and 59-62 & Figures 2D, 4A-C). In Sweden, PFOS and PFOA concentrations declined consistently over time (PFOS: β: -0.089, 95%CI: -0.103, -0.075; PFOA: β: -0.049, 95%CI: -0.062, -0.036) (Tables 63 and 64 & Figure 5A); while the other PFAS chemicals including PFHxS, PFNA and PFDA increased over time, particularly, PFUnDA showed a consistent increasing linear trend (β: 0.019, 95%CI: 0.003, 0.034) (Table 68 & Figure 5A). Nunavik also showed decreasing trends for PFOS (β: -0.078, 95%CI: -0.171, 0.014) (Table 63 & Figure 5B) and PFOA (β: -0.045, 95%CI: -0.049, -0.040) (Table 64 and Figure 5B), however in contrast to Sweden, PFHxS concentrations showed declining trend in Nunavik (β: -0.053, 95%CI: -0.103, -0.002) (Table 65 & Figure 5B).

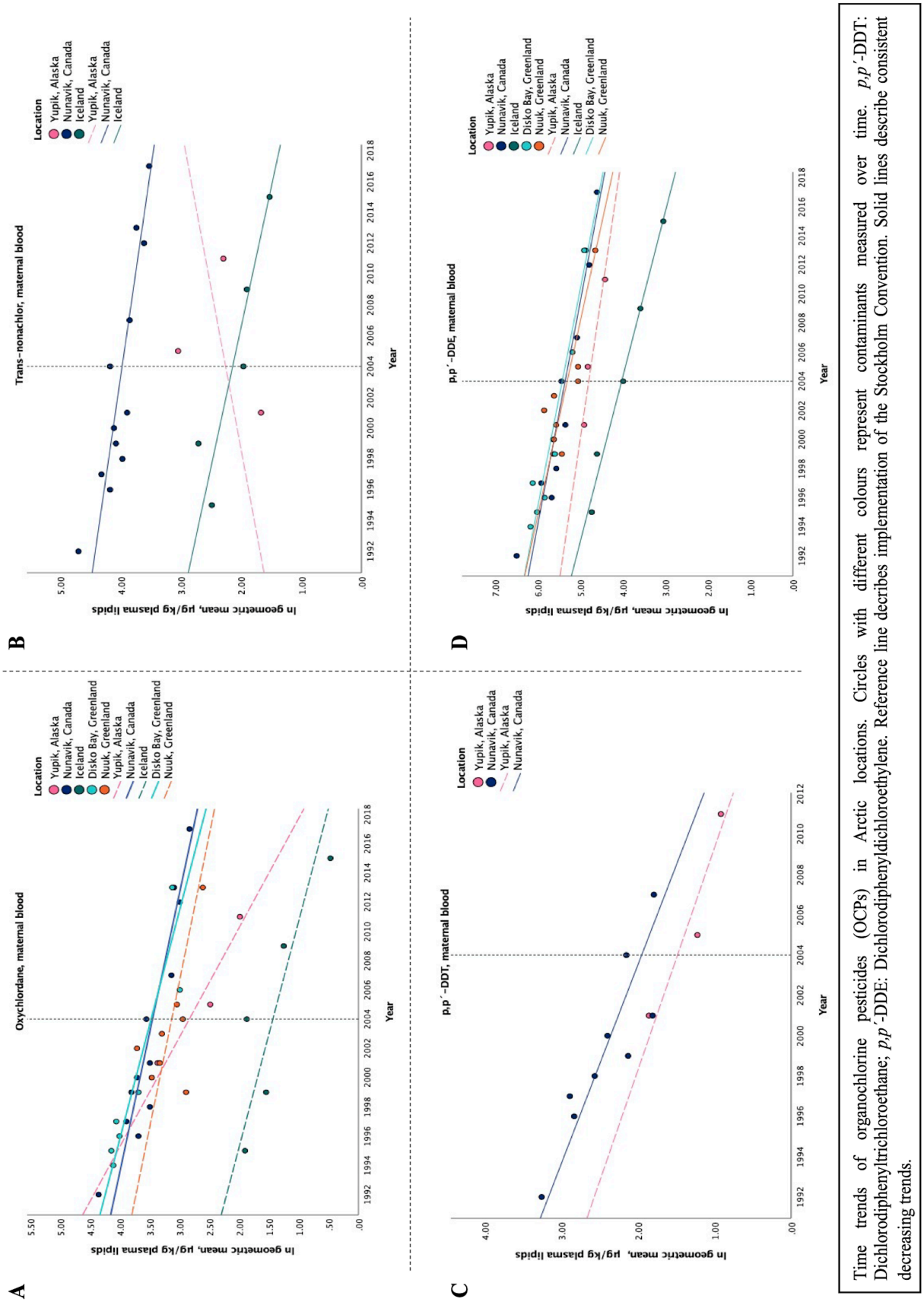


Figure 2. Time trends of OCPs (oxychlordane, trans-nonachlor, p,p´-DDT and p,p´-DDE) in maternal blood.

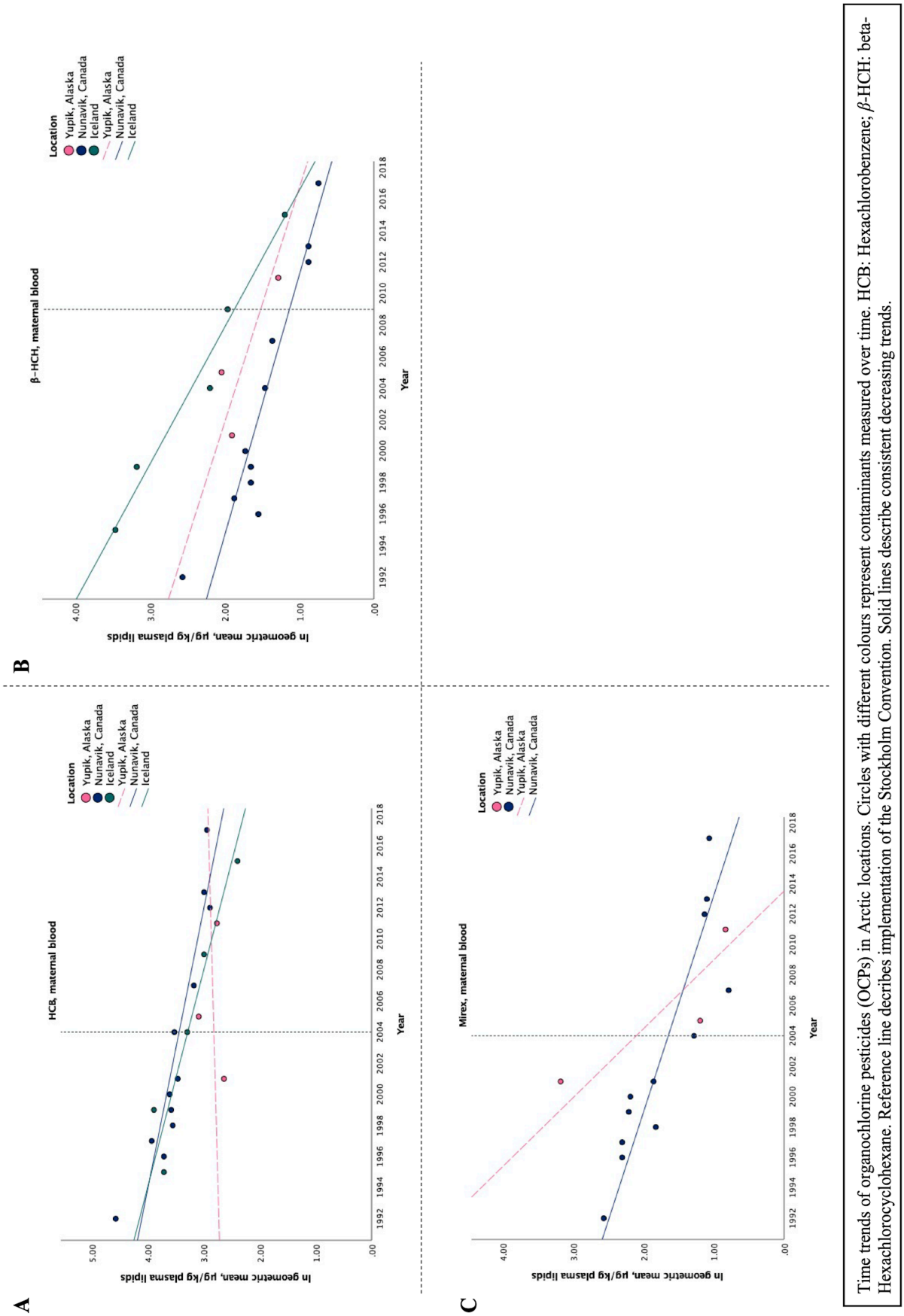
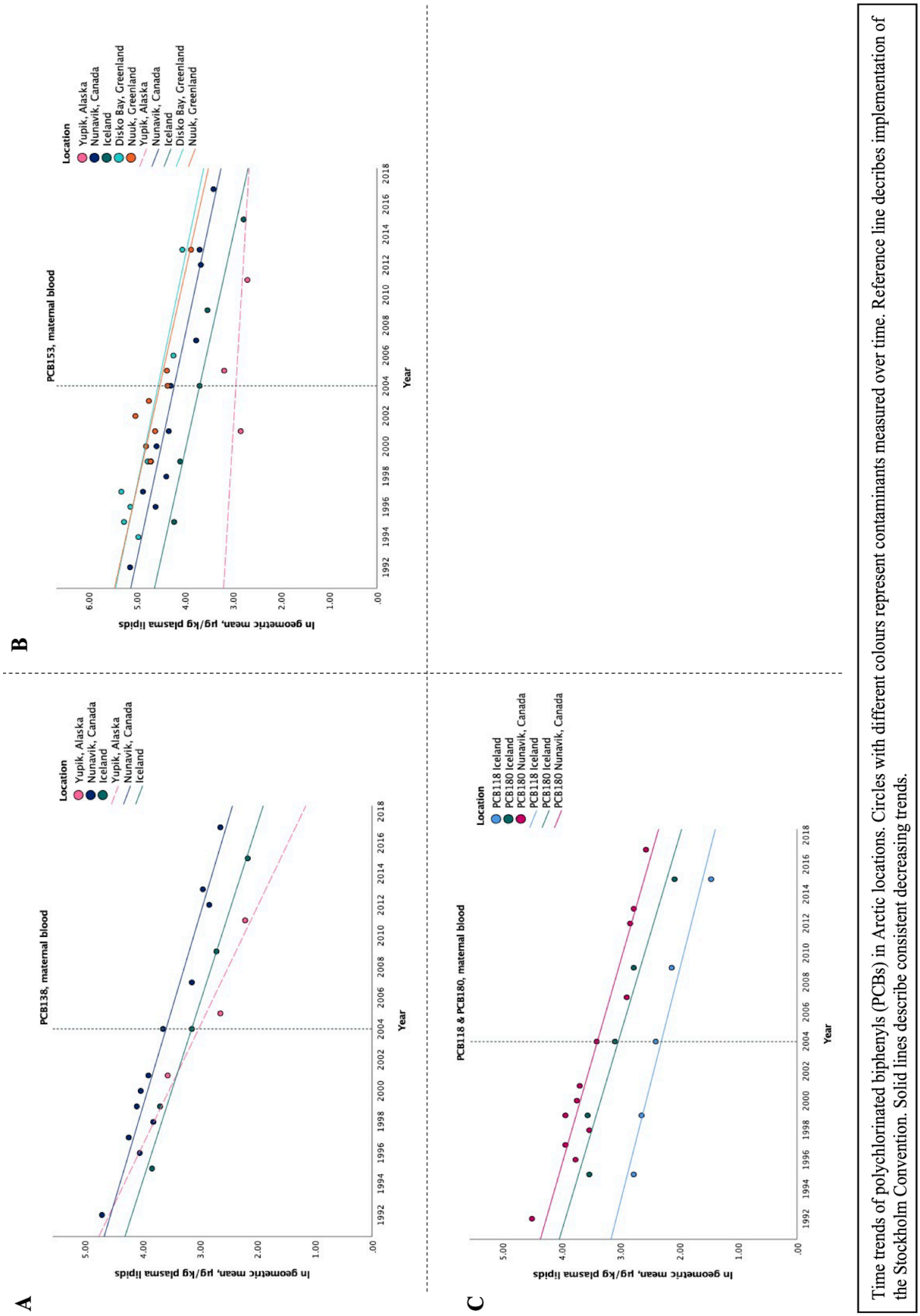


