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Department of Arctic and Marine Biology

Concentrations and patterns of organochlorines (OCs) and perfluoro-alkyl substances (PFASs) in eggs of two Arctic seabird species and their relationship with eggshell thickness

Emilie Os-Trandem

Master's thesis in Biology BIO-3950, May 2024

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The illustration on the front page is made by Vibeke Os

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Tromsø, May 2024
Emilie Os-Trandem

Preface

This project involves Brünnich's guillemot eggs sampled from Svalbard (Norway) and ivory gull eggs sampled from Svalbard and Uyedineniya (Russia).

On Svalbard, all samples were collected under permits provided by the Norwegian Food Safety Authority and by the Governor of Svalbard in accordance with § 37 letter a in *Forskrift om nasjonalparkene Sør-Spitsbergen, Forlandet og Nordvest-Spitsbergen, om naturreservatene Nordaust-Svalbard og Søraust-Svalbard, og om naturreservatene for fugl på Svalbard - FOR-2014-04-04-377*.

Uyedineniya is located within the border security zone of Russia, and the fieldwork was conducted under permits for fulfilment of the economic activity in the border zone of Russian Federation 34 *Permit № 155*, provided by the border management administration for the Western Arctic Region. Furthermore, Uyedineniya is a part of the Great Arctic Nature Reserve, and a *Permit № 118* was provided by the Federal State Budgetary Organization and Taimyr Nature Reserves to conduct fieldwork in the area. The collection of ivory gull eggs was done under the *Rosprirodnadzor Permits № 93 & 94* issued by the Federal Service for Supervision of Natural Resources.

This master`s thesis was written at the Department of Arctic and Marine Biology at UiT in collaboration with the Norwegian Polar Institute.

Abstract

Despite the remoteness of the Arctic, long-range transport of anthropogenic organohalogenated contaminants (OHCs) has led to their detection at high concentrations in various Arctic animals for decades. Seabirds have been commonly used as biomonitors of OHCs, and the current study investigated the concentrations and patterns of organochlorines (OCs) and perfluoro-alkyl substances (PFASs) in eggs of two Arctic seabird species, namely the Brünnich's guillemot (*Uria lomvia*) and the ivory gull (*Pagophila eburnea*). In addition, stable isotopes of carbon and nitrogen were analysed in the eggs and used as proxies for feeding habitat and trophic level, respectively. The Brünnich's guillemot is one of the most abundant seabird species breeding in the Arctic, and feeds mainly on prey at lower trophic levels. The ivory gull is a rare High Arctic seabird species roaming in ice filled waters positioned at the top of the Arctic food web. Unlike the Brünnich's guillemot, the ivory gull has been less frequently monitored. This is the second study to report contaminant concentrations from the Norwegian and Russian Arctic. During the period 2018-2022, a total of 20 Brünnich's guillemot eggs were collected from two locations (Bjørnøya and Kongsfjorden) within the Norwegian Arctic, and a total of 13 ivory gull eggs were collected from two locations (Nordaustlandet and Uyedineniya) within the Norwegian and Russian Arctic. In Brünnich's guillemot eggs, we reported differences in the concentration of several contaminant groups between the two locations, while ivory gull eggs exhibited lower differences across sampling areas. Compared to Brünnich's guillemot eggs, ivory gull eggs showed levels of OCs and PFASs 21 and 2.6 times higher, respectively. Additionally, the ivory gull had higher values of both carbon and nitrogen stable isotopes, reflecting their higher tropic position and stronger connection to the pelagic ecosystem compared to Brünnich's guillemots. Our results indicated decreasing concentrations of several major contaminants over the last decade in both species. Moreover, we investigated the association between eggshell thickness and contaminants as potential drivers of the population declines observed over the last decades in the Brünnich's guillemot and the ivory gull. For both species, the lack of correlations observed between OHC concentrations and eggshell thickness does not support contaminant-induced eggshell thinning. Although this was expected for the Brünnich's guillemot, the ivory gull has previously been linked to contaminant-induced eggshell thinning. This result might indicate better outcomes for the species at the population level, however, other stressors such as climate change continue to threaten seabird populations.

Abbreviations

BFR	Brominated flame retardant
C	Carbon
DCM	Dichloromethane
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
GC	Gas chromatography
GC-MS	Gas chromatography-mass spectrometry
HCB	Hexachlorobenzene
LC-MS	Liquid chromatography-mass spectrometry
LOD	Limit of detection
LOQ	Limit of quantification
N	Nitrogen
OC	Organochlorine
OCP	Organochlorine pesticide
OHC	Organohalogenated contaminant
PCB	Polychlorinated biphenyl
PFAS	Perfluoro-alkyl substance
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
POP	Persistent organic pollutant
rpm	Revolutions per minute
RRF	Relative response factor
SD	Standard deviation
SRM	Standard reference material
$\delta^{13}C$	Delta carbon 13, ratio of stable carbon isotopes, ^{13}C : ^{12}C
$\delta^{15}N$	Delta nitrogen 15, ratio of stable nitrogen isotopes, ^{15} : ^{14}N

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1 Introduction

1.1 Contaminants in the Arctic

Alongside habitat degradation, over-exploitation of ecosystems, loss of biodiversity, climate change and invasive species, pollution is considered to be one of the greatest human-made threats towards the biodiversity (CAFF, 2013; IUCN, 2018; Rantanen et al., 2022; Venter et al., 2006; Wilcove et al., 1998; Woo-Durand et al., 2020). Although the Arctic is a remote region with few local sources of anthropogenic organohalogenated contaminant (OHC) emissions, OHCs have been detected at high levels in various Arctic animals for decades (Braune et al., 2005; Dietz et al., 2019; Letcher et al., 2010). OHCs are organic compounds substituted with halogenated aromatic components such as chlorine, bromine or fluorine, encompassing organochlorines (OCs), brominated flame retardants (BFRs) and perfluoro-alkyl substances (PFASs) (Letcher et al., 2010). OCs include polychlorinated biphenyls (PCBs), typically used in electrical equipment for industrial purposes, and organochlorine pesticides (OCPs), typically used in agriculture and recognized as some of the most hazardous contaminants (Akhtar et al., 2021). PFASs are used for a wide range of purposes including textile impregnation and fire-fighting foam (Glüge et al., 2020).

Although OHCs originate from agriculture, industry, maritime and urban human activities in southern latitudes, they can be transported into the Arctic via long-range transport through northward patterns of atmospheric and oceanic currents (AMAP, 1998; Bard, 1999; Barrie et al., 1992). Other transport pathways include discharges from Arctic rivers, migrating animals and drift ice transported by the transpolar drift (AMAP, 1998; Barrie et al., 1992; Borgå et al., 2004). These transport pathways combined with decelerated degradation of OHCs due to low annual temperatures in the Arctic, results in the region acting as a sink for anthropogenic contaminants (AMAP, 2017; Bard, 1999). Due to their persistence, OHCs have the potential to accumulate within organisms over time, and to magnify through the food chain, which causes top predators to have high concentrations (Bard, 1999; Borgå et al., 2001; Hop, Borgå, et al., 2002). OCs have lipophilic properties and tend to accumulate in fatty tissues (Borgå et al., 2004; Pelletier et al., 2003). PFASs on the other hand, tend to accumulate in protein and phospholipid rich tissues such as blood, liver and kidneys (AMAP, 2017). In the Arctic, high concentrations of OHCs have been found in top predators such as polar bears (*Ursus maritimus*), killer whales (*Orcinus orca*) and predatory seabirds such as glaucous gulls (*Larus hyperboreus*) and ivory

gulls (*Pagophila eburnea*) (Borgå et al., 2001; Braune et al., 2019; Gabrielsen, 2007; Miljeteig et al., 2009). Detectable levels have also been found in species positioned lower in the food web, such as the Brünnich's guillemot (*Uria Lomvia*) (Braune et al., 2019). Across various taxa and species, exposure to OHCs has been linked to negative health effects such as endocrine disruption (La Merrill et al., 2020; Marlatt et al., 2022; Nordstad et al., 2012; Verreault et al., 2004; Verreault et al., 2008), reduced immune response (Bustnes et al., 2004), altered vitamin levels (Miljeteig et al., 2012), altered antioxidant response (Sletten et al., 2016), and reduced fertility (Marlatt et al., 2022).

The widespread application of OCs as pesticides in agriculture began in the 1940s, (Carson, 2018), and in the 1960s mainstream publications like *Silent Spring* (Carson, 1962) highlighted the adverse health effects of contaminants, sparking public awareness about the topic. This awareness led to global cooperation to regulate and ban various compounds, and PCBs and dichlorodiphenyltrichloroethane (DDT) were among the compounds that were banned in several countries in the 1970s (Bianchini et al., 2022; Nygard et al., 2019). Subsequently, a global treaty, the Stockholm Convention on Persistent Organic Pollutants, was established in 2001 and enacted in 2004 (Bianchini et al., 2022; Matthies et al., 2016; Stockholm Convention, 2019a). As of today, most OHCs are classified as persistent organic pollutants (POPs) under the Stockholm Convention (Stockholm Convention, 2019d). POPs and/or their degradation products are characterized by their toxicity, persistence, potential for environmental long-range transport, and their potential for bioaccumulation and magnification up in the food chain (Akhtar et al., 2021; AMAP, 2017; Matthies et al., 2016). Many OCs, such as PCBs and DDT, are classified as "legacy" POPs" included in the original 12 contaminants banned or restricted by the Stockholm Convention in 2004 (Stockholm Convention, 2019b). PFASs are of more recent concern in the Arctic (AMAP, 2017), and several PFAS-variants started being subjected to restriction in 2008. Furthermore, new chemicals are constantly under evaluation to be included in the Stockholm Convention (Bianchini et al., 2022; Stockholm Convention, 2019c).

Overall, regulated or banned OHCs have shown trends of decreasing levels in Arctic biota over the last decades, while newer OHCs have demonstrated mixed trends (AMAP, 2014; Bianchini et al., 2022; Rigét et al., 2019). With climate change and increasing temperatures in the Arctic, distribution of contaminants and their dynamics may shift due to multiple factors. These factors include for instance a shift in the Arctic biota towards more boreal species, the release of

historically trapped OHCs through melting ice and permafrost, changes in precipitation, altered bioaccumulation of OHCs due to temperature changes, and increased human activity (AMAP, 2021; Borgå et al., 2022; Borgå et al., 2010; Descamps & Strøm, 2021; Hung et al., 2022; Vihtakari et al., 2018). In addition, there is a constant development of new chemicals (AMAP, 2017). Therefore, continuous monitoring of OHCs in the Arctic is essential, and monitoring efforts and surveillances will also indicate whether legislative and mitigation initiatives taken to reduce production and release of OHCs have been effective (Olsson & Reutergårdh, 1986).

1.2 Arctic seabirds as biomonitors of contamination

Measuring OHCs in biota provides information about the availability of environmental OHCs for uptake and to which extent such uptake occurs (Bianchini et al., 2022; Olsson & Reutergårdh, 1986). Seabirds are a commonly used species for biomonitoring (Bianchini et al., 2022; Mallory & Braune, 2012a). Birds are widely studied across the globe and may act as indicators of the status of other taxa in the environment in which they live (BirdLife International, 2022; Furness & Camphuysen, 1997). Seabirds commonly occupy high trophic levels, making them prone to biomagnification of contaminants, thereby indicating the food chain exposure to contaminants (Furness & Camphuysen, 1997; Hop, Borgå, et al., 2002). Furthermore, higher concentrations of contaminants contribute to reducing the chemical analytical error (Bignert & Helander, 2015). In a study analysing trends of OHCs in different animal tissues across the Arctic, bird eggs had the highest statistical power (Rigét et al., 2019). Arctic seabirds often breed in numbers and may return to the same breeding grounds year after year, making them an accessible research animal in the wild (BirdLife International, 2022; Furness & Camphuysen, 1997; Mallory & Braune, 2012a). Additionally, birds have been of human interest for a long time, making them one of the most extensively studied groups of animals (BirdLife International, 2022). This interest in birds has resulted in archived bird samples, which can be utilized for research purposes decades after collection (Bianchini et al., 2022; Mallory & Braune, 2012a).

Across the world, seabirds are currently experiencing rapid population declines (BirdLife International, 2022), and the adverse health effects caused by contaminants emphasize the need for understanding the role of contaminants in the ongoing population declines. As different

species exhibit diverse feeding habits, breeding grounds and migration patterns, it is advantageous to assess the contamination status in various seabird species. This approach enables a comprehensive evaluation of contamination across different areas and food webs in the Arctic (Bianchini et al., 2022; Mallory & Braune, 2012a).

Bird eggs have been used for decades to assess the contaminant status in avian populations (Bianchini et al., 2022; Braune et al., 2019; Helgason et al., 2008; Mallory & Braune, 2012a). Contaminants are maternally transferred into the eggs upon egg formation and the concentrations in the eggs may reflect the female contaminant burden (Drouillard & Norstrom, 2001; Verboven et al., 2009; Verreault et al., 2006).

There is a wide range of Arctic seabirds that have been studied in relation to OHCs in the Arctic environment. A commonly used species in studying trends and patterns of contaminants is the Brünnich's guillemot (*Uria lomvia*), whose eggs have been collected for various studies across the Arctic for decades (Braune et al., 2019; Miljeteig & Gabrielsen, 2010). The Brünnich's guillemots are one of the most numerous seabird species in the Arctic, breeding in colonies ranging from a few pairs to over two hundred thousand pairs (Anker-Nilssen et al., 2000; Strøm & Descamps, 2013). Their diet consists of key species such as polar cod (*Boreogadus saida*), capelin (*Mallotus villosus*) and crustaceans including *Pandalus borealis* along with smaller amphipods such as *Parathemisto libellula* and *Gammarus wilkitzkii* (Anker-Nilssen et al., 2000; Lønne & Gabrielsen, 1992; Mehlum & Gabrielsen, 1993). Therefore, the Brünnich's guillemot is an accessible study animal that provides information about the status of the ecosystem in which they live (MOSJ, 2023). The Brünnich's guillemot has shown declines in most legacy OCs and PFASs such as perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) over the last decades (Braune et al., 2019; Miljeteig & Gabrielsen, 2010; Norwegian Polar Institute, 2022a, 2022b, 2022c, 2022d). Furthermore, the species displays some regional differences in contaminant concentrations between the colonies in Bjørnøya and Kongsfjorden, with higher levels of several major OCs in the Kongsfjorden colony, and higher levels of PFASs in the Bjørnøya colony (Norwegian Polar Institute, 2022a, 2022b, 2022c, 2022d). In general, the Brünnich's guillemot has lower levels of organochlorines (OCs) compared to various Arctic seagull species (Braune et al., 2019).

Although the IUCN red list of threatened species categorizes the Brunnich's guillemot as of least concern on a global scale, the Norwegian Biodiversity Information Centre has categorized the population breeding at Svalbard as vulnerable (BirdLife International, 2018b; Stokke et al., 2021). Despite their abundance, Brünnich's guillemots breeding on Svalbard have been experiencing a population decline of about 4 % each year (Descamps & Strøm, 2021; Norwegian Polar Institute, 2023). The reasons for the decline are not fully understood, but the ongoing warming of the Arctic and a changing prey composition are thought to play a role (Descamps & Ramírez, 2021; Descamps & Strøm, 2021; Hop et al., 2019).

Another Arctic seabird that has been studied in relation to contaminants is the ivory gull (*Pagophila eburnea*) (Braune et al., 2007; Lucia et al., 2015; Miljeteig et al., 2009). This High Arctic seagull is relatively rare with a global population of 8000-11500 breeding pairs (Gilchrist et al., 2008). The ivory gulls typically breed in small colonies that may occasionally change localization (Mallory et al., 2012b; Volkov & De Korte, 1996). The species lives strongly associated with sea ice (Spencer et al., 2014), and its habitat is therefore highly threatened by the ongoing reduction of the Arctic sea ice due to climate change (Vinnikov et al., 1999). The ivory gulls feed on small fish and crustaceans, where polar cod has been reported as a main prey. However, their diet also consists of seal carcasses and faeces left by polar bears, positioning them as top predators (Bateson & Plowright, 1959; Karnovsky, 2009; Mehlum & Gabrielsen, 1993). A study on ivory gull eggs collected from the Norwegian and Russian Arctic revealed that the concentrations of organochlorines (OCs) are comparable to, or higher than levels found in other top predatory Arctic seabird species, while levels of PFAS were comparable to levels found in seabirds positioned lower in the food web (Miljeteig et al., 2009). Across different colonies of ivory gulls breeding in the Norwegian and Russian Arctic, levels of PFASs have been found to be similar, while levels of OCs have been found to vary significantly across the different colonies (Miljeteig et al., 2007). Russian colonies had the highest and lowest concentrations of OCs, while the Norwegian colony had intermediate levels (Miljeteig et al., 2007). In general, the levels of some organochlorines (OCs) are reaching thresholds associated with biological effects reported in other seagull species (Lucia et al., 2015; Miljeteig et al., 2009). The ivory gull has also experienced eggshell thinning of 7-17 %, reaching a degree of thinning associated with declines in bird populations (Miljeteig et al., 2012; Walker et al., 2012).

Over the last decades, the ivory gulls have experienced alarming population declines, with an estimated 40 % decline among the ivory gulls breeding in the Svalbard archipelago (Strøm et al., 2020), and declines up to 80 % from the 1980s to 2003 in the Canadian Arctic (Gilchrist & Mallory, 2005). The IUCN red list of threatened species categorizes the ivory gull as near threatened on a global scale and as vulnerable in Europe (BirdLife International, 2018a, 2021). The high levels of contaminants and the rapid population declines of the species advocate for a regular monitoring efforts of the ivory gull.

1.3 Diet and other biological factors influencing OHCs bioaccumulation

The concentration of OHCs in organisms is strongly linked to their diet (Letcher et al., 2010). This was reflected in a study on glaucous gulls (*Larus hyperboreus*) breeding in the Svalbard archipelago, where individuals feeding on guillemot (*Uria spp.*) eggs, thus occupying a higher trophic level, exhibited higher concentrations of various OCs compared to gulls with a more fish-based diet (Bustnes et al., 2000). The diet is again influenced by habitat and migration patterns (Borgå et al., 2004). Furthermore, there are numerous factors influencing the accumulation of OHCs in biota, such as lipid dynamics and interspecies variations in ability to biotransform OHCs (Borgå et al., 2004). Although diet exerts the most prominent influence on the accumulation of OHCs, this accumulation is also influenced by various interconnected biological factors (Borgå et al., 2004).

Analysing stable isotopes of nitrogen (N) and carbon (C) can be used to indicate the trophic position and feeding habitat of seabirds, respectively (Hobson et al., 1994). The ratio of ^{15}N to ^{14}N ($\delta^{15}N$) increases with trophic level and can thereby be used as a proxy for trophic position (Hobson & Welch, 1992; Hobson et al., 1994). The ratio of ^{13}C to ^{12}C ($\delta^{13}C$) can be used to indicate different feeding habitats (Hobson & Welch, 1992; Hobson et al., 1994). Elevated $\delta^{13}C$ values in seabirds have been linked to inshore and benthic feeding habitats, while lower $\delta^{13}C$ values have been linked to pelagic feeding habitats (Hobson et al., 1994).

1.4 Eggshell thinning following contaminant exposure

Following the wide use of DDT as a pesticide in the second half of the 1940s (Ratcliffe, 1970), increased instances of clutch depletion in the peregrine falcon in Great Britain were observed, with eggs breaking or disappearing from the nests (Ratcliffe, 1967, 1970). The pesticide DDT was thought to be the cause behind this observation (Ratcliffe, 1967, 1970). DDT and its metabolite dichlorodiphenyldichloroethylene (DDE) are now known as the most prominent chemicals involved in eggshell thinning, although other substances like PCBs, hexachlorobenzene (HCB), oxychlordane, mirex, dieldrin, heavy metals and non-steroidal anti-inflammatory drugs (NSAIDs) have also been linked to this effect (Cooke, 1973; de Solla et al., 2023; Eeva & Lehikoinen, 1995; Mason et al., 1997; Nygard, 1999; Pain et al., 1999; Wiemeyer et al., 1984). Eggshell thinning is associated with a reduction in the calcium carbonate fraction in the eggshell, indicating that eggshell thinning is caused by a disturbance in the calcium carbonate metabolism (Ratcliffe, 1970). DDT is thought to be inhibiting the activity of an enzyme involved in calcium transport as well as other enzymes involved in eggshell formation (Holm et al., 2006; Kolaja & Hinton, 1977; Peakall, 1993).

DDT and DDE have been associated with eggshell thinning in various bird species across the globe, such as California condors (*Gymnogyps californianus*), osprey (*Pandion haliaetus*) and peregrine falcons (*Falco peregrinus*) (Burnett et al., 2013; Nygard et al., 2019; Odsjö & Sondell, 2014; Ratcliffe, 1967, 1970). This has also been recognized in the High Arctic seabird species ivory gull (Miljeteig et al., 2012). For Brünnich's guillemots, the data on potential eggshell thinning following contaminant exposure is scarce. However, eggshell thinning has been observed in the closely related common guillemot (*Uria aalge*) (Bignert et al., 1995). Eggs of poor quality may be rejected, accidentally or purposely damaged or foraged upon by the parents, leading to a reduction in breeding success (Ratcliffe, 1970). Eggshell thinning of 17-20 % has been associated with population declines (Hickey & Anderson, 1968; Walker et al., 2012). Ivory gulls are among the numerous bird species that are believed to have experienced population declines caused by eggshell thinning (Miljeteig et al., 2012). In general, following the restriction and banning of DDT and other hazardous chemicals, species that previously suffered from eggshell thinning have been experiencing a recovery in eggshell thickness (Bignert et al., 1995; Odsjö & Sondell, 2014) and populations (Nygard et al., 2019).

1.5 Aim of study

This study aims to provide an assessment of the concentrations and patterns of different OCs and PFASs in the eggs of Brünnich's guillemots breeding in the Norwegian Arctic, as well as in ivory gull eggs from the Norwegian and Russian Arctic. The Brünnich's guillemot eggs included in this study were collected from Bjørnøya and Kongsfjorden (Svalbard) during the period 2018-2022. The ivory gull eggs were collected from Nordaustlandet (Svalbard) in 2021 and 2022, and from Uyedineniya (Russia) in 2019. The contaminant level in the two different species will be compared, as well as carbon and nitrogen stable isotopes as proxies of their feeding habitat diet. Furthermore, this study will use eggshell thickness as an endpoint for potential health effects caused by OHCs. We predict 1/ higher levels of OHCs in eggs of ivory gulls eggs compared to Brünnich's guillemot eggs; 2/ different signatures of $\delta^{13}C$ and $\delta^{15}N$ between the species due to them feeding at different trophic levels and in different habitats; 3/ intra-species variations in concentrations and patterns of OHCs, especially in ivory gull eggs from the Russian Arctic and Norwegian Arctic, and 4/ a negative relationship between eggshell thickness and OHCs in ivory gulls, but not in the Brünnich's guillemots.

2 Materials and methods

2.1 Study areas

The eggs included in this study were collected from various areas within the Svalbard archipelago; Bjørnøya, Kongsfjorden and Weaselbukta on Nordaustlandet, as well as samples collected from Uyedineniya in the Russian Arctic (Figure 1).

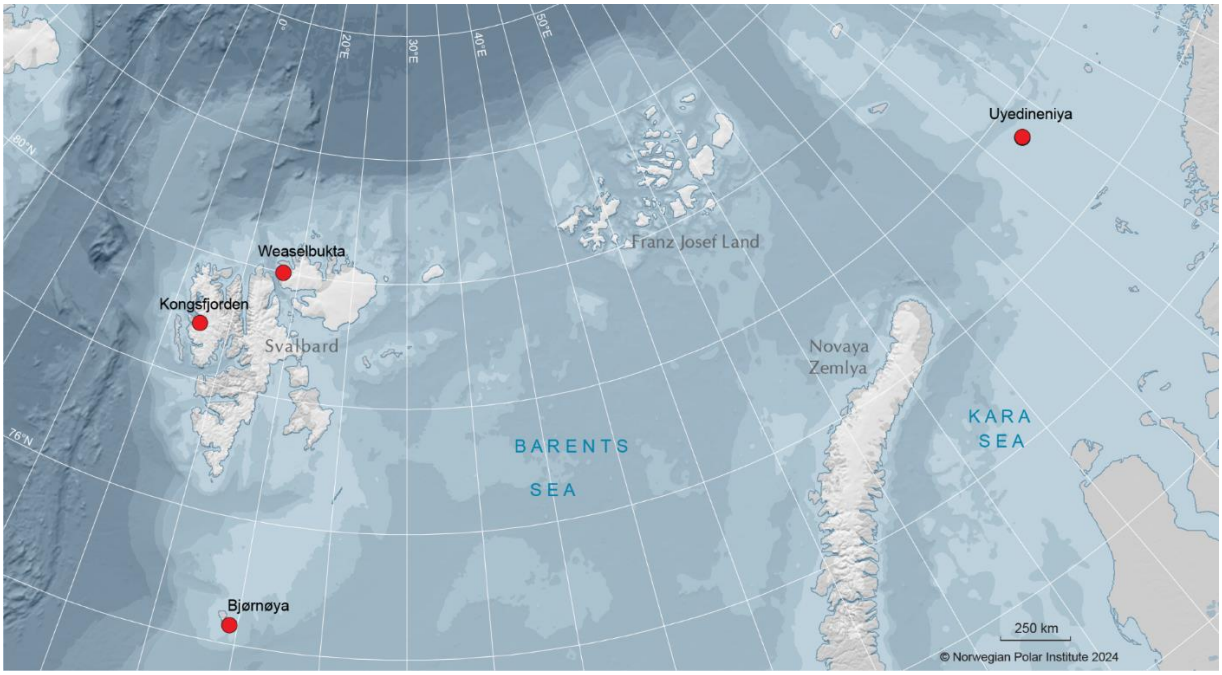

***Figure 1**: A map over the study area. The areas of sampling (Bjørnøya, Kongsfjorden, Weaselbukta and Uyedineniya) are marked with red dots.*

Bjørnøya is an isolated island located in the western Barents Sea, being the southernmost island of the Svalbard archipelago. The surrounding waters of Bjørnøya are strongly shaped by the influx of Atlantic water coming in from the southwest through the North Atlantic current and into Arctic water masses. The convergence of these two water masses form an area of upwelling and mixing known as the "polar front", which provides good foraging opportunities within flight distance for the seabirds breeding on Bjørnøya (Loeng, 1991; Mehlum et al., 1998). The major aggregation of breeding seabirds is found in the cliffs at the south part of the island (Mehlum et al., 1998; Thuesen & Barr, 2005-2007).