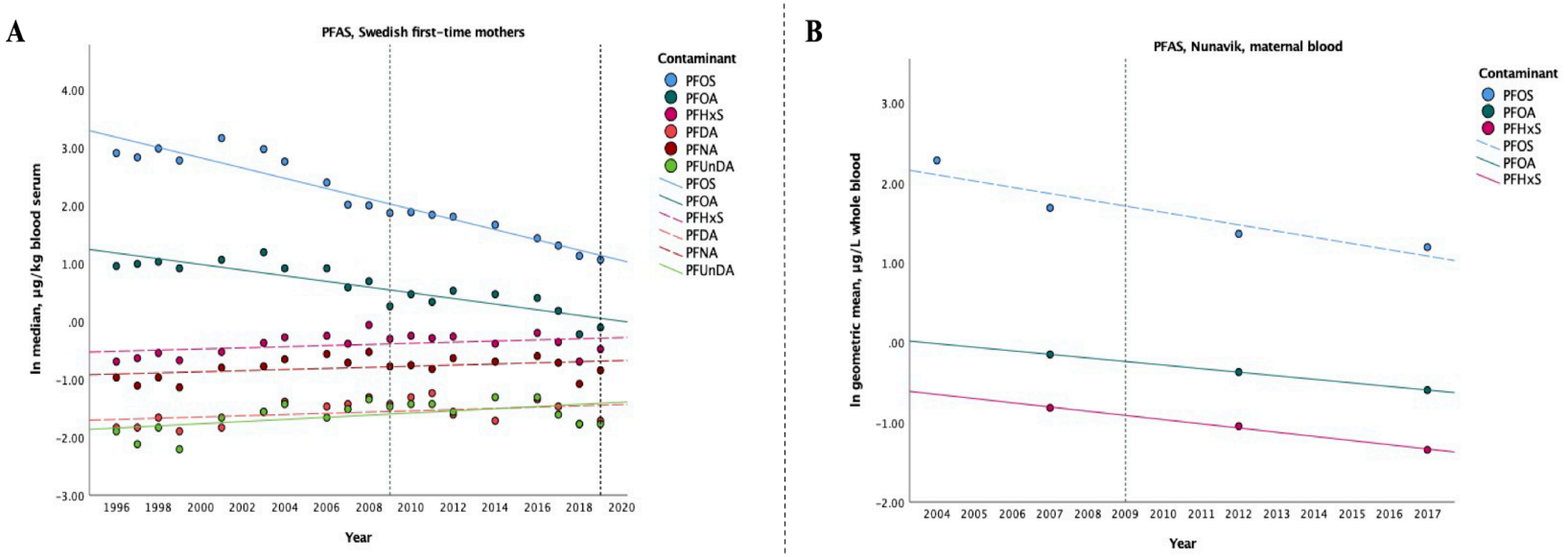
Figure 3. Time trends of OCPs (HCB, β-HCH and Mirex) in maternal blood.



Time trends of polychlorinated biphenyls (PCBs) in Arctic locations. Circles with different colours represent contaminants measured over time. Reference line decribes implementation of the Stockholm Convention. Solid lines describe consistent decreasing trends.

Figure 4. Time trends of PCBs in maternal blood.

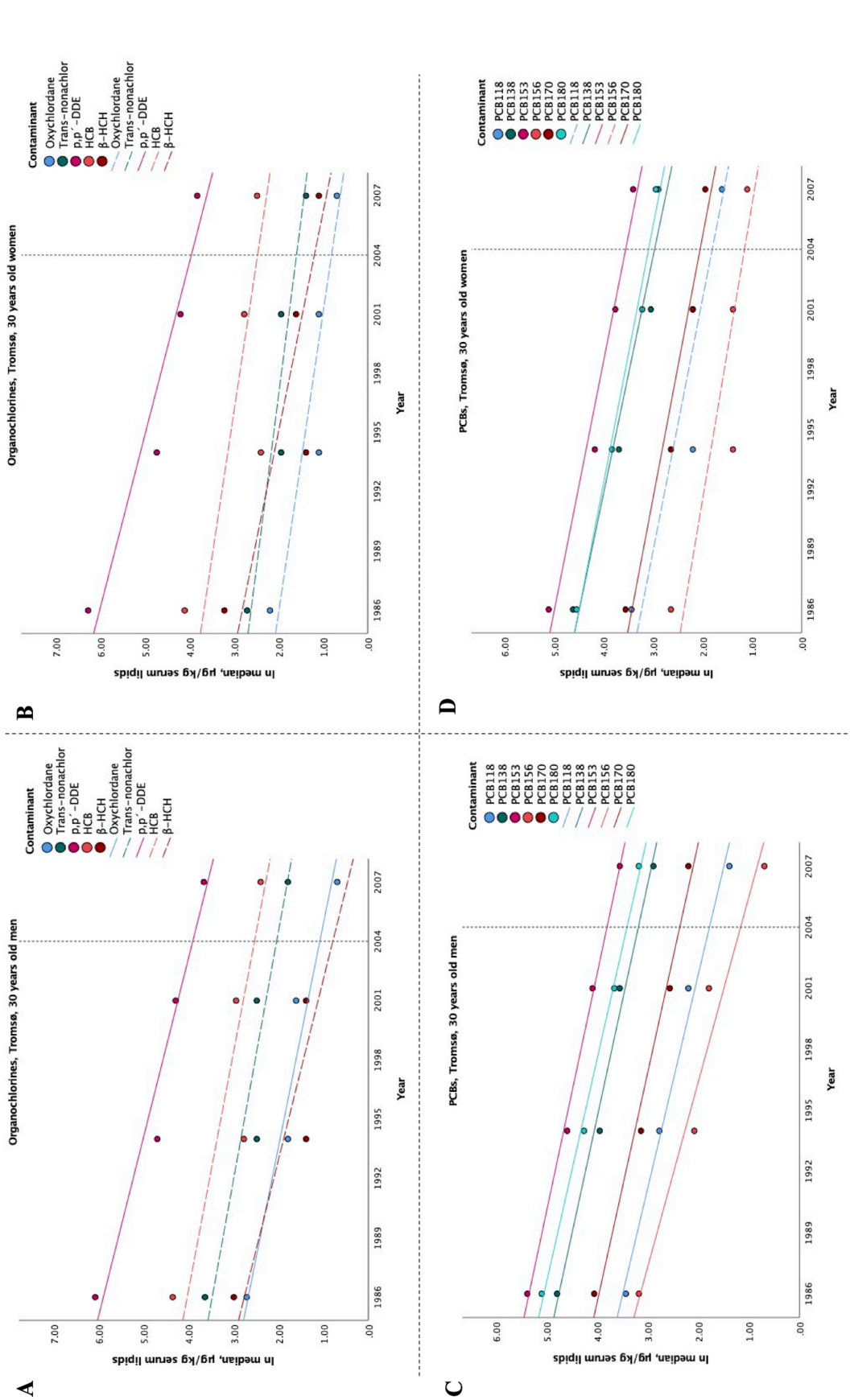
Figure 5. Time trends of PFAS in maternal blood.



Time trends of per- and polyfluoroalkyl substances (PFAS) in Arctic locations. Circles with different colours represent contaminants measured over time. Reference line decribes implementation of the Stockholm Convention for PFOS (2009) and PFOA (2019). PFOS: Perfluorooctanesulfonic acid; PFOA: Perfluorooctanoic acid; PFHxS: Perfluorohexanesulfonic acid; PFDA: Perfluorodecanoic acid; PFNA: Perfluorononanoic acid; PFUnDA: Perfluoroundecanoic acid. Solid lines describe consistent decreasing or increasing trends.

3.2 Time trends of POPs in adults

Time trends of POP concentrations in 30 years old men and women from Tromsø (Norway) are shown in Figure 6. All POPs decreased over time for both genders. Particularly *p,p´*-DDE showed consistent decreasing linear trend in both men and women (men: β: -0.111, 95%CI: -0.184, -0.037; women: β: -0.115, 95%CI: -0.213, -0.016) (Table 71 & Figures 6A and 6B). For oxychlordane the decrease was consistent in men (β: -0.089, 95%CI: -0.115, -0.023) (Table 69 & Figure 6A). *Trans*-nonachlor, HCB and *β*-HCH had decreasing concentrations over time in both men and women (Figures 6A and 6B). Consistent decreasing linear trends were observed for most PCB congeners (linear trends $p < 0.05$) (Tables 74-79 & Figures 6C and 6D) except for PCB-118 and 156 in women.