Kongsfjorden is a fjord located on the west coast of the island Spitsbergen within the Svalbard archipelago. The fjord is influenced by several glaciers that run into the fjord, as well as Atlantic water masses, Arctic water masses and Polar Surface Water (Hop, Pearson, et al., 2002;

Svendsen et al., 2006). In addition to the glaciers, the fjord landscape consists of small islands, islets, bird cliffs and surrounding mountains (Barr, 2024).

Weaselbukta is a small bay located in the inner part of the shallow fjord Murchisonfjorden, situated on the west coast of Nordaustlandet (Svalbard). The mouth of the fjord is situated towards the Hinlopen Trough, which receives a strong inflow of Atlantic water masses, although the surface waters are recognized as Polar Surface Waters (Menze et al., 2020). The landscape of Murchinsonfjorden is characterized by small islands, islets and surrounding mountains, with several bird cliffs present in the area (Evju et al., 2010).

Uyedineniya is a small island located in the Kara Sea between Novaya Zemlya and the Severnaya Zemlya archipelago (Russia). The Kara Sea is connected to the Barents Sea and Arctic Basin in the north, and the waters around Uyedineniya are heavily influenced by freshwater inflow from Russian rivers coming from the south (Johnson et al., 1997).

2.2 Study species

The two Arctic seabird species in this study are top predators, the Brünnich's guillemot is a diving bird which feeds on pelagic species, while the ivory gull is a surface feeder foraging in ice-filled waters.

2.2.1 The Brunnichs guillemot - *Uria lomvia*

The Brünnich's guillemot (*Uria Lomvia*), which belongs to the Alcidae family, is one of the most abundant seabird species breeding in the northern hemisphere and has a circumpolar distribution ranging from 46°N to 82°N (Anker-Nilssen et al., 2000; Strøm & Descamps, 2013). Brünnich's guillemots breed in colonies commonly located in cliffs along the coast at various locations dispersed throughout the Arctic, including locations at Bjørnøya and Spitsbergen in the Svalbard Archipelago (Anker-Nilssen et al., 2000; Lønne & Gabrielsen, 1992). On Bjørnøya, the population is estimated to be around 95 000 breeding pairs, while the rest of the Svalbard archipelago has a population of about 520 000 breeding pairs (Anker-Nilssen et al., 2015). Brünnich's guillemots breeding on Bjørnøya tend to overwinter in the waters around Iceland, whilst birds originating from Spitsbergen overwinter in waters around Iceland and west of Greenland (Frederiksen et al., 2016). On Svalbard, the breeding season starts in the middle

of June, and the incubation period lasts for 32 days (Strøm & Descamps, 2013). Brünnich's guillemots lay one-egg clutches, but may invest energy in producing a replacement egg if their egg is predated upon or lost (Hipfner et al., 1999). The Brünnich's guillemot invests in thick eggshells relative to egg weight (Williams et al., 1982).

The diet of this marine diving bird consists mainly of fish and crustaceans, such as polar cod (*Boreogadus saida*), capelin (*Mallotus villosus*), *Pandalus borealis*, *Parathemisto libellula* and *Gammarus wilkitzkii* (Anker-Nilssen et al., 2000; Lønne & Gabrielsen, 1992; Mehlum & Gabrielsen, 1993). The Brünnich's guillemot typically reaches a weight ranging from 700 to 1200 g, and is a long-lived bird with the oldest recorded individual reaching an age of 27 years (Strøm & Descamps, 2013).

2.2.2 The ivory gull - *Pagophila eburnea*

The ivory gull (*Pagophila eburnea*) is a High Arctic seabird species sorted into the Laridae family, which breeds in the Arctic regions of Canada, Greenland, Svalbard and Russia (Anker-Nilssen et al., 2000; Blomqvist & Elander, 1981). The global population of ivory gulls is estimated to be around 8000-11 500 pairs, of which about 86 % breeds in the Russian Arctic (Gilchrist et al., 2008). On Uyedineniya in 2019, a total of 140 ivory gull nests were recorded though visual sightings (Gavrilo et al., Unpublished report). On Svalbard, the number of breeding pairs was estimated to be 1500-2000 pairs, with the highest aggregations found in the northeast of the archipelago (Anker-Nilssen et al., 2000; Anker-Nilssen et al., 2015; Strøm et al., 2020; Strøm & Descamps, 2013). The ivory gull has a mixed pattern of migration outside of the breeding season. Some birds stay close to their breeding areas throughout the year, while others migrate long distances to areas such as the Labrador Sea and the Bering Sea (Anker-Nilssen et al., 2000; Gilg et al., 2010; Strøm, 2013). The species is strongly associated with the sea ice, which greatly influences their migration patterns (Spencer et al., 2014). The ivory gulls breed in small colonies, and breeding locations can vary between cliffs and tundra, shoreline and inland, sea level and high altitudes of up to 800 meters above sea level (Anker-Nilssen et al., 2000). The ivory gulls exhibit some breeding-site fidelity, but the breeding site may also change location (Mallory et al., 2012b; Volkov & De Korte, 1996). They are found in their breeding areas from May until late August and early September, and the incubation period lasts for approximately 25 days (Strøm, 2013). The clutch size varies from one to three eggs, although clutches of two eggs are most common (Bateson & Plowright, 1959).

The ivory gulls are opportunistic surface feeders foraging in ice-filled waters, and their diet consist of polar cod (*Boreogadus saida*) and macro zooplankton such as marine crustaceans. In addition, they scavenge on seal carcasses left after polar bears (*Ursus maritimus*), which positions them at the top of the food chain (Bateson & Plowright, 1959; Karnovsky, 2009; Mehlum & Gabrielsen, 1993). With a weight ranging from 400-700 g, they are recognized as a medium-sized gull and have been recorded to reach over 28 years of age (Mallory et al., 2012b).

2.3 Sampling procedures

As a part of a long-term monitoring program on Svalbard and Jan Mayen (MOSJ; https://mosj.no/en/), a total of 20 Brünnich's guillemot eggs were collected from Bjørnøya and Kongsfjorden in June 2018, 2020, 2021 and 2022 (Table 1). Eggs were sampled from individual nests, regardless of their developmental stage or status as first or replacement egg. As the eggs were collected by different staff over different years, there were inconsistencies in the biological characteristics that were measured. However, the width and length of most eggs were measured with a calliper to the nearest 0.1 mm.

A total of 13 ivory gull eggs were collected in Uyedineniya and Nordaustlandet, Svalbard during the incubation period (Table 1). At Uyedineniya, 10 eggs were randomly selected from nests with two or three eggs, and only one egg was collected from each nest. Both the laying sequence as well as the development stage of the collected eggs were unknown, as the birds had not been monitored prior to sampling. At Nordaustlandet in 2021, only one egg was collected, which was the only egg in the nest. In 2022, two eggs were collected, but were mistakenly from the same nest of two eggs. These two ivory gull eggs were treated as sampled from individual nests due to small sample size. For the eggs from Nordaustlandet, width and length were measured with a calliper to the nearest 0.1 mm, and the eggs were weighed. No biometry was recorded in the field for the eggs from Uyedineniya.

All eggs were individually wrapped in aluminium foil, frozen down and stored at approximately -20 °C until analysis. Although there is a slight chance that eggs sampled from the same colonies in different years may originate from the same parents, it was presumed that they originated from different individuals. The validity of this latter assumption can only be confirmed through a DNA analysis.

***Table 1**: Number of eggs, location and date of sampling for Brünnich's guillemot and ivory gull eggs included in this study.*

Species	No. of eggs	Date	Area	Location	Coordinates
Br. guillemot	5	19.06.2018	Bjørnøya	Evjebukta	74.351 °N 19.099 °E
Br. guillemot	5	08.06.2020	Kongsfjorden	Krykkjefjellet	78.896 °N 12.194 °E
Br. guillemot	5	08.06.2021	Kongsfjorden	Krykkjefjellet	78.896 °N 12.194 °E
Br. guillemot	5	06.06.2022	Kongsfjorden	Krykkjefjellet	78.896 °N 12.194 °E
Ivory gull	10	16.07.2019	Uyedineniya	Uyedineniya	77.512 °N 82.231 °E
Ivory gull	1	27.06.2021	Nordaustlandet	Weaselbukta	80.018 °N 18,967 °E
Ivory gull	2	26.06.2022	Nordaustlandet	Weaselbukta	80.018 °N 18.967 °E

2.4 Contaminant analysis

The eggs of Brünnich's guillemots (n=20) and ivory gulls (n=13), were analysed for compounds of organochlorines (OCs) and poly- and perfluoroalkyl substances (PFASs) at the laboratories of NILU, The Climate and Environmental Research Institute (Tromsø, Norway). All compounds are listed in Table 2.

Table 2: Table of all contaminants analysed in eggs of Brünnich's guillemots and ivory gulls.

OHCs	Group	Compound	Note
OCs	Chlordane (CHL) and mirex	*cis*-Chlordane *trans*-Chlordane Heptachlor Mirex *cis*-Nonachlor *trans*-Nonachlor Oxychlordane	

	Dichlorodiphenyltrichloroethane (DDT)	*o,p´*-DDD *p,p´*-DDD *o,p´*-DDE *p,p´*-DDE *o,p´*-DDT *p,p´*-DDT	
	Hexachlorobenzene (HCB)	HCB	
	Hexachlorocyclohexane (HCH)	a-HCH b-HCH g-HCH	
	Polychlorinated biphenyl (PCB)	PCB 18 PCB 28/31 PCB 47 PCB 52 PCB 66 PCB 74 PCB 99 PCB 101 PCB 105 PCB 118 PCB 123 PCB 128 PCB 138 PCB 141 PCB 149 PCB 153 PCB 156 PCB 157 PCB 167 PCB 170 PCB 180 PCB 183 PCB 187	Except 2020 Br. guillemot eggs

		PCB 189 PCB 194 PCB 206 PCB 209	
PFAS	Perfluoroalkyl carboxylic acid (PFCA)	PFPeA PFHxA PFHpA PFOA PFNA PFDA PFUnDA PFDoDA PFTrDA PFTeDA PFHxDA PFODcA	
	Perfluoroalkane sulfonic acid (PFSA)	4:2 FTS 6:2 FTS 8:2 FTS 10:2 FTS PFBS PFPS PFHxS PFHpS PFOSlin sumPFOS PFNS PFDS FOSA	

2.4.1 Egg homogenization and preparation for analysis

Due to missing measurements of length, width and weight of ivory gull eggs collected from Uyedineniya, the measurements were attempted on frozen eggs before opening them. The dimensions of the eggs were compromised due to damages from the transportation and freezing process. Consequently, only the weight was measured on the frozen eggs (weighed on a Sartorius, Mettler Toledo, Colombus, Ohio, USA). The ivory gull eggs from Svalbard were weighed as well, to allow for comparison of weight of frozen eggs across the colonies. Several of the eggs from Uyedineniya were severely damaged, and some content had leaked, which likely affected the accuracy of the weight. The eggs from Svalbard were intact and the weight was reliable.

The eggs of Brünnich's guillemots and ivory gulls (Figure 2) were thawed and the content was added to glass flasks. The content of the Brünnich's guillemot and ivory gull eggs were extracted in two different ways, depending on whether the eggshell was intact or had cracked during transportation and freezing. In the cases where the eggshell had cracked, the content was extracted while the egg was still frozen. The eggshell was removed by using tweezers and spatulas, and the content was added to a glass flask. If the eggshell was intact, the egg was thawed at room temperature before the content was added to a glass flask. The room tempered eggs were carefully hit on a flat and clean area until a small crack appeared. Once carefully opened, the content was poured into the flask. Development stage was not assessed, as five of the Brunnich guillemot eggs had already been opened and homogenized in relation to other projects, and handling of the eggs was reduced to a minimum to prevent contamination from external sources.

The egg contents were homogenized using a mixer (ULTRA-TURRAX® IKA® T18 basic, IKA instruments), and were then frozen down to approximately -20 °C and stored until further analysis. The samples were thawed and stirred before subsampling for the different analysis.

Figure 2*: Pictures taken of the eggs from Brünnich's guillemot (Uria lomvia, on the left) and ivory gull (Pagophila eburnea, on the right).*

2.4.2 Analysis of OCs and determination of lipid %

For all Brünnich's guillemot eggs and ivory gull eggs collected in 2018, 2021 and 2022 the analysis was performed in 2023. The five Brünnich's guillemot eggs collected in 2020 were, in connection with other projects, analysed in 2020-2021.

Extraction

Approximately 1 g of egg homogenate was added to Precellys tubes of 7 mL containing small ceramic beads, and the exact sample weight was accounted for (weighed on a Sartorius, Mettler Toledo, Colombus, Ohio, USA). The samples were spiked with 40 µL of internal standard (PBDE I, PCB I, DDT I and PEST I, 0.5 ng/ µL) and vortexed (VWR international, Radnor, Pennsylvania, USA). The samples were then left for 30 minutes before 0.5 mL of 6 % NaCl/ Milli-Q and 3 mL of an acetone and n-hexane mix (1:1) was added. Afterwards, the samples were run in a Precellys (Precellys Evolution, Bertin Technologies, Montigny-le-Bretonneux, France) twice at 5000 revolutions per minute (rpm) for 10 seconds followed by centrifugation (Centrifuge 5702 R, Eppendorf) at 3500 rpm for 5 minutes. The supernatants were pipetted into pre-weighed 15 mL glass tubes. Then 3 mL of n-hexane was added to the Precellys tubes before they were processed again in the Precellys and centrifuged as indicated above. The supernatant was pipetted out and added to the same 15 mL glass tubes. The extracts in the 15 mL glass tubes

were concentrated in a miVac (miVac QUATTRO, Centrifugal Concentrators, Genevac™, Ipswich, UK) until near dryness and left in room temperature loosely covered with aluminum foil for 2-3 days until they had dried up. To account for % lipid weight in the samples, the dried samples were weighed before they were reconstituted in 0.5 mL acetonitrile and vortexed.

EZ-POP clean up

The samples were cleaned up by running them through 12ml SupelClean EZ-POP NP cartridges (Supelco, 54341-U). The solvent containing the chemicals was pipetted out of the glass tubes and into the cartridges, while the visible fat was left in the glass tube. The samples were run through the cartridges together with 15 mL of acetonitrile and added to new 15 mL glass tubes (Figure 3).

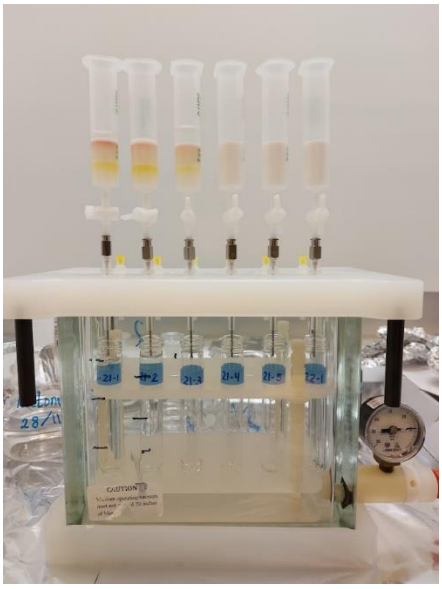

Figure 3*: The assembled station for the EZ-POP clean up procedure. Samples have been added to the three cartridges on the left.*

EZ-prep 123 clean up

For the next clean up procedure, the samples were eluted in a lipid soluble solvent. The samples were carefully evaporated to dryness using the miVac, and the samples were taken out of the machine as soon as dryness were achieved. They were reconstituted by adding 0.5 mL n-hexane and vortexed. The cartridges used for the EZ-prep 123 clean up procedure were prepared by hand. Florisil was activated by burning at 450°C for 8 hours, before adding MilliQ-water (ZLXS5003Y, Millipore S. A., Molsheim, France). 3 mL of MilliQ-water was added for every 100 g florisil and distributed evenly by shaking the glass flask containing the florisil by hand and on a shaking table (HS 501 digital, IKA®-WERKE) for approximately 2 hours. The

cartridges were packed with 3 g florisil enclosed by a fiber frit (rinsed with dichloromethane in ultrasonic bath for 10 min) in each end of the cartridge. A solution of dichloromethane (DCM) and n-hexane in a ratio of 26:74 was prepared. The samples were then run through the cartridges together with 20 mL of the DCM and n-hexane solution. The samples were added to 60 mL glass vials, and 0.5 mL isooctane was added. The 60 mL glass vials containing the samples were left in room temperature loosely covered in aluminum foil to allow for evaporation until the sample could be transferred into 15 mL glass tubes. Further concentration down to 2 mL was done by evaporation in the miVac. Approximately 0.5 mL isooctane was added, before the samples were evaporated down to 0.2 mL and transferred to vials with insert. Then the samples were evaporated to exactly 30 µL by using Nitrogen evaporation on a Reacti vap (Thermo Fisher Scientific, MS, USA) and lastly, 20 µL of recovery standard (13C PCB 159, 23.4 pg/ µL) was added after which the samples were vortexed and stored at 4 °C until instrumental analysis.

Instrumental analysis

The analysis of OCs was performed with chromatography-mass spectrometry (GC-MS) which was performed on a TSQ 9000 Triple Quadrupole GC-MS/MS (Thermo Fisher Scientific Corporation, MA, USA). 2 µL of the sample was injected into the split/splitless inlet equipped with a Helium saver unit. The inlet, which held a temperature of 250 °C, was connected to a Thermo TD5SilMS column (30 m × 0.25 mm, 0.25 µm) with a 5 m retention gap with Helium as carrier gas with a flow rate of 1.2 mL/min. The temperature program of the GC oven was held at 40 °C for 1.5 min, succeeded by an increase of 25 °C per min until reaching 90 °C which was held for 1.5 min. This was followed by a temperature increase of 25 °C per min until reaching 180 °C, followed by a further temperature increase of 5 °C per min until reaching 280 °C. Thereafter, there was a final temperature increase of 10 °C per min until reaching 300 °C, which was held for 5 minutes. The transfer line held a temperature of 300 °C, while the ion-source, which was an Advanced Electron Ionization (AEI), was held at 320 °C with EI at 50eV.

2.4.3 Analysis of PFASs

For all eggs included in this study, the analysis for PFASs was performed in 2022.

Extraction

The procedure of analysing for PFASs was performed according to Hanssen et al., 2013, with some modifications. 1-2 g of homogenous egg was added to a polypropylene centrifuge tube (50 ml), and the exact sample weight (measured on a Sartorius, Mettler Toledo, Colombus, Ohio, USA) was noted. The samples were spiked with 20 µl of internal standard (0.5 ng/µl PFAS mix) before addition of 8 ml acetonitrile. Then the tubes were vortexed (VWR international, Radnor, Pennsylvania, USA) to thoroughly mix the samples with the additives. To extract the PFASs out of the egg tissue and into the solvent, the samples were exposed to ultrasonic waves immersed in an ultrasonic bath (Ultrasonic cleaner, VWR, USC-THD) in a series of three treatments, each treatment lasting for 10 minutes, and the samples were vortexed in between every ultrasonic treatment.

Clean up

After extraction, the samples were centrifuged (Centrifuge 5702 R, Eppendorf) at 2000 rpm for 5 minutes to separate the phases. The supernatant was transferred to a new polypropylene centrifuge tube (15 ml) and then concentrated down to 2 mL using a RapidVap (Rapid Vap; Labconco Corp., Kansas City, MO, USA). Eppendorf tubes were prepared with approximately 25 mg ENVI-Carb 120/140 and 50 µL glacial acetic acid, before 0.8 mL of the concentrated supernatant was added and vortexed for 15 seconds, followed by a centrifugation (Centrifugeur A-14, Jouan, St. Herblain, France) at 10 000 rpm for 10 minutes. After centrifugation, 0.5 mL of the supernatant was transferred into glass vials (2 mL), and 20 µL of recovery standard (3,7-dimethyl PFOA, 0.1 ng/µL) was added. Finally, the samples were vortexed and stored at 4 °C until instrumental analysis.

Instrumental analysis

The instrumental analysis was performed with liquid chromatography-mass spectrometry (LC-MS) as described in Hanssen et al., 2013. The samples were run through ultrahigh pressure liquid chromatography triple-quadrupole mass-spectrometry (UHPLC-MS/MS) on a Thermo Scientific quaternary Accela 1250 pump (Thermo Fisher Scientific Inc., Waltham, MA, USA) in conjunction with a PAL Sample Manager (Thermo Fisher Scientific Inc., Waltham, MA,

USA) linked to a Thermo Scientific Vantage MS/MS (Vantage TSQ) (Thermo Fisher Scientific Inc., Waltham, MA, USA). 50 µL of the samples were mixed with 25 µL buffer (2 mM of NH_4OAc in 90:10 methanol/water), before 10 µL of the mixed samples were injected on a Waters Acquity UPLC HSS 3 T column (2.1× 100 mm, 1,8 µm) (Waters Corporation, Milford, MA, USA) set up with a Waters Van guard HSS T3 guard column (2.1× 5 mm, 1.8 µm) (Waters Corporation, Milford, MA, USA). The columns held a temperature of 40 °C. The mobile phases used to separate the compounds in the samples were 2 mM of NH_4OAc in 90:10 methanol/water and 2 mM of NH_4OAc in methanol.

2.4.4 Quantification and quality assurance

Quantification

The internal standard method was used to quantify OCs and PFASs in the samples. The method involves adding known concentrations of ^{12}C and ^{13}C labeled compounds at the beginning of the analysis procedure. Both the labeled chemicals and the original chemicals are identified as peaks on the output from the GC-MS and the LC-MS. The area of the peaks of labeled compounds was compared to the area of the original compounds, and the concentration of chemicals was calculated according to *Equation 1*, where relative response factor (RRF) was calculated according to *Equation 2.* A known concentration of recovery standard was added to all the samples prior to the instrumental analysis and used to account for PFAS that were lost along the procedure.

$$Amount_{C12\_sample} = \frac{Area_{C12\_sample} \times Amount_{C13\_sample}}{RRF \times Area_{C13\_sample}} \qquad \textit{Equation 1}$$

$$RRF = \frac{Area_{C12\_standard} \times Amount_{C13\_standard}}{Area_{C13\_standard} \times Amount_{C12\_standard}} \qquad \textit{Equation 2}$$

Quality assurance

The samples were prepared through the extraction and clean up procedures in groups of 10-13 samples. For every group, a blank and a standard reference material (SRM) of known

contaminant concentrations were prepared together with the samples. For the OCs analysis, the SRM was 0.5 g freeze dried fish tissue (WMF 030517, Reference Freeze Dried Fish Tissue, Wellington Laboratories Inc., Canada) prepared with 15 drops of Milli-Q water (ZLXS5003Y, Millipore S. A., Molsheim, France). For the PFAS analysis, the SRM was 500 µL human plasma (AM-S-Y2109 for the Arctic Monitoring and Assessment Programme Ring Test for Persistent Organic Pollutants in Human Serum). The blanks and the SRMs underwent the same methods as the samples, except in the case of OCs analysis where the blanks were not dried up during the extraction process. Limit of detection (LOD) was defined as the average value of the blanks plus three times the standard deviation of the blanks. Limit of quantification (LOQ) was defined as the average value of the blanks plus 10 times the standard deviation.
As a comparison of methods for OC analysis performed in different years, two Brünnich's guillemot eggs from the 2020 batch (originally analysed in 2020-2021) were analysed together with the group of eggs analysed in 2023.

Throughout the lab procedures, cautions were taken to avoid contamination or cross-contamination of the samples. Namely, work surfaces were regularly cleaned and covered up with aluminium foil and all glassware was rinsed with acetone and cyclohexane and burned at 450°C for 8 hours prior to being used. Metal equipment such as spoons, tweezers and spatulas were rinsed with acetone and n-hexane between each sample, and regularly put in ultrasonic bath. All solvents used in the procedures were acquired from SupraSolv®.