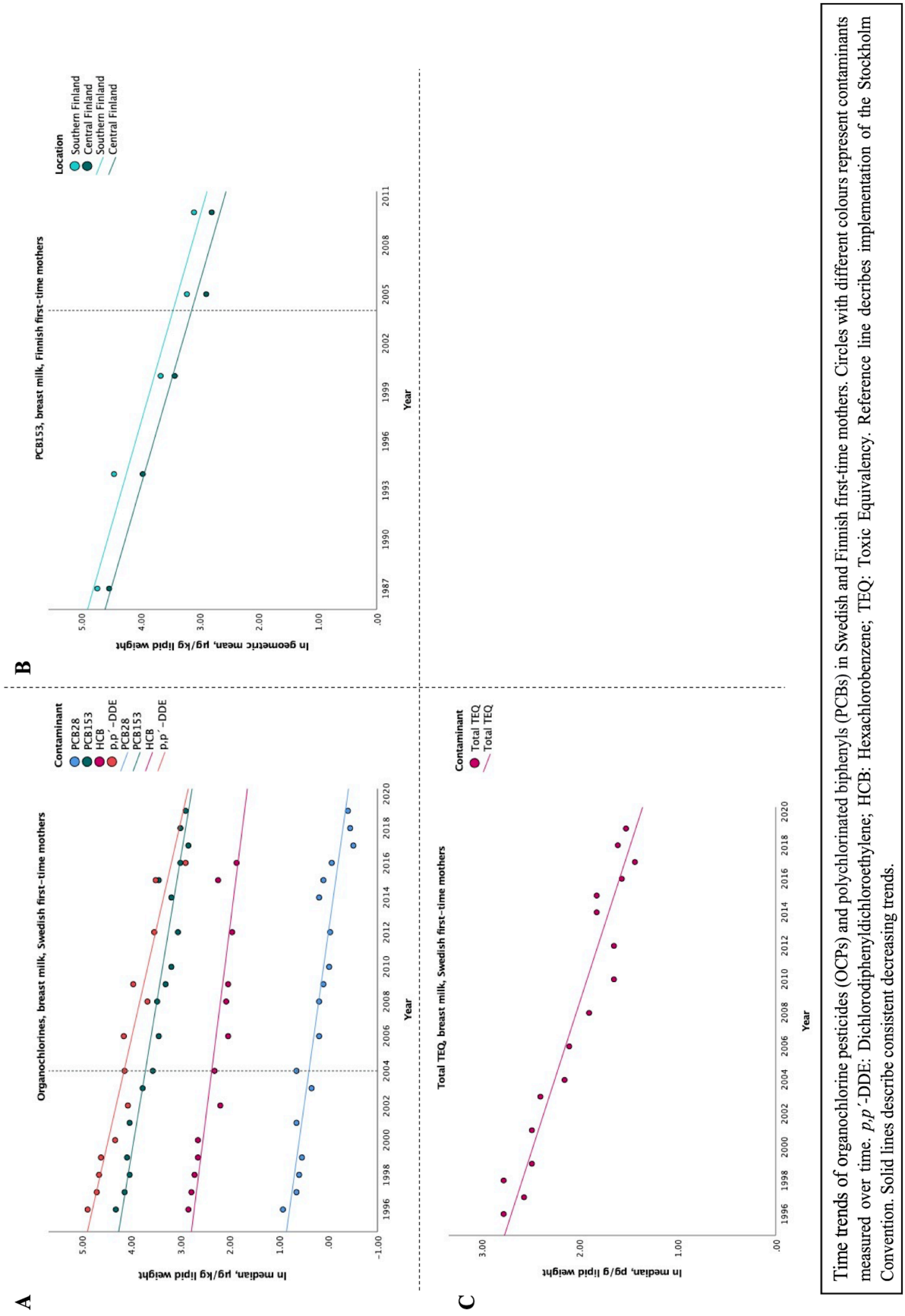


Time trends of organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) in 30 years old from Tromsø, Norway. Circles with different colours represent contaminants measured over time. *p,p´*-DDE: Dichlorodiphenyldichloroethylene; HCB: Hexachlorobenzene; *β*-HCH: beta-Hexachlorocyclohexane. Reference line decribes implementation of the Stockholm Convention. Solid lines describe consistent decreasing trends.

Figure 6. Time trends of OCPs (oxychlordane, trans-nonachlor, p,p´-DDE and β-HCH) and PCBs in adults.

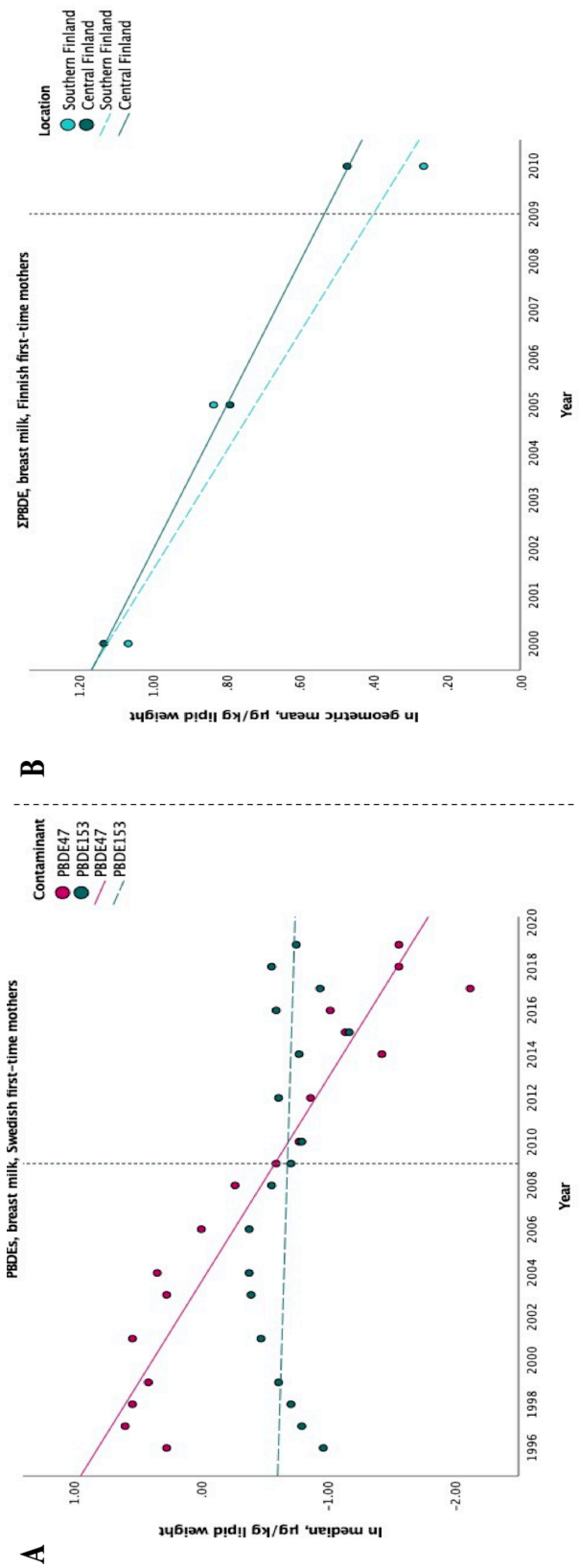
3.3 Time trends of POPs in breast milk

Time trends of POP concentration in breast milk among Finnish and Swedish mothers are shown in Figures 7 and 8. All legacy POP concentrations decreased over time in both countries. Sweden showed consistent decrease for *p,p´*-DDE, HCB, PCB-28 and total TEQ (linear trends $p<0.001$) (Tables 80-82 and 85 & Figures 7A and 7C). For PCB-153, consistent declining concentrations were observed in both Sweden and Finland (Sweden: β: -0.058, 95%CI: -0.068, -0.049; Southern Finland: β: -0.079, 95%CI: -0.111, -0.047; Central Finland: β: -0.080, 95%CI: -0.103, -0.057) (Table 83 & Figures 7A and 7B). For PBDEs, similar declining trends were shown for PBDE-47 in Sweden and sum of PBDEs (PBDE-47+99+100+153+209) in Finland (Sweden: β: -0.107, 95%CI: -0.126, -0.087; Southern Finland: β: -0.080, 95%CI: -0.329, 0.168; Central Finland: β: -0.066, 95%CI: -0.084, -0.048) (Table 84 & Figures 8A and 8B). However, PBDE-153 concentrations in Sweden had an inconsistent trend (Table 84 & Figure 8A).



Time trends of organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) in Swedish and Finnish first-time mothers. Circles with different colours represent contaminants measured over time. *p,p´*-DDE: Dichlorodiphenyldichloroethylene; HCB: Hexachlorobenzene; TEQ: Toxic Equivalency. Reference line decribes implementation of the Stockholm Convention. Solid lines describe consistent decreasing trends.

Figure 7. Time trends of OCPs (HCB and p,p´-DDE) and PCBs in breast milk.

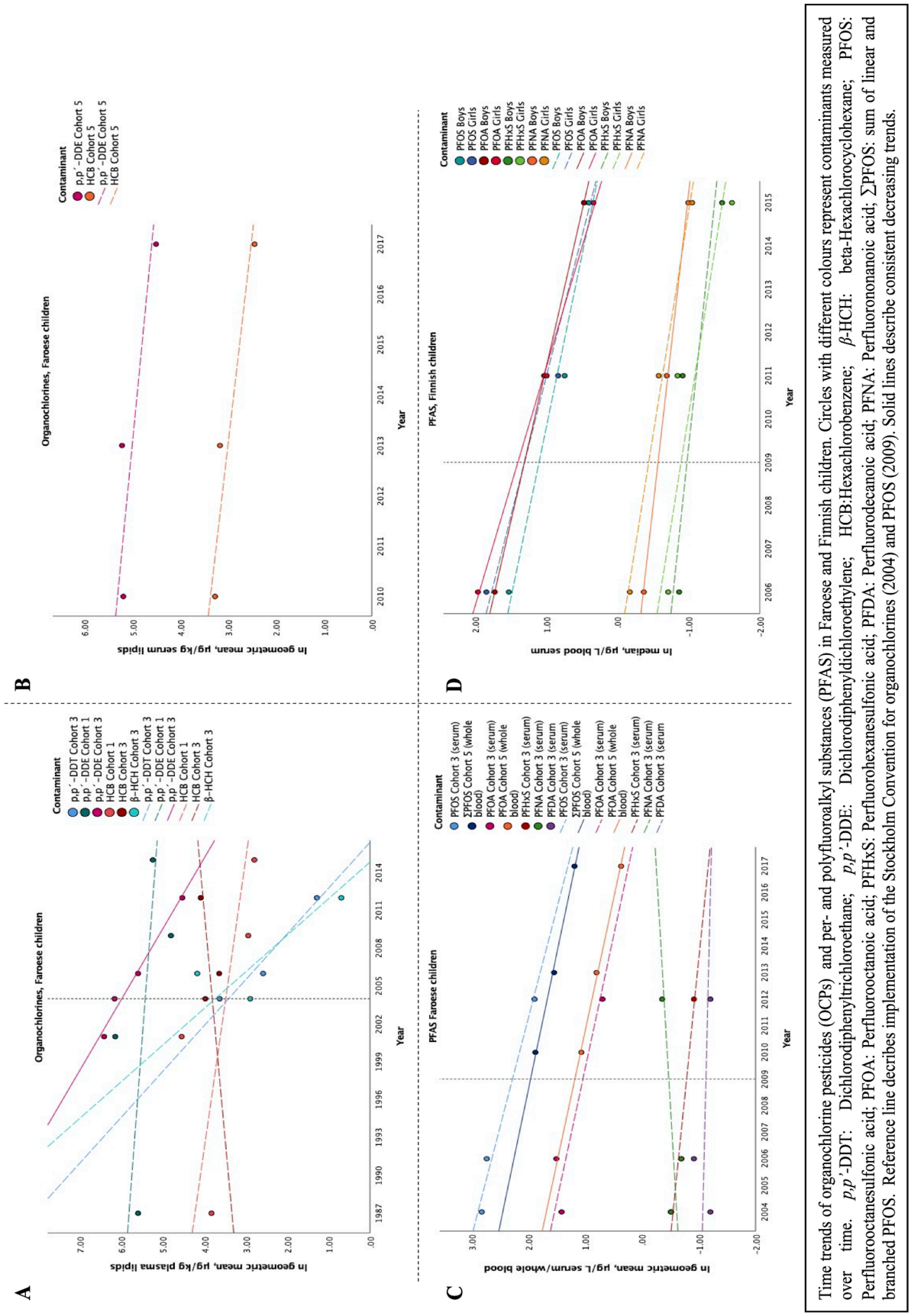


Time trends of polybrominated diphenyl ethers (PBDEs) in Swedish and Finnish first-time mothers. Circles with different colours represent contaminants measured over time. ΣPBDE: PBDE47+99+100+153+209. Reference line decribes implementation of the Stockholm Convention for PBDEs (2009). Solid lines describe consistent decreasing trends.

Figure 8. Time trends of PBDEs in breast milk.

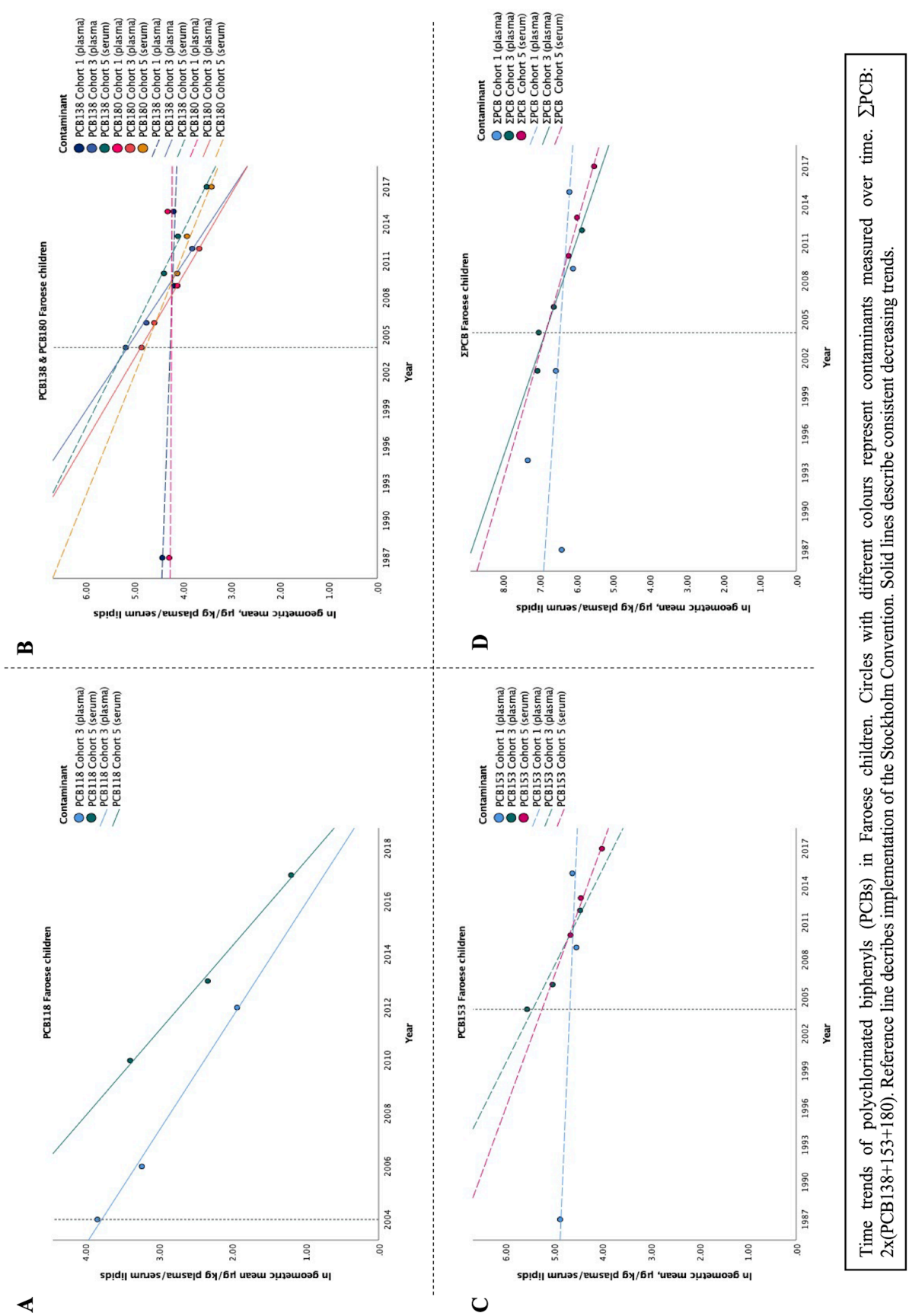
3.4 Time trends of POPs in children

Time trends of POPs in children from Faroe Islands and Finland are shown in Figures 9 and 10. Most POP concentrations decreased over time with differences in linear trends. For *p,p´*-DDT and *β*-HCH declining trends were observed in Faroe Island Cohort 3 (Tables 86 and 89 & Figure 9A). For *p,p´*-DDE, decreasing trend was shown in all Faroe Island Cohorts (1, 3 and 5) with particularly Cohort 3 showing consistent decreasing linear trend (β: -0.179, 95%CI:-0.258, -0.099) (Table 87 & Figure 8A). Considering HCB, Cohort 1 and 5 showed decreasing concentrations over time, however an increasing trend was observed in Cohort 3 (β: 0.028, 95%CI: -0.585, 0.640) (Table 88 & Figure 8A). Declining trends were observed for all PCB congeners in all Faroe Island Cohorts. Consistent decreasing linear trends were shown for PCB-118, 138, 180 and ∑PCBs [2x(PCB-138+153+180)] in Cohort 3, and for PCB-118 in Cohort 5 (linear trends $p<0.05$) (Tables 90, 91, 93 and 94 & Figures 10A, B and D). Most PFAS concentrations decreased over time in Faroe Islands and Finland. Consistent decreasing linear trends were shown in ∑PFOS (linear and branched) and PFOA concentrations in Faroe Island Cohort 5 (∑PFOS: β: -0.098, 95%CI: -0.169, -0.027; PFOA: β: -0.100, 95%CI: -0.169, -0.032) (Tables 96 and 97 & Figure 9C). Similar trends were seen for PFOA in Finnish boys and girls (boys: β: -0.139, 95%CI: -0.144, -0.135; girls: β: -0.181, 95%CI: -0.286, -0.076) (Table 97 & Figure 9D). For other PFAS chemicals, PFHxS and PFDA concentrations showed declining trends over time among Faroese and Finnish children. However, PFNA concentrations were increasing in Faroe Island Cohort 3 (β: 0.028, 95%CI: -0.346, 0.402) (Table 99 & Figure 9C), in contrast to consistent decreasing linear trend among Finnish boys (β: -0.069, 95%CI: -0.108, -0.030) (Table 99 & Figure 9D).



Time trends of organochlorine pesticides (OCPs) and per- and polyfluoroalkyl substances (PFAS) in Faroese and Finnish children. Circles with different colours represent contaminants measured over time. *p,p´*-DDT: Dichlorodiphenyltrichloroethane; *p,p´*-DDE: Dichlorodiphenyldichloroethylene; HCB:Hexachlorobenzene; *β*-HCH: beta-Hexachlorocyclohexane; PFOS: Perfluorooctanesulfonic acid; PFOA: Perfluorooctanoic acid; PFHxS: Perfluorohexanesulfonic acid; PFDA: Perfluorodecanoic acid; PFNA: Perfluorononanoic acid; ∑PFOS: sum of linear and branched PFOS. Reference line decribes implementation of the Stockholm Convention for organochlorines (2004) and PFOS (2009). Solid lines describe consistent decreasing trends.

Figure 9. Time trends of OCPs (p,p´-DDT, p,p´-DDE, HCB and β-HCH) and PFAS in children.



Time trends of polychlorinated biphenyls (PCBs) in Faroese children. Circles with different colours represent contaminants measured over time. ∑PCB: 2x(PCB138+153+180). Reference line decribes implementation of the Stockholm Convention. Solid lines describe consistent decreasing trends.

Figure 10. Time trends of PCBs in children.

4 Discussion

4.1 Summary of main findings

This study examines time trends of POPs in maternal, adult and child blood samples and breast milk samples in Arctic populations. Overall decreasing time trends were observed for all PCBs and most OCPs in Arctic populations including USA, Canada, Iceland, Norway, Sweden, Finland, Greenland, and Faroe Islands. Regulated PFAS showed declining trends in Sweden and Finland, but increasing trends were observed for unregulated PFAS in Sweden and Faroe Islands. Most PBDEs showed decreasing trends in Sweden and Finland. Of all the contaminants, greatest declines over time were observed for *p,p´*-DDE and PCBs across the Arctic.

Maternal blood contaminant time trends were analyzed for concentrations measured in Yupik (Alaska/USA), Nunavik (Canada), Disko Bay and Nuuk (Greenland), Iceland and Sweden. From Sweden only concentrations for PFAS were available. Decreasing trends were observed for all PCBs in all populations. Considering OCPs, *trans*-nonachlor and HCB showed increasing trends in Yupik in contrary to Nunavik and Iceland. Regarding other OCPs measured, all populations showed decreasing trends over time. Nunavik and Disko Bay showed consistent decreasing linear trends for all measured OCPs and PCBs but also had the highest concentrations at the different measurement points, except for *β*-HCH in Iceland. Greatest declines over time were observed for *p,p'*-DDE and PCB-153 in all populations, in addition to *β*-HCH in Iceland. PFAS were measured from mothers in Sweden and Nunavik, with declining trends observed in both populations for regulated compounds PFOS and PFOA. In Sweden increasing trends were shown for PFHxS, PFNA, PFDA and PFUnDA, in contrary to decreasing trend observed for PFHxS in Nunavik.

Time trends of adult serum POP concentrations were analyzed in Tromsø, Norway. Men had higher concentrations than women at the different measurement points. However, both men and women showed declining trends for all PCBs and OCPs. Of the contaminants, greatest declines were observed for *p,p´*-DDE and PCBs in both men and women.

Time trends of POPs were analyzed from POPs measured in breast milk from Swedish and Finnish first-time mothers. Decreasing trends were observed for all OCPs and PCBs in both populations. Considering PBDEs, declining trends were observed for PBDE-47 in Sweden and ∑PBDE (PBDE-47+99+100+153+209) in Finland, but PBDE-153 showed an inconsistent

trend in Sweden. Greatest declines over time were observed for *p,p´*-DDE in Sweden and for PCB-153 in Finland.

Time trends of OCPs and PCBs were analyzed in Faroese children and PFAS in Faroese and Finnish children. Decreasing trends were observed for all OCPs and PCBs, except for HCB in Faroe Island Cohort 3 that showed an increasing trend. In contrary, declining trends for HCB were observed in Cohorts 1 and 5. In general, contaminants measured in Faroe Island Cohort 3 showed greater declines, with many of the trends being consistent. All PFAS showed declining trends in both Faroese and Finnish children, except PFNA in Faroe Island Cohort 3.

4.2 General comparisons and contributing factors

All OCPs and PCBs included in this study, except *β*-HCH, were part of the 'dirty dozen' contaminants listed for eliminations or restriction in the Stockholm Convention in 2004. In 2009, *β*-HCH, PBDEs and PFOS were added to the convention, and latest PFOA in 2019 (55). Rest of the PFAS compounds are not regulated, but PFHxS is proposed to be added to the Stockholm Convention (23).

Results from this study regarding decreasing trends of restricted and banned OCPs and PCBs are similar to trends reported in other studies among the Arctic populations (15, 27-29, 56); as well as trends reported in non-Arctic populations such as USA, Spain, Korea and Australia (57-60). Similarly, decreasing trends of OCPs and PCBs in breast milk are also reported in populations outside the Arctic in Japan and New Zealand (61, 62); as well as among children outside the Arctic in Spain, Germany and USA (63-65). Even though most OCPs showed declining trends in this study, increasing trends were observed for HCB in Yupik and Faroe Island cohort 3, and for *trans*-nonachlor in Yupik. There are many factors that can explain the increasing trends, one being that for each population only three measurement points were available from a period of approximately 10 years. As the measured concentrations were inconsistent during the study periods, biomonitoring over longer time is needed to see if the increasing trends are consistent.