In addition to the standard cleaning of the equipment, extra caution was taken when handling the OCs samples. Before use, the Precellys tubes containing ceramic beads were rinsed with a mix of acetone and n-Hexane, and the solvents were pipetted out of the tubes before the tubes were left to air dry. Also, the tips and taps used in the clean-up procedures, were pre-rinsed in acetone and put in ultrasonic bath for 10 minutes. Prior to the clean-up procedures, the assembled cartridges were rinsed. For the EZ-POP clean up procedure, each cartridge was rinsed with 15 ml of acetone prior to use. For the EZ-prep 123 clean up procedure, each cartridge was rinsed with 10 mL of a DCM and n-hexane mix (26:74), and then rinsed with 10 mL of n-hexane only.

The laboratory at NILU, Tromsø regularly participates in an interlaboratory comparison program to ensure the quality of the laboratory analysis.

2.5 Stable isotopes

The analysis of stable isotopes of carbon and nitrogen was conducted at the University of Alaska Anchorage. The five Brünnich's guillemot eggs collected in 2020 were analysed in 2021, while the rest of the eggs were analysed in 2024. The analysis for stable isotopes was, with modifications for egg tissue, conducted as described by Rogers et al., 2015, with lipid extractions as described by Montanari et al., 2020. 1-1.5 mL of egg homogenate was transferred to plastic vials and freeze dried at -80 °C for 24 hours. The first step of lipid extraction involved adding a solution in a ratio of 2:1 of chloroform and methanol of about three to five times the sample volume, before shaking the samples on a vortex. The samples were left to rest for 30 minutes before being centrifugated at 3400 rpm for 10 minutes. The supernatant containing the lipids was removed, and the steps of lipid extraction were repeated until the supernatant was clear.

Following the lipid extraction, the samples were dried at 50 °C for 24 hours. From the dried samples, smaller volumes were packed in 3.5 ×5 mm tin cups (Costech, Valencia, CA) and weighed on a Sartorius ME5 microbalance (Sartorius AG, Goettingen, Germany). The analysis for $\delta^{13}C$ and $\delta^{15}N$ was performed employing a Costech ECS 4010 elemental analyzer (Costech, Valencia, CA) in accordance with a ThermoFinnigan Delta^{Plus} XP continuous-flow isotope ratio mass spectrometer (CF-IRMS; Thermo Scientific, Bremen, Germany). International reference materials (IAEA-N1, IAEA-CH7, IAEA-C3, USGS-25, USGS-40 and USGS-41) were used for calibration and internal standards were analysed with the samples for quality control, and included methionine (Alfa, Aesar) and Chinook salmon muscle (UAA Stable isotope lab). The carbon stable isotopes results are presented in δ notation in reference to Vienna Pee Dee Belemnite (VPDB), while the nitrogen stable isotopes are presented in δ notation in reference to air.

2.6 Eggshell thickness measurements

A common methodology for measuring eggshell thickness implies measuring the thickness of several fragments at 1/ the pointy end, 2/ the blunt end and, 3/ around the equator, which are used to calculate the mean thickness for each of these points (Sun et al., 2012). The eggshell

measurement methodology was based on methods from Birkhead et al., 2017; Miljeteig et al., 2012; Pirie-Hay & Bond, 2014; Sun et al., 2012.

Prior to eggshell thickness measurements, the eggshells were rinsed with tap water and the double-layered membrane was removed by using tweezers, spatulas and careful circular movements with gloved fingers to carefully and gradually rub off the membranes. Permanent markers were used to indicate or circle out the points of interest in cases where the egg would easily crack upon handling. After rinsing, the eggshells were left at room temperature for at least two weeks to dry up fully. For the Brünnich's guillemot eggs, the eggshells were frozen after the removal of their contents. Subsequently, the frozen eggshells were thawed and processed as outlined above.

The eggshell thickness was measured with a thickness gauge (Mitutoyo, ABSOLUTE Digimatic Indicator ID-CX, Series No. 547) to the nearest 0.01 mm. Five fragments from each point of interest – the blunt end, the pointy end, and the equator – were measured, and the mean thickness was used for each point. Areas exhibiting visual damage as well as those marked with a permanent marker were deliberately avoided to prevent any potential impact on the measurements.

The eggshells displayed varying degrees of damage after the freezing process. In certain cases, this damage adversely affected the precision of determining the points of interest, especially at the equator. Additionally, damage or obstruction to the eggshell itself was observed. When the extent of damage was substantial, one or several of the measuring areas were excluded.

2.7 Statistical analysis

The statistical analysis was conducted in R-studio (R-version 4.3.3, 2024-02-29). The chosen significance level for all statistical tests was 0.05. Due to low sample sizes, and the fact that several variables did not follow a normal distribution assessed by Shapiro-Wilk tests and visual examination of qqplots, non-parametric tests were used for statistical analysis.

The quality control of methodological differences in OC analysis, where two Brünnich's guillemot eggs (collected in 2020) analysed in 2020-2021 were re-analysed in 2023, revealed some differences in contaminant concentrations between the batches (Appendix C). Due to the

small sample size, the 2020 eggs were not excluded from analysis. Instead, for the two eggs involved in the quality control, the average contaminant level and lipid % from the two different batches were used.

For Brunnich`s guillemots, the biological variables measured in most eggs and thus used as biological variables were length, width, and lipid %. For the ivory gulls, the biological variables that were measured in most eggs and used as biological variables were weight of the frozen eggs and lipid %. The weight from three eggs that had leaked notable amounts of content were excluded from statistical analyses. First, we investigated the differences in biological variables within and among (i.e. lipid %) the species using non-parametric Mann-Whitney U tests (also known as Wilcoxon Rank-Sum test), which are less sensitive to small sample sizes. Mann-Whitney U tests were also used to investigate differences within- and among-species in stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) as well as contaminant concentrations. Finally, the relationships between biological variables, stable isotopes and OHCs were investigated with Spearman´s rank correlations.

Statistical analyses were performed on contaminants detected in at least 75 % of the samples, and detection rate was calculated separately for each species. Values below the detection limit for contaminants included in statistical analysis were assigned half the value of LOD. The eggs had been analysed for OCs in different batches, thereby having different LOD levels (Appendix C, Table A4). The LOD from the batch analysed for OCs in 2023 was used, as it was the largest group of eggs.

Contaminants were grouped together based on chemical groups; ΣCHLOR, ΣDDT, HCB, ΣHCH, ΣPCB, ΣPFCA and ΣPFSA as indicated by Table 2. As sumPFOS includes LC-MS outputs from both linear (PFOSlin) and branched PFOS-compounds, only sumPFOS was used for statistical analysis and hereafter referred to as PFOS. Spearman`s rank correlations were conducted to ensure that compounds exhibiting strong negative correlations were not grouped together.

In Brünnich's guillemot eggs, the analysis included Σ_6CHLOR (*cis*-Chlordane, heptachlor, mirex, *cis*-Nonachlor, *trans*-Nonachlor and oxychordane), Σ_4DDT (*o,p´*-DDE, *p,p´*-DDE, *o,p´*-DDT and *p,p´*-DDT), Σ_2HCH (a-HCH and b-HCH), Σ_{26}PCB (PCB-28/31, -47, -52, -66, -74, -99, -101, -105, -118, -123, -128, -138, -141, -149, -153, -156, -157, -167, -170, -180, -183, -

187, -189, -194, -206 and -209), Σ_6PFCA (PFOA, PFDA, PFNA, PFUnDA, PFDoDA, and PFTeDA) and Σ_1PFSA (PFOS). Most of the grouped compounds were positively correlated, although PCB-52 and PCB-141 had a negative association with most of the PCBs. However, the correlations were weak, and concentrations of PCB-52 and PCB-141 were among the lowest of all PCBs, and they were grouped together with the rest of the PCBs.

In ivory gull eggs, the analysis included Σ_6CHLOR (*cis*-Chlordane, heptachlor, mirex, *cis*-Nonachlor, *trans*-Nonachlor and oxychordane), Σ_6DDT (*o,p´*-DDD, *p,p´*-DDD, *o,p´*-DDE, *p,p´*-DDE, *o,p´*-DDT and *p,p´*-DDT), HCB, Σ_3HCH (a-HCH, b-HCH and g-HCH), Σ_{26}PCB (PCB-28/31, -47, -52, -66, -74, -99, -101, -105, -118, -123, -128, -138, -141, -149, -153, -156, -157, -167, -170, -180, -183, -187, -189, -194, -206 and -209), Σ_7PFCA (PFOA, PFDA, PFNA, PFUnDA, PFDoDA, PFTrDA and PFTeDA) and Σ_3PFSA (PFHxS, PFHpS and PFOS). None of the grouped compounds were negatively correlated.

Prior to statistical testing, contaminant concentrations were logarithmically (ln) transformed to reduce skewness and reduce the impact of outliers. When assessing intraspecies patterns of OHCs, the contaminants were compared in ng/g wet weight as there were no significant differences in lipid % between the colonies in any of the species. Due to the small sample size and short time span between collection years, year was not considered as a factor in the statistical analyses, and eggs from the same colonies were grouped together for statistical analysis (see Appendinx E for information about year differences in OHC concentrations in Brünnich's guillemot eggs collected from Kongsfjorden over three different years). Also, the two ivory gull eggs from Nordaustlandet mistakenly sampled from the same nest in 2022, were treated as sampled from individual nests during statistical analysis due to the small sample size.

When comparing contaminant concentrations between the two species, all eggs from each species were grouped together regardless of colony. Concentrations of the highly lipophilic OCs were transformed into ng/g lipid weight using *Equation 3*, as lipid % varied significantly between the species. All PFASs were analysed and compared in ng/g wet weight.

$$lipid\ weight_{(ng/g)} = wet\ weight_{(ng/g)} / (lipid_{(\%)} / 100) \qquad Equation\ 3$$

When investigating the effect of contaminant concentrations on eggshell thickness, all contaminants were analysed in ng/g wet weight. Due to damage or irregularities on the pointy

end for many of the eggs from both species, the measurements from the blunt end and the equator were the most consistent measurements and subsequently used as proxies of eggshell thickness in statistical analyses. All contaminant groups as well as single compounds known to affect eggshell thickness (i.e., *p,p´*-DDE, *p,p´*-DDT, mirex and oxychlordane) were tested against eggshell thickness with Spearman`s rank correlations. Spearman´s rank correlations were also used to investigate the relationships between eggshell thickness, biological variables and stable isotopes.

3 Results

3.1 Biological variables

The length, width and lipid content of Brünnich's guillemot eggs collected from Bjørnøya and Kongsfjorden, are presented in Table 3. Neither length, width nor lipid % differed significantly between the two colonies (Table 3).

The frozen weight and lipid content of ivory gull eggs collected from Nordaustlandet and Uyedineniya are presented in Table 4. Although the weight of the frozen eggs was significantly higher in eggs from Nordaustlandet compared to eggs from Uyedineniya, lipid % did not differ between the two colonies (Table 4).

Lipid % was significantly higher in Brünnich's guillemot eggs compared to ivory gull eggs (Mann-Whitney U test, $p < 0.001$).

***Table 3**: Mean and standard deviation (Mean ± SD) and range (Min – Max) for length (mm), width (mm) and lipid (%) of Brünnich's guillemot eggs from Bjørnøya, Svalbard (n=10) and Kongsfjorden, Svalbard (n=20). Number of eggs (n) used for each measurement is indicated. P-values from Mann-Whitney U tests contrasting the two colonies are listed.*

	Bjørnøya		**Kongsfjorden**		**All eggs**		**Bjørnøya vs. Kongsfjorden**
n (total)	5		15		20		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	Mean ± SD	Min-Max	p-value
Length (mm)	81.7 ± 1.3	80.4 – 83.2	82.2 ± 5.3	74.4 – 91.7	82.1 ± 4.6	74.4 – 91.7	0.69
n	5		15		20		
Width (mm)	51.1 ± 2.6	47.0 – 53.1	50.8 ± 1.8	47.0 – 53.5	50.9 ± 2.0	47.0 – 53.5	0.54
n	5		15		20		
Lipid (%)	13.0 ± 1.2	11.1 – 14.4	12.6 ± 1.5	10.1 – 14.6	12.7 ± 1.4	10.1 – 14.6	0.74
	5		15		20		

***Table 4**: Mean and standard deviation (Mean ± SD) and range (Min – Max) for weight (g) of frozen eggs and lipid (%) of ivory gull eggs from Nordaustlandet, Svalbard (n=3) and Uyedineniya, Russia (n=10). Number of eggs (n) used for each measurement is indicated. P-values from Mann-Whitney U tests contrasting the two colonies are listed.*

	Nordaustlandet		**Uyedineniya**		**All eggs**		**Nordaustlandet vs. Uyedineniya**
n (total)	3		10		13		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	Mean ± SD	Min-Max	p-value
Weight (g)	57.6 ± 1.9	55.6 – 59.4	50.2 ± 3.8	46.3 – 55.2	52.4 ± 4.8	46.3 – 59,4	**0.02**
n	3		7		10		
Lipid (%)	10.1 ± 0.7	9.5 – 10.8	9.4 ± 3.1	3.1 – 15.8	9.5 ± 2.7	3.1 – 15.8	0.22
n	3		10		13		

3.2 Stable isotopes

Signatures of $\delta^{13}C$ and $\delta^{15}N$ in Brünnich's guillemot eggs did not vary significantly between the Bjørnøya and Kongsfjorden colonies (Table 5, Figure 4). Moreover, $\delta^{13}C$ and $\delta^{15}N$ were not correlated with each other, nor with any of the biological variables (Spearman´s rank correlations, $p > 0.1$ in all cases).

Ivory gull eggs from Uyedineniya exhibited significantly lower levels of $\delta^{13}C$, and significantly higher levels of $\delta^{15}N$ compared to ivory gull eggs from Svalbard (Table 6, Figure 4). Furthermore, $\delta^{15}N$ showed a strong negative correlation with the weight of frozen eggs (Spearman rank´s correlation, $r_s = -0.81$, $p < 0.01$), while $\delta^{13}C$ was positively correlated with lipid % (Spearman rank´s correlation, $r_s = 0.65$, $p = 0.02$). $\delta^{13}C$ and $\delta^{15}N$ were not correlated with each other (Spearman´s rank correlation, $p > 0.2$).

When comparing the $\delta^{13}C$ and $\delta^{15}N$ signatures between Brünnich's guillemot eggs and ivory gull eggs, both varied significantly between the species. The Ivory gull eggs displayed significantly lower $\delta^{13}C$ values, and significantly higher $\delta^{15}N$ values compared to Brünnich's guillemot eggs (Table 7, Figure 4).

***Table 5**: Mean and standard deviation (Mean ± SD) and range (Min-Max) of stable carbon ($\delta^{13}C$ in ‰) and nitrogen ($\delta^{15}N$ in ‰) in eggs of Brunnich's guillemots breeding in Kongsfjorden (n=15) and Bjørnøya (n=5). P-values from Mann-Whitney U tests contrasting the two colonies are listed.*

	Bjørnøya		**Kongsfjorden**		**Bjørnøya vs. Kongsfjorden**
n	5		15		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	p-value
$\delta^{13}C$ ‰	-20.52 ± 0.11	-20.63 – -20.37	-20.75 ± 0.42	-21.47 – -20.12	0.50
$\delta^{15}N$ ‰	12.06 ± 0.72	11.14 – 13.03	12.06 ± 0.82	10.68 – 13.87	0.93

***Table 6**: Mean and standard deviation (Mean ± SD) and range (Min-Max) of stable carbon ($\delta^{13}C$ in ‰) and nitrogen ($\delta^{15}N$ in ‰) in eggs of ivory gulls breeding in Nordaustlandet (n=3) and Uyedineniya (n=10). P-values from Mann-Whitney U tests contrasting the two colonies are listed.*

	Nordaustlandet		**Uyedineniya**		**Nordaustlandet vs. Uyedineniya**
n	3		10		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	p-value

$\delta^{13}C$ ‰	-21.40 ± 0.18	-21.57 – -21.21	-21.81 ± 0.38	-22.66 – -21.49	**<0.05**
$\delta^{15}N$ ‰	15.09 ± 0.34	14.70 – 15.31	15.87 ± 0.41	15.45 – 16.74	**<0.01**

***Table 7**: Mean and standard deviation (Mean ± SD) and range (Min-Max) of stable carbon ($\delta^{13}C$ in ‰) and nitrogen ($\delta^{15}N$ in ‰) in eggs of Brunnich's guillemots (n=20) and ivory gull (n=13). P-values from Mann-Whitney U tests contrasting the two species are listed.*

	Br. guillemot		**Ivory gull**		**Br. guillemot vs. ivory gull**
n	20		13		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	p-value
$\delta^{13}C$ ‰	-20.69 ± 0.38	-21.47 – -20.12	-21.71 ± 0.38	-22.66 – -21.21	**<0.001**
$\delta^{15}N$ ‰	12.06 ± 0.78	10.68 – 13.87	15.69 ± 0.51	14.70 – 16.74	**<0.001**

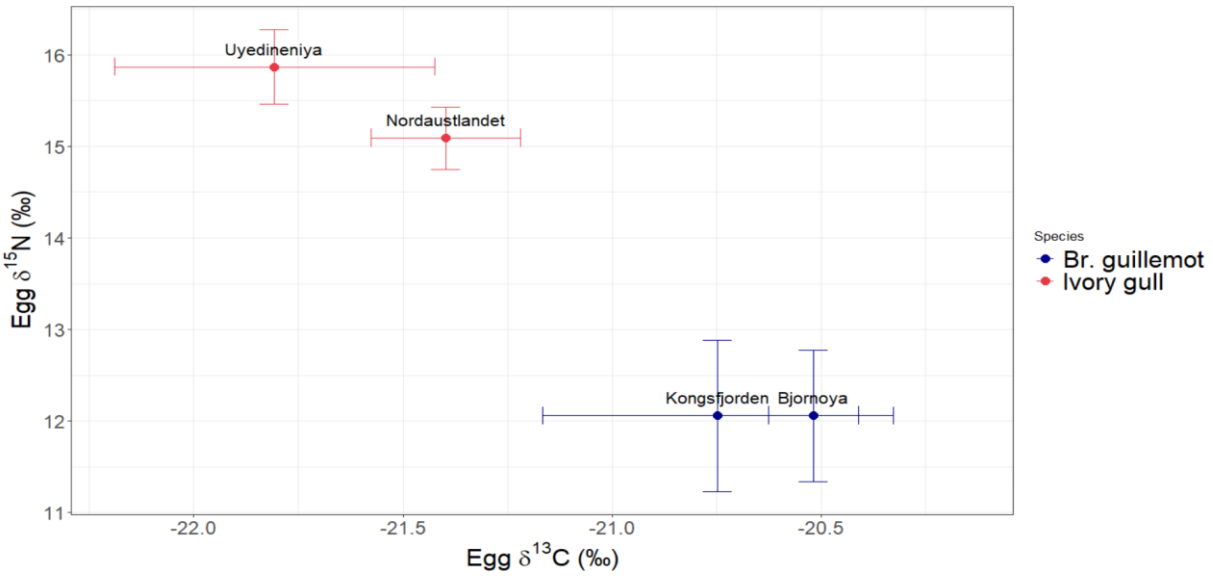

***Figure 4**: Mean ± SD (‰) of stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes in eggs of Brunnich's guillemots breeding in Kongsfjorden (n=15) and Bjørnøya (n=5), and of ivory gulls breeding in Nordaustlandet (n=3) and Uyedineniya (n=10).*

3.3 Contaminants

3.3.1 Contaminant concentrations and patterns in Brünnich's guillemot eggs

The analysis of OCs and PFASs detected a total of 47 compounds in 75 % or more of the samples (Appendix 1). The mean, SD and range of concentrations of contaminant-groups for both colonies are presented in ng/g wet weight in Table 8. Several contaminant groups varied significantly between the two colonies (Table 8). Namely, Σ_6CHLOR, Σ_2HCH and Σ_{26}PCB were significantly higher in the eggs from Kongsfjorden, and concentrations in these eggs ranged from being approximately 1.5 to 1.7 times higher compared to the eggs from Bjørnøya. Σ_6PFCA on the other hand, was significantly higher in the eggs from Bjørnøya being approximately 1.7 times compared to eggs from Kongsfjorden. Σ_4DDT was negatively correlated with the width of the eggs (Spearman`s rank correlation, $r_s = -0.54$, $p = 0.01$). The contaminant groups did not correlate with any other biological variable (i.e., length and lipid % of eggs) nor stable isotopes (Spearman´s rank correlations, $p > 0.1$ in all cases).

Contaminant concentration patterns are presented in Figure 5. OCs were the dominating contaminants, accounting for 81 % and 91 % of all OHCs detected in the eggs from Bjørnøya and Kongsfjorden, respectively. Across both colonies, Σ_4DDT dominated the profiles, accounting for 34 % (Bjørnøya) and 37 % (Kongsfjorden) of all OHCs. Of all compounds detected in the Brünnich's guillemot eggs, *p,p´*-DDE was the dominating compound accounting for 33 % and 37 % in the eggs from Bjørnøya and Kongsfjorden, respectively. The predominant PFAS was PFUnDA, accounting for 38 % (Bjørnøya) and 39 % (Kongsfjorden) of all PFASs. PFOS was the only detected PFSA in this species and accounted for 36 % of all PFASs in both colonies.

***Table 8**: Mean and standard deviation (Mean ± SD) and range (Min – Max) for Σ_6CHLOR, Σ_4DDT, HCB, Σ_2HCH, Σ_{26}PCB, Σ_6PFCA and Σ_1PFSA (in ng/g ww) in Brünnich's guillemot eggs from Bjørnøya, Svalbard (n=5) and Kongsfjorden, Svalbard (n=15). P-values from Mann-Whitney U tests contrasting the two colonies are listed.*

	Bjørnøya		**Kongsfjorden**		**Bjørnøya vs. Kongsfjorden**
n	5		15		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	p-value
Σ_6CHLOR	5.14 ± 1.35	3.32 – 6.86	8.54 ± 3.40	3.71 – 13.37	**0.04**
Σ_4DDT	63.14 ± 15.98	43.87 – 84.95	82.88 ± 18.33	59.85 – 128.84	0.07
HCB	30.55 ± 4.04	25.88 – 36.05	32.67 ± 8.01	16.42 – 47.12	0.44
Σ_2HCH	1.38 ± 0.20	1.15 – 1.66	2.42 ± 0.75	1.48 – 4.48	**<0.01**
Σ_{26}PCB	52.52 ± 16.42	30.41 – 72.18	76.66 ± 21.31	51.76 – 122.47	**0.02**
Σ_6PFCA	22.83 ± 3.43	17.68 – 26.84	13.66 ± 4.14	6.78 – 22.04	**<0.001**
Σ_1PFSA	12.68 ± 6.59	6.28 – 23.55	7.58 ± 2.17	4.96 – 12.65	0.05

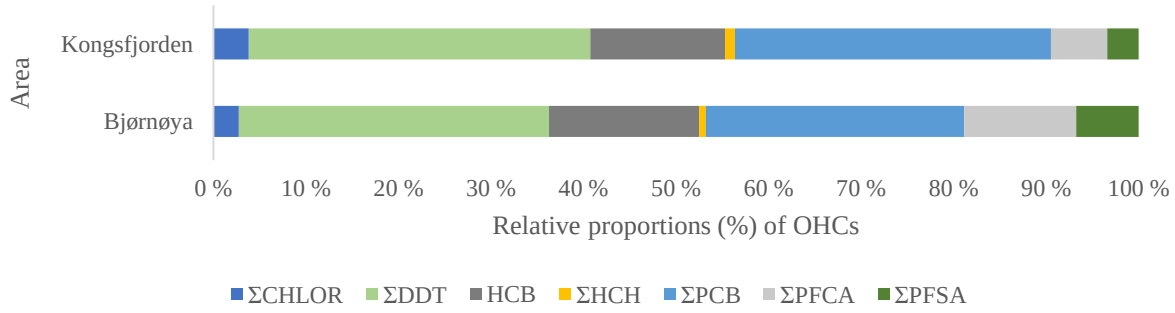

***Figure 5**: Concentration patterns (%) of OCs (Σ_6CHLOR, Σ_4DDT, HCB, Σ_2HCH and Σ_{26}PCB) and PFASs (Σ_6PFCA and Σ_1PFSA) in Brünnich's guillemot eggs from Bjørnøya (n=5) and Kongsfjorden (n=15). The proportions represent mean concentration of contaminants in ng/g wet weight.*

3.3.2 Contaminant concentrations and patterns in ivory gull eggs

The analysis of OCs and PFASs detected a total of 52 compounds in more than 75 % of the ivory gull eggs from Nordaustlandet and Uyedineniya (Appendix 2). The mean, SD and range of concentrations of Σ_6CHLOR, Σ_6DDT, HCB, Σ_3HCH, Σ_{26}PCB, Σ_7PFCA and Σ_3PFSA are presented in ng/g wet weight in Table 9. The two colonies showed similar concentrations, except for Σ_3HCH which was approximately 6.5 times higher in the eggs from Uyedineniya (Table 9). There was no evidence of correlations between the contaminant groups and frozen weight, lipid % nor stable isotopes (Spearman´s rank correlations, $p > 0.1$ in all cases).