Declining trends of legacy POPs in Arctic human populations started already before the global regulations were implemented, attributed to decreasing intake of traditional foods and decreasing contaminant levels in Arctic biota (33, 66, 67). A transition to more imported foods instead of local hunting, fishing, and gathering is experienced in all Arctic countries, with both negative and positive impacts on health and wellbeing of the Arctic populations. Fish is a

significant part of diet in all Arctic populations, while marine mammals are an important part of diet among Indigenous populations in Greenland, Alaska and Canada, and terrestrial land mammals in Norway, Finland and Sweden (8). Species highest up on the marine food web have generally higher contaminant levels than terrestrial animals (33), which can partly explain the higher contaminant levels observed in Canadian and Greenlandic populations in this study. Decline in marine food intake has resulted in lower contaminant concentrations in human populations, but also in deficiencies in nutrients and vitamins such as vitamin-D and omega-3 fatty acids (29, 33, 68, 69). Transition from traditional food is also increasing food insecurity in the Arctic areas in terms of economic and physical access to healthy food, and causing other health related problems including overweight and higher incidence of non-communicable diseases (8).

Consistent declining trends of regulated and banned contaminants highlight the importance and effectiveness of international regulations, but also underline the importance to increase focus on new emerging contaminants in the Arctic, including PFAS (15, 70). 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 on PFAS conducted in the Arctic (28, 70, 71). The production of PFAS started in 1950s and the substances are used in different industrial and consumer applications such as firefighting foams and surface coatings (72). Global production of one of the most used compound PFOS declined drastically in the beginning of 2000 as the main manufacturer 3M phased out their production (73), and shortly after declining concentrations were observed in human populations, mirroring the changes in global production (74). The use of PFOS was restricted in many countries before it being listed in the Stockholm Convention in 2009 (70). Even though the persistency in the environment of PFAS have been known, and with over 4000 PFAS present, biomonitoring of the substances in Arctic populations has mostly started after 2000, except in Sweden where biomonitoring of PFAS among pregnant women started in 1996 in Uppsala. It was later discovered that the drinking water in Uppsala was polluted by PFAS, and the concentrations are not comparable with pregnant women outside the area, but biomonitoring over three decades gives important information of the time trends (42).

In this thesis, we could only assess concentrations of PFAS in pregnant women from Sweden and Nunavik based on AMAP 2021, but there are other studies conducted in the Arctic

evaluating PFAS time trends, including studies from northern Norway where time trends in PFAS concentrations were assessed among 30 years old men and women between 1986-2007 (70), and in adult men between 1979-2007 (74). Both studies show decreasing trends for PFOS and PFOA, mainly after 2001, and increasing trends for PFNA, PFDA and PFUnDA through the study period (70, 74). The trends reported in these studies are similar to observed trends among Swedish pregnant women in Uppsala. In contrary, a study examining PFAS levels among pregnant women in Danish general population reported decreasing trends between 2008-2013 for PFNA, PFDA and PFUnDA, in addition to PFOS and PFOA (75).

Similar decreasing trends for PFOS and PFOA are reported in general populations outside the Arctic, for instance in Australia, Germany, and USA (76-80). Consistent decreasing trends were observed in Germany for PFHxS and PFNA between 2005 and 2019 (78) and in Australia for PFHxS and PFUnDA between 2002-2013 and 2006-2013 respectively (77). These decreasing trends differ from the increasing trends reported in the Arctic regarding PFHxS, PFNA and PFUnDA among Swedish mothers and in studies from adults in Tromsø, Norway (70, 74). Increasing trends for PFNA are also reported in other studies in the Arctic among women in Yupik, Nunavik, and Greenland (8, 15, 28). PFAS trends among Faroese and Finnish children in this thesis show declining 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 declining trends for PFOS and PFOA and increasing trend for PFUnDA. No consistent trend was observed for PFNA in Swedish children (81). 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 (74), and also by long-range transport of PFAS into the Arctic areas (82).

One Health -approach is important when assessing environmental contaminants in the Arctic due to interdependence between human, animal, and environmental health. Biomonitoring of POPs in biota is needed to evaluate concentrations in food webs and levels of exposure to humans (83). Low levels of legacy POPs have been reported in Arctic terrestrial biota compared to marine and freshwater biota (84, 85). New emerging chemicals including PFAS have been detected in Arctic marine, freshwater, and terrestrial biota, but time trends of PFAS in terrestrial biota are poorly studied (82). Regarding Arctic marine and freshwater biota, declining time trends are observed for certain PFAS such as PFOS, and increasing trends are observed for PFNA, PFDA and PFUnDA (67). These findings are similar to trends observed

in Arctic human populations and highlight the importance of continued biomonitoring in humans, animals and the environment, and the need to increase focus on the new emerging contaminants in the Arctic.

Global regulations such as the Stockholm Convention are expected to decrease the POP concentrations in humans in the future as well, but climate change effects with increases in temperature, precipitation and wind speeds can influence the transport and fate of POPs and their release from primary and secondary sources (86). Between 1971-2017 the annual average temperature in the Arctic rose with 2.7 °C, which is 2.4 times the average temperature increase in Northern Hemisphere (87). Raise in temperatures and rainfall can increase POP degradation in the environment, and in Arctic areas cold temperatures can also lead to increased deposition of POPs in the biota (86). Global climate change modelling studies assessing POPs in the Arctic are inconsistent, and with current knowledge climate change might either have an increasing or decreasing effect in POP concentrations in the Arctic (86, 88). It has been modelled that PCB levels will further decline in Arctic despite the changing climate, but indirect effects of climate change can affect contaminant concentrations in Arctic populations for example through changing diet (89).

4.3 Associated health effects of contaminants in the Arctic

Biomonitoring is essential when assessing POP exposure and related health effects in human populations (90). Most of the studies done in the Arctic are prospective maternal and child cohort studies, as fetuses and young children are most vulnerable to contaminant exposure (91, 92), although some studies have also focused on the general adult population (8). The main effects studied concentrate on neurobehavioral, immunological, reproductive, cardiovascular, endocrine, and carcinogenic effects. Many factors including genetics, lifestyle, place of residence and diet can influence the risk of environmental contaminants on health, and there can be confounding between nutrients and contaminants (91).

The research on POP exposure and neurobehavioral effects in the Arctic concentrates predominantly on pre- and postnatal POP exposure, and current evidence is inconsistent. No association between prenatal PCB exposure and neurophysiological effects was found among children in Faroe Islands and Nunavik (91), but studies from Greenland and Faroe Islands suggest that exposure to organochlorines and PFAS might have a negative impact on child neurobehavioral development (8). Exposure to POPs might also contribute to D-vitamin deficiency, which has been suggested to be a risk factor for neurobehavioral disturbances such

as autism (8). POP exposure and immunological effects have been studied across the Arctic, as some organochlorine substances are known to have immunotoxic properties and have negative effect on the developing immune system. An association between prenatal exposure to POPs and higher risk for infections, especially middle ear infection, has been reported among Inuit children (91). It has also been found that children with increased PCB and PFAS levels showed reduced antibody serum levels for routine childhood vaccinations such as tetanus and diphtheria vaccines in Faroe Islands. Among Faroese adults, POP exposure is associated with higher risk for other immune system deficits such as inflammatory bowel disease (8). Studies of POP exposure to reproductive effects among Arctic populations show that exposure to POPs during pregnancy is associated with negative effects on fetal development and growth. In Greenland higher maternal PFOA levels were associated with lower birth weight and longer gestational age at birth (8). Exposure to a mixture of POPs might have a negative impact on male reproductive health, but no consistent exposure effect on female fertility or male reproductivity is shown. Increased male to female live birth ratio was found to be associated with maternal exposure to ΣPCB and *p,p´*-DDE in Faroe Islands (8).

Studies investigating contaminant exposure and cardiovascular effects have mostly been concentrated on mercury exposure. In Greenland, no association between organochlorine and PCB exposure and blood pressure was found (8). Considering endocrine effects, different POPs including OCPs, PCBs and PFAS are reported to be endocrine-disrupting chemicals (91). Association between POP exposure and effects on thyroid hormone concentrations has been reported among Inuit populations in Canada (91). Association between pre- and postnatal POP exposure and obesity later in life as well as prenatal POP exposure and disturbances in insulin levels have been reported in the Arctic by some studies. These might contribute to developing metabolic diseases such as type 2 diabetes later in life (8). Lung, breast and colon cancer incidences started to increase considerably among Arctic Inuit populations after 1950s, and cancer has become one of increasing public health concerns among Arctic populations (91). Changes towards western-style diet and lifestyle affect the cancer risk, and exposure to POPs can also play a role in developing cancer as they are potential carcinogens (8). PFAS and POP exposure has been linked to an increased risk of breast and other cancers in the Arctic, and interaction between some POPs and Hepatitis B virus might play a role in high liver cancer rates among Arctic populations (8).

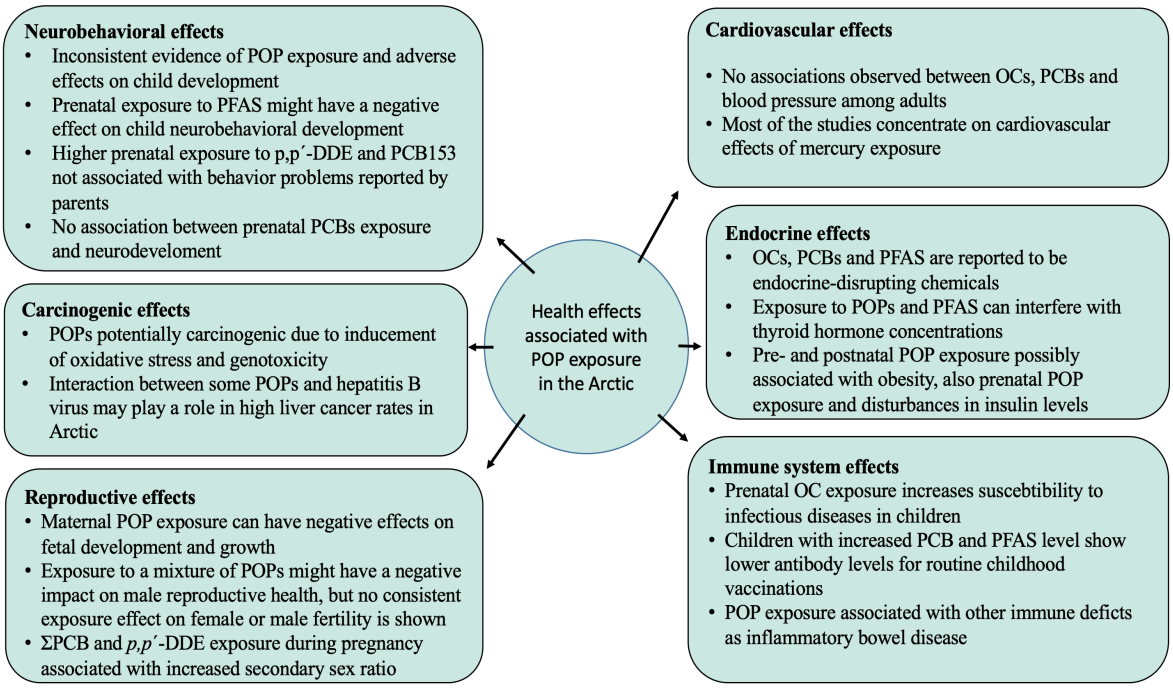


Figure 11. Health effects associated with POP exposure in the Arctic. Figure modified from AMAP 2021 assessment (8).