Contaminant concentration patterns are presented in Figure 6. The OCs dominated the contaminant profiles, accounting for 98 % of detected contaminants in both ivory gull colonies. Σ_{26}PCB was the dominating contaminant group in eggs from both Nordaustlandet and Uyedineniya, accounting for 49 % and 53 % of all contaminants, respectively. PCB-153 was the dominating PCB in both colonies. Overall, the predominant compound was *p,p´*-DDE, accounting for 38 % and 34 % of all compounds detected in eggs from Nordaustlandet and Uyedineniya, respectively. Among PFASs, PFOS was the predominant compound, accounting for 53 % of all PFASs in eggs from Nordaustlandet, and 63 % of all PFASs in eggs from Uyedineniya.

***Table 9**: Mean and standard deviation (Mean ± SD) and range (Min – Max) for Σ_6CHLOR, Σ_6DDT, HCB, Σ_3HCH, Σ_{26}PCB, Σ_7PFCA and Σ_3PFSA (in ng/g ww) in ivory gull eggs from Nordaustlandet, Svalbard (n=3) and Uyedineniya, Russia (n=10). P-values from Mann-Whitney U tests contrasting the two colonies are listed.*

	Nordaustlandet		**Uyedineniya**		**Nordaustlandet vs. Uyedineniya**
n	3		10		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	p-value
Σ_6CHLOR	278.90 ± 251.90	127.21 – 569.67	224.81 ± 129.25	58.73 – 538.74	0.81
Σ_6DDT	1362.28 ± 680.42	845.22 – 2133.11	1044.29 ± 357.82	369.60 – 1669.42	0.57
HCB	41.76 ± 12.73	30.96 – 55.80	47.19 ± 11.75	20.82 – 61.64	0.57
Σ_3HCH	6.99 ± 5.24	3.95 – 13.04	45.25 ± 27.16	13.04 – 94.95	**<0.01**
Σ_{26}PCB	1673.16 ± 562.14	1221.55 – 2302.74	1602.14 ± 619.62	475.11 – 2528.31	1.00
Σ_7PFCA	36.30 ± 23.98	15.57 – 62.56	21.99 ± 9.23	9.73 – 42.55	0.29
Σ_3PFSA	42.25 ± 26.79	13.69 – 66.83	39.44 ± 17.65	18.85 – 72.86	1.00

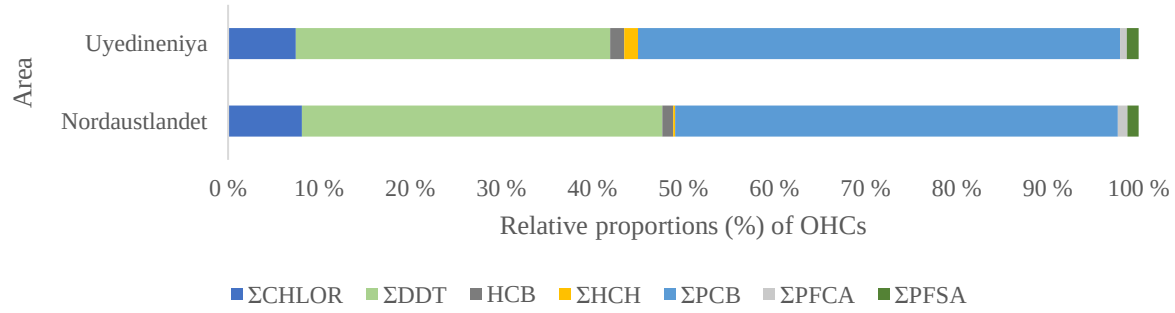

***Figure 6**: Concentration patterns (%) of OCs (Σ_6CHLOR, Σ_6DDT, HCB, Σ_3HCH and Σ_{26}PCB) and PFASs (Σ_7PFCA and Σ_3PFSA) in ivory gull eggs from Nordaustlandet (n=3) and Uyedineniya (n=10). The proportions represent mean concentration of contaminants in ng/g wet weigh.*

3.3.3 Comparison of contaminant concentrations and patterns in eggs of Brünnich's guillemot and ivory gull

The mean, SD and range of OHC concentrations of both species are listed in Table 10. The concentrations of all OC groups (ΣCHLOR, ΣDDT, HCB, ΣHCH and ΣPCB (ng/g lipid weight) were significantly higher in the ivory gull eggs, with all OCs combined being 21 times higher compared to Brünnich's guillemot eggs (Table 10). For ΣCHLOR and ΣPCB, the same six organochlorine pesticides and the same 26 PCB compounds were detected in 75 % or more of the samples. For ΣDDT and ΣHCH, the number of contaminants detected in each species varied. Four types of DDTs were detected in Brünnich's guillemot eggs, while all six types were detected in the ivory gull eggs. For HCHs, two compounds were detected in Brünnich's guillemot eggs, while all three compounds were detected in the ivory gull eggs. In Brünnich's guillemot eggs, the dominating group of OCs was Σ_4DDT, while Σ_{26}PCB was the dominating group in the ivory gull eggs (Figure 7).

Both ΣPFCA and ΣPFSA concentrations were significantly higher in the ivory gull eggs, with all PFASs combined being over 2.6 times higher in ivory gull eggs compared to Brünnich's guillemot eggs. Six compounds of PFCAs were detected in 75 % or more of the Brünnich's guillemot eggs, while seven compounds were detected in the ivory gull eggs. Only one compound of PFSA was detected in the Brünnich's guillemot eggs, while three compounds were detected in the ivory gull eggs. In Brünnich's guillemot eggs, the dominating group of PFAS was Σ_6PFCA, while Σ_3PFSA was the dominating group in the ivory gull eggs (Figure 8).

***Table 10**: Mean and standard deviation (Mean ± SD) and range (Min – Max) for OCs (ng/g lipid weight) and PFASs (ng/g wet weight) detected in eggs of Brünnich's guillemots (n=20) and ivory gulls (n=13). Brünnich's guillemots: Σ_6CHLOR, Σ_4DDT, HCB, Σ_2HCH, Σ_{26}PCB, Σ_6PFCA and Σ_1PFSA. Ivory gulls: Σ_6CHLOR, Σ_6DDT, HCB, Σ_3HCH, Σ_{26}PCB, Σ_7PFCA and Σ_3PFSA. P-values from Mann-Whitney U tests contrasting the two colonies are listed.*

	Brünnich's guillemot		**Ivory gull**		**Br. guillemot vs. ivory gull**
n	20		13		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	p-value
ΣCHLOR	61.14 ± 27.95	28.16 – 120.33	2503.16 ± 1486.49	1125.81 – 5972.28	**<0.001**
ΣDDT	623.60 ± 195.47	345.95 – 1274.62	11924.05 ± 3859.24	6862.04 – 19710.35	**<0.001**
HCB	255.94 ± 65.99	137.87 – 429.19	498.28 ± 107.19	305.95 – 662.51	**<0.001**
ΣHCH	17.42 ± 7.92	7.95 – 44.30	395.58 ± 302.16	39.38 – 1052.58	**<0.001**
ΣPCB	565.16 ± 207.91	228.14 – 1211.54	17252.67 ± 5593.32	10999.78 – 28028.17	**<0.001**

ΣPFCA	15.95 ± 5.63	6.78 – 26.84	25.29 ± 14.11	9.73 – 62.56	**0.02**
ΣPFSA	8.86 ± 4.21	4.96 – 23.55	40.09 ± 18.83	13.69 – 72.86	**<0.001**

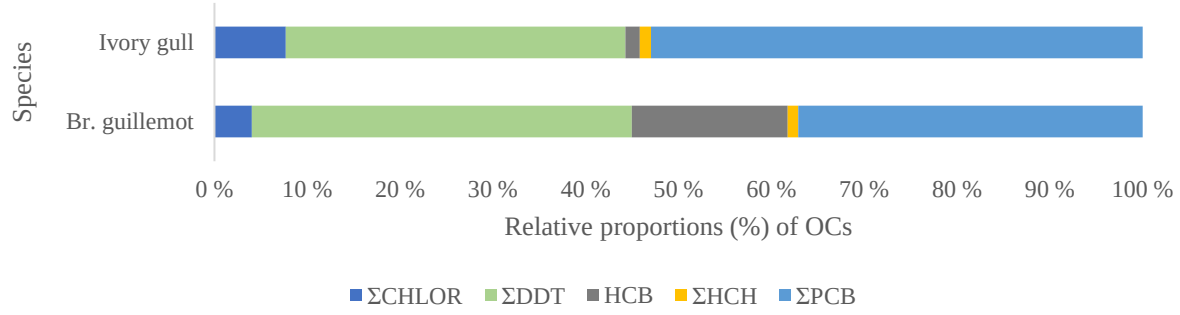

***Figure 7**: Concentration patterns (%) of OCs in Brünnich's guillemot eggs (n=20) and ivory gull eggs (n=13). Brünnich's guillemot: Σ_6CHLOR, Σ_4DDT, HCB, Σ_2HCH and Σ_{26}PCB. Ivory gull: Σ_6CHLOR, Σ_6DDT, HCB, Σ_3HCH and Σ_{26}PCB. The proportions represent mean concentration of contaminants in ng/g lipid weight.*

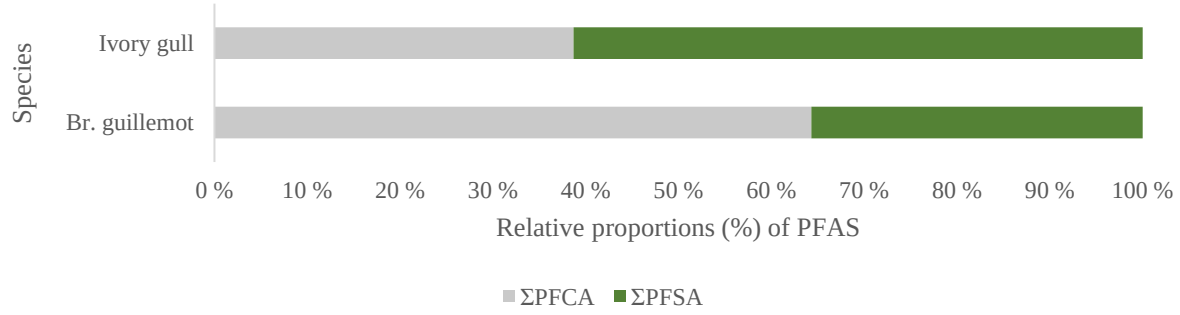

***Figure 8**: Concentration patterns (%) of PFASs in Brünnich's guillemot eggs (n=20) and ivory gull eggs (n=13). Brünnich's guillemot: Σ_6PFCA and Σ_1PFSA. Ivory gull: Σ_7PFCA and Σ_3PFSA. The proportions represent mean concentration of contaminants in ng/g wet weight.*

3.4 Response variable – eggshell thickness

The eggshell thickness did not vary between the colonies within each species (Mann-Whitney U test, $p > 0.1$), and eggshell thickness from the eggs for the different colonies can be found in Appendix F, while and the average eggshell thickness for the two species is listed in Table 11.

Eggshell thickness did not correlate with biological variables (i.e., egg measurements and lipid %) nor with stable isotopes in either of the species (Spearman´s rank correlations, $p > 0.06$ in all cases).

There was no statistical evidence of significant correlations between eggshell thickness and contaminant concentrations in Brünnich's guillemot eggs or in ivory gull eggs (Spearman´s rank correlations, $p > 0.07$ in all cases). In ivory gull eggs however, oxychlordane and eggshell thickness tended to be negatively correlated (blunt end: $r_s = -0.54$, $p = 0.07$; equator: $r_s = -0.53$, $p = 0.08$; Figure 9). Likewise, there was a negative, yet not significant, correlation between Σ_3PFSA and equatorial eggshell thickness ($r_s = -0.52$, $p = 0.08$; Figure 9).