4.4 Strengths

This is the first study to evaluate time trends of environmental contaminants across the Arctic to assess consistency in the time trends. This study also provides an overview of the time trends in POPs across the different Arctic countries. An added strength is that it includes a wide range of study populations including children, adults, and pregnant women, as well as concentrations measured in different biological matrices including breast milk and maternal, adult and child blood. Another strength is that only data consisting of minimum three measurement points was included, providing a more reliable evaluation of the time trends. For time trend analyses it´s important that methods for chemical analyses between the studies are similar, and that used data is of high quality. AMAP has been coordinating and creating biomonitoring programs in the Arctic for the last three decades and laboratories providing contaminant data for the AMAP assessments participate in the AMAP Ring Test (93). All the participating laboratories are expected to participate in external quality assurance and quality control protocols. This is essential especially for time trend analyses to know that the measured concentrations are accurate, reliable and comparable despite the laboratory providing the concentrations (8). Because of these meticulous quality control measures, the data included in the thesis is reliable and gives a good measure of the time trends.

4.5 Limitations

Many factors can affect the measured contaminant concentrations, for instance age, diet, weight, seasonality, and location. As the goal for this study was to provide time trend analyses in the big picture, the statistical analyses were not adjusted for any covariates. There are also big variations between the sample sizes of the included study populations, as the number of participants for measurements varied from 9 to 1022. It is to be noted though that some of the Arctic populations are small, including for example only a few pregnant women. Most of the studies conducted in the Arctic concentrate on maternal and child cohort studies, and therefore very few of the biomonitoring studies have included men. Also, some of the studies measuring the same contaminants present the values in different units and the contaminants have been measured from different matrices. Comparing median and geometric mean values is not possible, and for some contaminants comparing values measured in blood plasma, blood serum or whole blood is impractical.

This study does not include data from Russia, as no time trend data of minimum three measurement points was available. Studies conducted in the Russian Arctic report high values of some POPs compared to other Arctic populations (28). Considering that Russian Arctic covers almost half of the Arctic area in total and inhabits two thirds of the population (94), not having biomonitoring studies over time from this area is a big limitation considering evaluating the overall levels and trends in the Arctic.

4.6 Future recommendations and study implications

Results from this study contribute to existing knowledge of decreasing trends of legacy POPs and inconsistent trends of new emerging contaminants in Arctic human populations. It is evident that legacy OCP and PCB concentrations are declining across the Arctic, but future biomonitoring is needed to see if the trends will continue to decline or level out. The results regarding PFAS and PBDEs highlight the need for biomonitoring of the new contaminants, especially the unregulated PFAS. There are also other new emerging chemicals not included in this thesis, for instance phthalates and bisphenols. Studies regarding these chemicals have been done so far in Canada, Greenland, and Sweden, but time trend data is available only for Sweden (8).

The exposure to POPs is a combination of different factors. Diet and consumption of traditional foods being the main route for human exposure in the Arctic, future studies regarding food consumption, seasonality, westernizing of diets and effects of climate change on food security

are needed. More studies on risk-benefit analysis in traditional food consumption and nutrition are needed.

Health effects of POPs exposure have been widely studied in mother-child cohorts across the Arctic, but there is limited information regarding male exposure and health effects. More focus is also needed on studying health effects of the emerging contaminants, as well as health effects of mixture of contaminants. Limited data on the effects of climate change on POP concentrations in the Arctic are available, underlining the importance of continued biomonitoring to be able to provide evidence-based knowledge to policy makers, health authorities and local communities in the Arctic.

5 Conclusions

Decreasing time trends of legacy POPs including OCPs and PCBs are evident in all Arctic populations. Regarding new emerging contaminants, declining trends were observed for regulated PFAS and increasing trends for unregulated PFAS in certain populations. For PBDEs the time trends were either declining or inconsistent.

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Appendix 1: Description of study populations

Contaminants measured in maternal blood

Table 3. Maternal blood: Oxychlordane

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013 2017	11 25 53 46 26 36 20 22 39 112 95 97	24 24 24 24 25 26 27 26 23 24 24 24	Blood plasma	(8, 33)
Iceland	1995 1999 2004 2009 2015	40 39 40 33 50	30 28.7 30.3 30.4 31.6	Blood plasma	(8)
Disko Bay, Greenland	1994 1995 1996 1997 1999 2006 2010-2015	9 94 63 12 21 20 117	25 27 27 25 21 27 27	Blood plasma	(8, 14, 35, 48)
Nuuk, Greenland	1999 2000 2001 2002 2003 2004 2005 2010-2015	20 38 50 37 28 24 10 280	28 27 27 29 28 26 27 27.3	Blood plasma	(8, 14, 39)

Table 4. Maternal blood: Trans-nonachlor

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001	11 25 53 46 26 36 20	24 24 24 24 25 26 27	Blood plasma	(8, 33)

	2004 2007 2012 2013 2017	22 39 112 95 97	26 23 24 24 24		
Iceland	1995 1999 2004 2009 2015	40 39 40 33 50	30 28.7 30.3 30.4 31.6	Blood plasma	(8)

Table 5. Maternal blood: p,p´-DDT

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013 2017	11 25 53 46 26 36 20 22 39 112 95 97	24 24 24 24 25 26 27 26 23 24 24 24	Blood plasma	(8, 33)

Table 6. Maternal blood: p,p´-DDE

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013 2017	11 25 53 46 26 36 20 22 39 112 95 97	24 24 24 24 25 26 27 26 23 24 24 24	Blood plasma	(8, 33)
Iceland	1995 1999 2004 2009 2015	40 39 40 33 50	30 28.7 30.3 30.4 31.6	Blood plasma	(8)
Disko Bay, Greenland	1994 1995 1996	9 94 63	25 27 27	Blood plasma	(8, 14, 35, 48)

	1997 1999 2006 2010-2015	12 21 20 117	25 25 27 27.1		
Nuuk, Greenland	1999 2000 2001 2002 2003 2004 2005 2010-2015	20 38 50 37 28 24 10 280	28 27 27 29 28 26 27 27.3	Blood plasma	(8, 14, 39)

Table 7. Maternal blood: HCB

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013 2017	11 25 53 46 26 36 20 22 39 112 95 97	24 24 24 24 25 26 27 26 23 24 24 24	Blood plasma	(8, 33)
Iceland	1995 1999 2004 2009 2015	40 39 40 33 50	30 28.7 30.3 30.4 31.6	Blood plasma	(8)

Table 8. Maternal blood: β-HCH

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013 2017	11 25 53 46 26 36 20 22 39 99 95 97	24 24 24 24 25 26 27 26 23 24 24 24	Blood plasma	(8, 33)
Iceland	1995	40	30	Blood plasma	(8)

	1999 2004 2009 2015	39 40 33 50	28.7 30.3 30.4 31.6		

Table 9. Maternal blood: Mirex

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013 2017	11 25 53 46 26 36 20 22 39 112 95 97	24 24 24 24 25 26 27 26 23 24 24 24	Blood plasma	(8, 33)

Table 10. Maternal blood: PCB118

	Measure points	N	Mean age	Biological matrice	Reference
Iceland	1995 1999 2004 2009 2015	40 39 40 33 50	30 28.7 30.3 30.4 31.6	Blood plasma	(8)

Table 11. Maternal blood: PCB138

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013 2017	11 25 53 46 26 36 20 22 39 112 95 97	24 24 24 24 25 26 27 26 23 24 24 24	Blood plasma	(8, 29)
Iceland	1995 1999 2004	40 39 40	30 28.7 30.3	Blood plasma	(8)

	2009 2015	33 50	30.4 31.6		

Table 12. Maternal blood: PCB153

	Measure points	N	Mean age	Biological matrice	Reference
Yupik, Alaska	1999-2003 2004-2006 2009-2012	106 206 156	26 26.4 26.5	Blood plasma	(35)
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013 2017	11 25 53 46 26 36 20 22 39 112 95 97	24 24 24 24 25 26 27 26 23 24 24 24	Blood plasma	(8, 29)
Iceland	1995 1999 2004 2009 2015	40 39 40 33 50	30 28.7 30.3 30.4 31.6	Blood plasma	(8)
Disko Bay, Greenland	1994 1995 1996 1997 1999 2006 2010-2015	9 94 63 12 21 20 117	25 27 27 25 25 27 27.1	Blood plasma	(8, 14, 35, 48)
Nuuk, Greenland	1999 2000 2001 2002 2003 2004 2005 2010-2015	20 38 50 37 28 24 10 280	28 27 27 29 28 26 27 27.3	Blood plasma	(8, 14, 39)

Table 13. Maternal blood: PCB180

	Measure points	N	Mean age	Biological matrice	Reference
Nunavik, Canada	1992 1996 1997 1998 1999 2000 2001 2004 2007 2012 2013	11 25 53 46 26 36 20 22 39 112 95	24 24 24 24 25 26 27 26 23 24 24	Blood plasma	(8, 29)

	2017	97	24		
Iceland	1995 1999 2004 2009 2015	40 39 40 33 50	30 28.7 30.3 30.4 31.6	Blood plasma	(8)

Table 14. Maternal blood: PFOS

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2007 2008 2009 2010 2011 2012 2014 2016 2017 2018 2019	33 76 94 19 28 31 32 43 17 30 76 29 25 30 30 30 30 30 50	na	Blood serum	(8, 42) (Irina Gyllenhammar, pers.comm.)
Nunavik, Canada	2004 2007 2012 2017	25 40 111 91	27 23 24 24	Whole blood	(8, 38)

Table 15. Maternal blood: PFOA

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2007 2008 2009 2010 2011 2012 2014 2016 2017 2018 2019	33 76 95 19 28 31 32 43 17 30 76 30 26 30 30 30 30 30 50	na	Blood serum	(8, 42) (Irina Gyllenhammar, pers.comm.)

Nunavik, Canada	2004 2007 2012 2017	25 40 111 91	27 23 24 24	Whole blood	(8, 38)

Table 16. Maternal blood: PFHxS

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2007 2008 2009 2010 2011 2012 2014 2016 2017 2018 2019	na	na	Blood serum	(8, 42) (Irina Gyllenhammar, pers.comm.)
Nunavik, Canada	2004 2007 2012 2017	25 40 111 91	27 23 24 24	Whole blood	(8, 38)

Table 17. Maternal blood: PFDA

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2007 2008 2009 2010 2011 2012 2014 2016 2017 2018 2019	33 76 95 19 28 31 32 43 17 30 76 30 26 30 30 30 30 30 50	na	Blood serum	(8, 42) (Irina Gyllenhammar, pers.comm.)

Table 18. Maternal blood: PFNA

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2007 2008 2009 2010 2011 2012 2014 2016 2017 2018 2019	33 76 95 19 28 31 32 43 17 30 76 30 26 30 30 30 30 30 50	na	Blood serum	(8, 42) (Irina Gyllenhammar, pers.comm.)

Table 19. Maternal blood: PFUnDA

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2007 2008 2009 2010 2011 2012 2014 2016 2017 2018 2019	33 76 95 19 28 31 32 43 17 30 76 30 26 30 30 30 30 30 50	na	Blood serum	(8, 42) (Irina Gyllenhammar, pers.comm.)

Contaminants measured in adult blood

Table 20. Adult blood: Oxychlordane

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)

Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 21. Adult blood: Trans-nonachlor

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 22. Adult blood: p,p´-DDE

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 23. Adult blood: HCB

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 24. Adult blood: β-HCH

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001	31 28 24	30 30 30	Women, blood serum	(8, 41)

	2007	25	30		

Table 25. Adult blood: PCB118

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 26. Adult blood: PCB138

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 27. Adult blood: PCB153

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 28. Adult blood: PCB156

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 29. Adult blood: PCB170

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Table 30. Adult blood: PCB180

	Measure points	N	Mean age	Biological matrice	Reference
Tromsø, Norway, men	1986 1994 2001 2007	14 17 21 20	30 30 30 30	Men, blood serum	(8, 41)
Tromsø, Norway, women	1986 1994 2001 2007	31 28 24 25	30 30 30 30	Women, blood serum	(8, 41)

Contaminants measured in breast milk

Table 31. Breast milk: p,p´-DDE

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000 2002 2004 2006 2008 2009 2012 2015 2016	26 68 88 21 28 30 32 30 31 29 30 15 15	na	Breast milk	(8, 31) (Irina Gyllenhammar, pers.comm.)

Table 32. Breast milk: HCB

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000 2002 2004	26 68 88 21 28 30 32		Breast milk	(8, 31) (Irina Gyllenhammar, pers.comm.)

	2006 2008 2009 2012 2015 2016	30 31 29 30 15 15			

Table 33. Breast milk: PCB28

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2008 2009 2010 2012 2014 2015 2016 2017 2018 2019	26 68 88 21 28 30 32 30 31 29 30 30 30 15 15 15 15 15	na	Breast milk	(8, 31) (Irina Gyllenhammar, pers.comm.)

Table 34. Breast milk: PCB153

	Measure points	N	Mean age	Biological matrice	Reference
Southern Finland	1987 1993-1994 2000 2005 2010	47 14 29 39 32	26.9 27.8 29.2 28.7 31.2	Breast milk	(35, 44, 45)
Central Finland	1987 1993-1994 2000 2005 2010	37 28 31 40 19	25.4 27 28.3 27.3 30.2	Breast milk	(35, 44, 45)
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2008 2009 2010 2012 2014 2015	26 68 88 21 28 32 32 30 31 29 30 30 30 15	na	Breast milk	(8, 31) (Irina Gyllenhammar, pers.comm.)

	2016 2017 2018 2019	15 15 15 15			

Table 35. Breast milk: PBDEs

	Measure points	N	Mean age	Biological matrice	Reference
Southern Finland (PBDE47+99+100+153+209)	1987 1993-1994 2000 2005 2010	47 14 29 39 32	26.9 27.8 29.2 28.7 31.2	Breast milk	(35, 44, 45)
Central Finland (PBDE47+99+100+153+209)	1987 1993-1994 2000 2005 2010	37 28 31 40 19	25.4 27 28.3 27.3 30.2	Breast milk	(35, 44, 45)
Uppsala, Sweden, PBDE47	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2008 2009 2010 2012 2014 2015 2016 2017 2018 2019	19 57 63 19 28 29 29 30 31 29 30 30 30 15 15 15 15 15	na	Breast milk	(8, 31) (Irina Gyllenhammar, pers.comm.)
Uppsala, Sweden, PBDE153	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2008 2009 2010 2012 2014 2015 2016 2017 2018 2019	19 57 63 19 28 29 29 30 31 29 30 30 30 15 15 15 15 15	na	Breast milk	(8, 31) (Irina Gyllenhammar, pers.comm.)

Table 36. Breast milk: Total TEQ

	Measure points	N	Mean age	Biological matrice	Reference
Uppsala, Sweden	1996 1997 1998 1999 2000-2001 2002-2003 2004 2006 2008 2009 2010 2012 2014 2015 2016 2017 2018 2019	15 38 29 15 23 16 15 30 30 na 30 30 30 15 15 15 15 15	na	Breast milk	(8, 31) (Irina Gyllenhammar, pers.comm.)

Contaminants measured in children

Table 37. Child blood: p,p´-DDT

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	555 498 526	5 7.5 13.2	Blood plasma	(35)

Table 38. Child blood: p,p´-DDE

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 1	1986-1987 1993-1994 (na) 2000-2001 2008-2009 2013-2016	1022 - 792 849 703	Cord blood - 13.8 22.1 28	Blood plasma	(8)
Faroe Islands Cohort 3	2000-2001 2002-2005 2005-2007 2011-2012	115 555 498 526	1.5 5 7.5 13.2	Blood plasma	(35)
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Blood serum	(8)

Table 39. Child blood: HCB

	Measure points	N	Mean age	Biological matrice	Reference

Faroe Islands Cohort 1	1986-1987 1993-1994 (na) 2000-2001 2008-2009 2013-2016	1022 - 792 849 703	Cord blood - 13.8 22.1 28	Blood plasma	(8)
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	555 498 526	5 7.5 13.2	Blood plasma	(35)
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Blood serum	(8)

Table 40. Child blood: β-HCH

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	555 498 526	5 7.5 13.2	Blood plasma	(35)

Table 41. Child blood: PCB118

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	555 498 526	5 7.5 13.2	Blood plasma	(35)
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Blood serum	(8)

Table 42. Child blood: PCB138

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 1	1986-1987 1993-1994 (na) 2000-2001 (na) 2008-2009 2013-2016	1022 - - 849 703	Cord blood - - 22.1 28	Blood plasma	(8)
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	555 498 526	5 7.5 13.2	Blood plasma	(35)
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Blood serum	(8)

Table 43. Child blood: PCB153

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 1	1986-1987 1993-1994 (na) 2000-2001 (na) 2008-2009	1022 - - 849	Cord blood - - 22.1	Blood plasma	(8)

	2013-2016	703	28		
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	555 498 526	5 7.5 13.2	Blood plasma	(35)
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Blood serum	(8)

Table 44. Child blood: PCB180

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 1	1986-1987 1993-1994 (na) 2000-2001 (na) 2008-2009 2013-2016	1022 - - 849 703	Cord blood - - 22.1 28	Blood plasma	(8)
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	555 498 526	5 7.5 13.2	Blood plasma	(35)
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Blood serum	(8)

Table 45. Child blood: ∑PCB 2x(PCB138+153+180)

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 1	1986-1987 1993-1994 2000-2001 2008-2009 2013-2016	1022 922 792 849 703	Cord blood 6.9 13.8 22.1 28	Blood plasma	(8)
Faroe Islands Cohort 3	2000-2001 2002-2005 2005-2007 2011-2012	115 555 498 526	1.5 5 7.5 13.2	Blood plasma	(35)
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Blood serum	(8)

Table 46. Child blood: PFOS

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	545 500 526	5 7.5 13.2	Blood serum	(8)
Finland, boys	2005-2006 2010-2011 2014-2015	26 26 26	1 6 10.5	Blood serum	(8, 46)
Finland, girls	2005-2006 2010-2011 2014-2015	28 28 28	1 6 10.5	Blood serum	(8, 46)

Table 47. Child blood: ∑PFOS (sum of linear and branched PFOS)

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Whole blood	(8)

Table 48. Child blood: PFOA

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	545 500 526	5 7.5 13.2	Blood serum	(8)
Faroe Islands Cohort 5	2009-2011 2012-2014 2016-2018	363 347 381	1.5 5 9	Whole blood	(8)
Finland, boys	2005-2006 2010-2011 2014-2015	26 26 26	1 6 10.5	Blood serum	(8, 46)
Finland, girls	2005-2006 2010-2011 2014-2015	28 28 28	1 6 10.5	Blood serum	(8, 46)

Table 49. Child blood: PFHxS

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	545 500 526	5 7.5 13.2	Blood serum	(8)
Finland, boys	2005-2006 2010-2011 2014-2015	26 26 26	1 6 10.5	Blood serum	(8, 46)
Finland, girls	2005-2006 2010-2011 2014-2015	28 28 28	1 6 10.5	Blood serum	(8, 46)

Table 50. Child blood: PFNA

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	545 500 526	5 7.5 13.2	Blood serum	(8)
Finland, boys	2005-2006 2010-2011 2014-2015	26 26 26	1 6 10.5	Blood serum	(8, 46)
Finland, girls	2005-2006 2010-2011 2014-2015	28 28 28	1 6 10.5	Blood serum	(8, 46)

Table 51. Child blood: PFDA

	Measure points	N	Mean age	Biological matrice	Reference
Faroe Islands Cohort 3	2002-2005 2005-2007 2011-2012	545 500 526	5 7.5 13.2	Blood serum	(8)

Appendix 2: Linear regression results

Contaminants measured in maternal blood

Table 52. Maternal blood: Oxychlordane

	Unstandardized B	95% CI	p-value	Biological matrice
Yupik, Alaska	-0.134	-0.612, 0.345	0.175	Blood plasma
Nunavik, Canada	-0.052	-0.067, -0.038	<0.001	Blood plasma
Iceland	-0.065	-0.132, 0.002	0.054	Blood plasma
Disko Bay, Greenland	-0.064	-0.095, -0.033	0.003	Blood plasma
Nuuk, Greenland	-0.050	-0.114, 0.014	0.104	Blood plasma

Table 53. Maternal blood: Trans-nonachlor

	Unstandardized B	95% CI	p-value	Biological matrice
Yupik, Alaska	0.048	-1.584, 1.679	0.774	Blood plasma
Nunavik, Canada	-0.037	-0.051, -0.023	<0.001	Blood plasma
Iceland	-0.055	-0.099, -0.011	0.028	Blood plasma

Table 54. Maternal blood: p,p´-DDT

	Unstandardized B	95% CI	p-value	Biological matrices
Yupik, Alaska	-0.091	-0.462, 0.281	0.199	Blood plasma
Nunavik, Canada	-0.101	-0.149, -0.054	0.001	Blood plasma

Table 55. Maternal blood: p,p´-DDE

	Unstandardized B	95% CI	p-value	Biological matrice
Yupik, Alaska	-0.050	-0.211, 0.110	0.156	Blood plasma
Nunavik, Canada	-0.065	-0.080, -0.050	<0.001	Blood plasma
Iceland	-0.088	-0.108, -0.068	<0.001	Blood plasma
Disko Bay, Greenland	-0.067	-0.090, -0.044	<0.001	Blood plasma
Nuuk, Greenland	-0.075	-0.127, -0.022	0.013	Blood plasma

Table 56. Maternal blood: HCB

	Unstandardized B	95% CI	p-value	Biological matrice
Yupik, Alaska	0.007	-0.573, 0.588	0.897	Blood plasma

Nunavik, Canada	-0.056	-0.074, -0.038	<0.001	Blood plasma
Iceland	-0.072	-0.113, -0.031	0.011	Blood plasma

Table 57. Maternal blood: β-HCH

	Unstandardized B	95% CI	p-value	Biological matrice
Yupik, Alaska	-0.067	-0.628, 0.494	0.370	Blood plasma
Nunavik, Canada	-0.061	-0.078, -0.043	<0.001	Blood plasma
Iceland	-0.115	-0.151, -0.080	0.002	Blood plasma

Table 58. Maternal blood: Mirex

	Unstandardized B	95% CI	p-value	Biological matrice
Yupik, Alaska	-0.221	-1.735, 1.294	0.315	Blood plasma
Nunavik, Canada	-0.070	-0.096, -0.044	<0.001	Blood plasma

Table 59. Maternal blood: PCB118

	Unstandardized B	95% CI	p-value	Biological matrices
Iceland	-064	-0.092, -0,035	0.006	Blood plasma

Table 60. Maternal blood: PCB138

	Unstandardized B	95% CI	p-value	Biological matrice
Yupik, Alaska	-0.130	-0.676, 0.417	0.204	Blood plasma
Nunavik, Canada	-0.080	-0.094, -0.067	<0.001	Blood plasma
Iceland	-0.087	-0.104, -0.069	<0.001	Blood plasma

Table 61. Maternal blood: PCB153

	Unstandardized B	95% CI	p-value	Biological matrice
Yupik, Alaska	-0.019	-0.599, 0.560	0.747	Blood plasma
Nunavik, Canada	-0.068	-0.081, -0.054	<0.001	Blood plasma
Iceland	-0.070	-0.101, -0.040	0.005	Blood plasma
Disko Bay, Greenland	-0.066	-0.098, -0.034	0.003	Blood plasma
Nuuk, Greenland	-0.070	-0.112, -0.029	0.006	Blood plasma

Table 62. Maternal blood: PCB180

	Unstandardized B	95% CI	p-value	Biological matrices
Nunavik, Canada	-0.072	-0.088, -0.056	<0.001	Blood plasma
Iceland	-0.075	-0.109, -0.040	0.006	Blood plasma

Table 63. Maternal blood: PFOS

	Unstandardized B	95% CI	p-value	Biological matrice
Uppsala, Sweden	-0.089	-0.103, -0.075	<0.001	Blood serum

Nunavik, Canada	-0.078	-0.171, 0.014	0.068	Whole blood

Table 64. Maternal blood: PFOA

	Unstandardized B	95% CI	p-value	Biological matrices
Uppsala, Sweden	-0.049	-0.062, -0.036	<0.001	Blood serum
Nunavik, Canada	-0.045	-0.049, -0.040	0.005	Whole blood

Table 65. Maternal blood: PFHxS

	Unstandardized B	95% CI	p-value	Biological matrices
Uppsala, Sweden	0.010	-0.002, 0.022	0.097	Blood serum
Nunavik, Canada	-0.053	-0.103, -0.002	0.048	Whole blood

Table 66. Maternal blood: PFDA

	Unstandardized B	95% CI	p-value	Biological matrices
Uppsala, Sweden	0.011	-0.003, 0.024	0.118	Blood serum

Table 67. Maternal blood: PFNA

	Unstandardized B	95% CI	p-value	Biological matrices
Uppsala, Sweden	0.010	-0.002, 0.021	0.099	Blood serum

Table 68. Maternal blood: PFUnDA

	Unstandardized B	95% CI	p-value	Biological matrices
Uppsala, Sweden	0.019	0.003, 0.034	0.019	Blood serum

Contaminants measured in adult blood

Table 69. Adult blood: Oxychlordane

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.089	-0.155, -0.023	0.029	Men, blood serum
Tromsø, Norway, women	-0.066	-0.151, 0.019	0.080	Women, blood serum

Table 70. Adult blood: Trans-nonachlor

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.080	-0.165, 0.005	0.057	Men, blood serum
Tromsø, Norway, women	-0.057	-0.115, 0.001	0.052	Women, blood serum

Table 71. Adult blood: p,p´-DDE

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.111	-0.184, -0.037	0.023	Men, blood serum
Tromsø, Norway, women	-0.115	-0.213, -0.016	0.038	Women, blood serum

Table 72. Adult blood: HCB

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.058	-0.176, 0.060	0.170	Men, blood serum
Tromsø, Norway, women	-0.067	-0.240, 0.106	0.238	Women, blood serum

Table 73. Adult blood: β-HCH

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.110	-0.843, 0.624	0.309	Men, blood serum
Tromsø, Norway, women	-0.090	-0.254, 0.074	0.142	Women, blood serum

Table 74. Adult blood: PCB118

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.095	-0.131, -0.059	0.008	Men, blood serum
Tromsø, Norway, women	-0.079	-0.172, 0.013	0.066	Women, blood serum

Table 75. Adult blood: PCB138

	Unstandardized B	95% CI	p-value	Biological matrices
Tromsø, Norway, men	-0.087	-0.118, -0.056	0.007	Men, blood serum
Tromsø, Norway, women	-0.084	-0.144, -0.025	0.026	Women, blood serum

Table 76. Adult blood: PCB153

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.086	-0.102, -0.070	0.002	Men, blood serum
Tromsø, Norway, women	-0.080	-0.125, -0.035	0.017	Women, blood serum

Table 77. Adult blood: PCB156

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.110	-0.184, -0.037	0.023	Men, blood serum
Tromsø, Norway, women	-0.068	-0.172, 0.037	0.109	Women, blood serum

Table 78. Adult blood: PCB170

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.089	-0.126, -0.051	0.009	Men, blood serum
Tromsø, Norway, women	-0.076	-0.128, -0.025	0.024	Women, blood serum

Table 79. Adult blood: PCB180

	Unstandardized B	95% CI	p-value	Biological matrice
Tromsø, Norway, men	-0.091	-0.109, -0.074	0.002	Men, blood serum
Tromsø, Norway, women	-0.078	-0.107, -0.048	0.008	Women, blood serum

Contaminants measured in breast milk

Table 80. Breast milk: p,p´-DDE

	Unstandardized B	95% CI	p-value	Biological matrice
Uppsala, Sweden	-0.080	-0.096, -0.064	<0.001	Breast milk

Table 81. Breast milk: HCB

	Unstandardized B	95% CI	p-value	Biological matrice
Uppsala, Sweden	-0.044	-0.061, -0.028	<0.001	Breast milk

Table 82. Breast milk: PCB28

	Unstandardized B	95% CI	p-value	Biological matrice
Uppsala, Sweden	-0.049	-0.060, -0.039	<0.001	Breast milk

Table 83. Breast milk: PCB153

	Unstandardized B	95% CI	p-value	Biological matrice
Southern Finland	-0.079	-0.111, -0.047	0.004	Breast milk

Central Finland	-0.080	-0.103, -0.057	0.002	Breast milk
Uppsala, Sweden	-0.058	-0.068, -0.049	<0.001	Breast milk

Table 84. Breast milk: PBDEs

	Unstandardized B	95% CI	p-value	Biological matrice
Southern Finland (PBDE47+99+100+153+209)	-0.080	-0.329, 0.168	0.152	Breast milk
Central Finland (PBDE47+99+100+153+209)	-0.066	-0.084, -0.048	0.014	Breast milk
Uppsala, Sweden, PBDE47	-0.107	-0.126, -0.087	<0.001	Breast milk
Uppsala, Sweden, PBDE153	-0.005	-0.020, 0.009	0.439	Breast milk

Table 85. Breast milk: Total TEQ

	Unstandardized B	95% CI	p-value	Biological matrice
Uppsala, Sweden	-0.055	-0.064, -0.046	<0.001	Breast milk

Contaminants measured in children

Table 86. Child blood: p,p´-DDT

	Unstandardized B	95% CI	p-value	Biological matric
Faroe Islands Cohort 3	-0.276	-1.055, 0.504	0.139	Blood plasma

Table 87. Child blood: p,p´-DDE

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 1	-0.023	-0.148, 0.101	0.509	Blood plasma
Faroe Islands Cohort 3	-0.179	-0.258, -0.099	0.011	Blood plasma
Faroe Islands Cohort 5	-0.102	-0.772, 0.568	0.303	Blood serum

Table 88. Child blood: HCB

	Unstandardized B	95% CI	p-value	Biological matric
Faroe Islands Cohort 1	-0.044	-0.201, 0.114	0.356	Blood plasma
Faroe Islands Cohort 3	0.028	-0.585, 0.640	0.666	Blood plasma
Faroe Islands Cohort 5	-0.121	-0.644, 0.401	0.208	Blood serum

Table 89. Child blood: β-HCH

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 3	-0.345	-3.441, 2.751	0.391	Blood plasma

Table 90. Child blood: PCB118

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 3	-0.233	-0.453, -0.013	0.047	Blood plasma
Faroe Islands Cohort 5	-0.312	-0.557, -0.068	0.039	Blood serum

Table 91. Child blood: PCB138

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 1	-0.009	-0.041, 0.022	0.169	Blood plasma
Faroe Islands Cohort 3	-0.168	-0.309, -0.026	0.042	Blood plasma
Faroe Islands Cohort 5	-0.127	-0.315, 0.062	0.074	Blood serum

Table 92. Child blood: PCB153

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 1	-0.011	-0.075, 0.054	0.282	Blood plasma
Faroe Islands Cohort 3	-0.127	-0.553, 0.299	0.164	Blood plasma
Faroe Islands Cohort 5	-0.094	-0.227, 0.040	0.071	Blood serum

Table 93. Child blood: PCB180

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 1	-0.001	-0.093, 0.091	0.894	Blood plasma
Faroe Islands Cohort 3	-0.150	-0.209, -0.090	0.020	Blood plasma
Faroe Islands Cohort 5	-0.102	-0.314, 0.110	0.103	Blood serum

Table 94. Child blood: ∑PCB 2x(PCB138+153+180)

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 1	-0.024	-0.091, 0.043	0.340	Blood plasma

Faroe Islands Cohort 3	-0.118	-0.207, -0.030	0.029	Blood plasma
Faroe Islands Cohort 5	-0.100	-0.245, 0.044	0.072	Blood serum

Table 95. Child blood: PFOS

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 3	-0.122	-0.366, 0.123	0.100	Blood serum
Finland, boys	-0.126	-0.388, 0.136	0.104	Blood serum
Finland, girls	-0.154	-0.554, 0.245	0.128	Blood serum

Table 96. Child blood: ∑PFOS (sum of linear and branched PFOS)

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 5	-0.098	-0.169, -0.027	0.036	Whole blood

Table 97. Child blood: PFOA

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 3	-0.100	-0.562, 0.361	0.221	Blood serum
Faroe Islands Cohort 5	-0.100	-0.169, -0.032	0.034	Whole blood
Finland, boys	-0.139	-0.144, -0.135	0.002	Blood serum
Finland, girls	-0.181	-0.286, -0.076	0.029	Blood serum

Table 98. Child blood: PFHxS

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 3	-0.048	-0.185, 0.089	0.142	Blood serum
Finland, boys	-0.065	-0.528, 0.399	0.328	Blood serum
Finland, girls	-0.097	-0.693, 0.500	0.288	Blood serum

Table 99. Child blood: PFNA

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 3	0.028	-0.346, 0.402	0.519	Blood serum
Finland, boys	-0.069	-0.108, -0.030	0.028	Blood serum
Finland, girls	-0.097	-0.228, 0.035	0.068	Blood serum

Table 100. Child blood: PFDA

	Unstandardized B	95% CI	p-value	Biological matrice
Faroe Islands Cohort 3	-0.011	-0.498, 0.476	0.821	Blood serum