Table 11*: Mean, SD and range (Min-Max) of eggshell thickness (mm) at the blunt end and the equator in eggs of Brünnich's guillemots and ivory gulls. Number of eggs (n) used for each measurement is indicated.*

	Brünnich's guillemot		**Ivory gull**	
	Mean ± SD	**Min-Max**	**Mean ± SD**	**Min-Max**
Blunt end	0.37 ± 0.50	0.28 – 0.45	0.19 ± 0.02	0.17 – 0.24
n	17		12	
Equator	0.49 ± 0.04	0.43 – 0.54	0.23 ± 0.02	0.20 – 0.26
n	17		12	

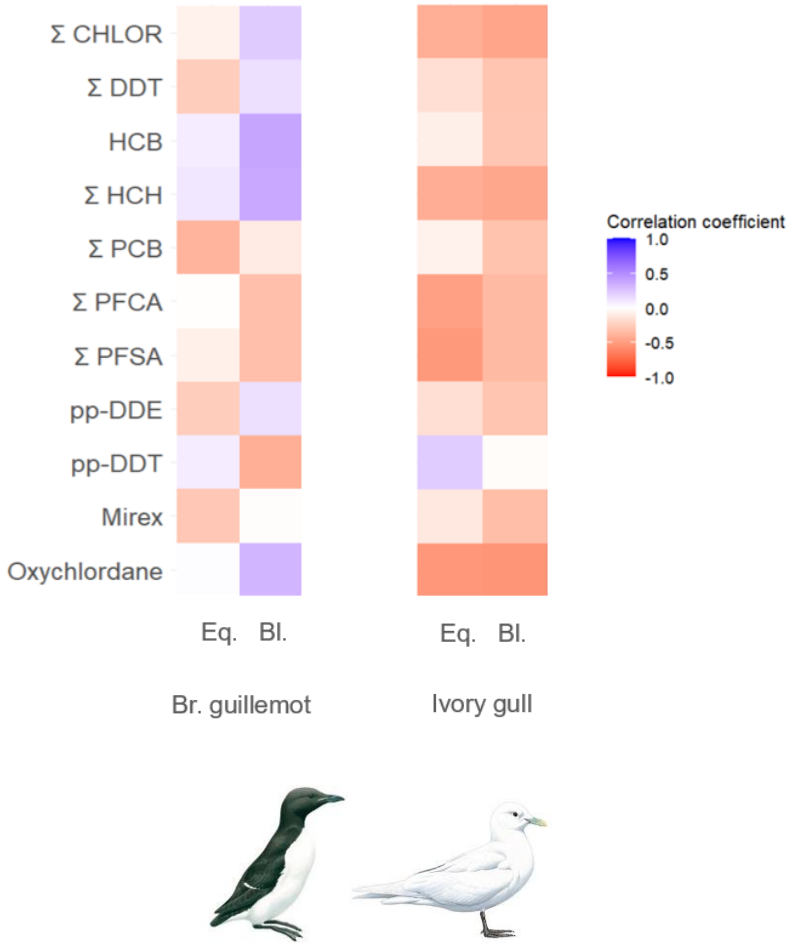

***Figure 9**: Spearman´s rank correlation matrix for correlations between contaminants and eggshell thickness of the equator (Eq.) and blunt end (Bl.) in eggs of Brünnich's guillemots (n=17) and ivory gulls (n=12). Brünnich's guillemots: Σ_6CHLOR, Σ_4DDT, HCB, Σ_2HCH, Σ_{26}PCB, Σ_6PFCA and Σ_1PFSA. Ivory gulls: Σ_6CHLOR, Σ_6DDT, HCB, Σ_3HCH, Σ_{26}PCB, Σ_7PFCA and Σ_3PFSA. Colour gradient indicates correlation coefficient ($r_{s)}$ where a value of 1 indicates a perfect positive correlation, and a value of -1 indicates a perfect negative correlation. None of the correlations displayed are significant (Spearman´s rank correlations, $p > 0.07$ in all cases).*

4 Discussion

This study reported the concentrations and patterns of OCs and PFASs in eggs of two different Arctic seabirds that roam at different latitudes and occupy different trophic levels, namely the Brünnich's guillemot and the ivory gull. The Brünnich's guillemot eggs were collected from two locations on Svalbard within the Norwegian Arctic, while the ivory gull eggs were collected from a location in the Norwegian Arctic as well as in the Russian Arctic. In Brunnich´s guillemot eggs, regional differences were reported for both OCs and PFASs, where OC groups were higher in the eggs from Kongsfjorden, and PFASs were higher in the eggs from Bjørnøya. In ivory gull eggs on the other hand, only HCH compounds differed between the sampling locations, with higher levels in the eggs from Russia compared to eggs from Norway. As predicted, ivory gull eggs showed 21 times higher levels of OCs compared to Brunnich´s guillemot eggs. The two species also displayed different levels of PFASs, with 2.6 times higher levels in the ivory gull eggs. Furthermore, stable isotopes of carbon and nitrogen differed between the two species, as expected from their different trophic levels and diets. We investigated both species for contaminant-induced eggshell thinning and reported no correlations between eggshell thickness and contaminants in either of the species. Although this was expected for the Brünnich's guillemot, the results contradicted our predictions for the ivory gull. These results must however be treated with caution due to the small sample size.

4.1 Contaminant concentrations and patterns

Across numerous field studies on contaminants in bird species, there are inconsistencies in reporting OC concentrations in wet weight or lipid weight. As OCs are highly lipophilic, many studies report OCs in lipid weight. However, analysis of OCs in wet weight allows for investigating relative proportions of OCs compared to PFASs. This study used OCs in wet weight for intraspecies comparisons, while using lipid weight for interspecies comparisons.

4.1.1 OHCs in Brünnich's guillemot eggs

The levels of several contaminant groups varied between the Brünnich's guillemot eggs collected in Bjørnøya and Kongsfjorden. The eggs from Kongsfjorden exhibited significantly

higher concentrations of several groups of OCs (Table 8). Namely, concentrations of Σ_6CHLOR, Σ_2HCH and Σ_{26}PCB were 1.5 to 1.7 times higher in the eggs from Kongsfjorden compared to Bjørnøya. PFASs on the other hand, were higher in the eggs from Bjørnøya, and levels of Σ_6PFCA were approximately 1.7 times higher in these eggs (Table 8).

Neither δ^{13}C nor δ^{15}N differed between the two colonies (Table 5), indicating minimal variances in diet. Although OHC concentrations have been shown to be highly linked to the diet (Letcher et al., 2010), we found no correlations between contaminant levels and stable isotope signatures, excluding diet as a driver of the observed differences in OHC concentrations between the colonies. These differences could be due to exposure to different concentrations of contaminants in the overwintering and breeding areas. Alternatively, an explaining factor could be the different years of sampling from the two colonies. Furthermore, the eggs included in this study were analysed for OCs in different batches over different years, and the lab procedures were performed by different personnel. Some differences in OC concentrations were observed between the two batches of analysis (Appendix C). However, the lab at NILU holds international standards, and the results were verified in accordance with their verification methods.

The OCs dominated the contaminant profiles in the Brünnich's guillemot eggs, with Σ_4DDT as the dominating contaminant group (Figure 5), and *p,p´*-DDE, a metabolite of DDT, as the predominant compound. This was expected due to the widely use of DDT in the mid- to late-1900s and the persistency of the compound. Although the use of DDT is strictly regulated, it is still used in certain regions to fight malaria (Stockholm Convention, 2019b). Consequently, DDT and its metabolites continue to be predominant compounds detected in the Arctic (Borgå et al., 2007; Norwegian Polar Institute, 2022a, 2022b). The dominating compound of PFASs was PFUnDA, followed by PFOS. Both compounds have been reported to dominate in other Arctic seabird species as well (Costantini et al., 2019).

The contaminant levels did not appear to be related to the width and length of the eggs, except for Σ_4DDT, which was negatively correlated with the width of the eggs. A previous study found that glaucous gull (*Larus hyperboreus*) females with higher concentrations of contaminants laid smaller eggs (Verboven et al., 2009). Alternatively, another factor explaining the observation could be the presence of replacement eggs in the sample size. A study on the closely related

common guillemot (*Uria aalge*), revealed that replacement eggs were smaller and had significantly higher levels of DDT and PCBs compared to the first egg (Bignert et al., 1995). As the Brünnich's guillemots were not monitored prior to sampling the eggs, this study has not considered whether the eggs collected were the first or a replacement egg, although this could explain the observed correlation between Σ_4DDT and the width.

The Brünnich's guillemot is a commonly monitored species in relation to contaminants (MOSJ; https://mosj.no/en/). Levels of most OHCs have shown decreasing trends in the species over the last decades (Norwegian Polar Institute, 2022a, 2022b, 2022c, 2022d). The levels reported in this study support the decrease of several major OCs. PFOS and PFOA on the other hand, showed increasing concentrations over the last decade. Accordingly, PFASs have shown more mixed trends in the Arctic compared to legacy POPs (Bianchini et al., 2022; Rigét et al., 2019).

4.1.2 OHCs in ivory gull eggs

The ivory gull eggs only displayed significant differences in Σ_3HCH between colonies, with higher concentrations in the eggs from Russia (Table 9), where b-HCH was the dominating compound. This did not support our predictions based on earlier studies which have reported significant differences in several major contaminants between ivory gull eggs from Svalbard and the Russian Arctic (Miljeteig et al., 2007; Miljeteig et al., 2009). The contaminant profiles in the ivory gull were clearly dominated by Σ_{26}PCB, followed by Σ_6DDT (Figure 6), with *p,p´*-DDE as the dominating compound. Among PFASs, PFOS was the dominating compound, followed by PFUnDA.

The signatures of δ^{13}C and δ^{15}N varied significantly between the colonies (Table 6), indicating that female ivory gulls from Svalbard and Russia likely fed at different trophic levels and had different diets. As the eggs from Uyedineniya exhibited higher values of δ^{15}N and lower values of δ^{13}C, this suggested that ivory gulls from Uyedineniya fed at a higher trophic position, and their diet was more coupled to the pelagic ecosystem (Hobson & Welch, 1992; Hobson et al., 1994). However, our study did not observe marked differences in OHC concentrations among colonies, which can likely be attributed to the small sample size. When collecting eggs from vulnerable and declining bird species, the sample size is decided with caution. In addition, the sampling of ivory gull eggs on Svalbard imposed challenges due to bad weather and their small

and scattered colonies, resulting in a smaller sample size than planned. For instance, the three ivory gull eggs from Svalbard do not offer a strong statistical power.

In addition, the OHC concentrations could have been impacted by the state of the eggs. Namely, while the ivory gull eggs from Nordaustlandet were intact, most eggs from Uyedineniya were broken and had leaked some of their content (mostly egg whites) upon the freezing process, as supported by their lower weight. Three eggs from Uyedineniya broke upon sampling and were severely damaged with extensive leakage. While the weight of these three frozen eggs was excluded from analysis, their lipid % was included to transform OC concentrations from wet weight to lipid weight and allow for interspecies comparison. However, the impact of egg leakage was likely minimal since lipid % did not vary between the colonies. $\delta^{15}N$ had a negative correlation with the weight of frozen eggs, and $\delta^{13}C$ were negatively correlated with lipid % in the eggs, which also could be explained by the loss of egg content.

Unlike Brünnich's guillemots, the levels of OHCs are not monitored on a regular basis in eggs of ivory gulls breeding in the Russian and Norwegian Arctic. This is the second study reporting contaminant levels in ivory gull eggs from these areas. When comparing the concentrations of several major OCs between eggs collected from Uyedineniya in 2019 (reported in this study) and eggs collected from the Domashny colony in 2006 (reported in Miljeteig et al., 2007; 2009), most OCs have shown a decrease over the last decade (Table 12). Namely, oxychlordanes, *p,p´*-DDE, HCB and PCB-153 have decreased by 5-29 % in ivory gull eggs from the Russian Arctic. Likewise, egg concentrations of PFASs have decreased in the Russian Arctic by 16 % for PFUnDA and 42 % for PFOS. The most prominent decrease was reported for *p,p´*-DDE, with a reduction of 97 %. These observations are in line with the general decreasing trends of legacy POPs in the Arctic (AMAP, 2014; Bianchini et al., 2022; Rigét et al., 2019). The exception was an increase of 59 % in b-HCH in eggs collected from the Russian Arctic. This was not in accordance with the decreasing trend of b-HCH observed in the Arctic over the last decades (Yang et al., 2023). While b-HCH was eliminated from intentional production by the Stockholm convention, this compound is still released as a by-product (Stockholm Convention, 2019d). b-HCH is mainly transported through ocean currents and rivers due to its high partition to water (Yang et al., 2023). As Uyedineniya is more closely located to large rivers that run into the Kara Sea from mainland Russia compared to the Russian ivory gull colonies sampled in 2006, this could explain the difference between the colonies. Release of trapped contaminants in

permafrost and ice following warming of the Arctic (AMAP, 2021; Borgå et al., 2022; Hung et al., 2022) could also explain the increase in b-HCH observed in the ivory gull eggs sampled in 2019.

Furthermore, when comparing the levels of OHCs between the ivory gull eggs sampled from locations within the Svalbard Archipelago in 2021-2022 and 2007, there has been a decreasing trend (Table 12). The sample size from Nordaustlandet in 2021-2022 is however too small to draw any firm conclusions.

The ivory gull eggs from Uyedineniya were not determined as first or second egg in the clutch. It is worth noting that the two ivory gull eggs mistakenly sampled from the same nest in Nordaustlandet 2022, exhibited notably different levels of contaminants. Remarkably, one of the two eggs had some of the highest levels of all ivory gull eggs included in this project. Although one cannot draw any conclusions based on the comparison of these two eggs, the intraclutch variability is supported by a study on glaucous gulls reporting variations in contaminant concentrations among eggs of the same clutch, with increase from the first to the last egg (Verreault et al., 2006). Future studies should further investigate the intraclutch variability in contaminant concentrations. Furthermore, development stage was not assessed in the eggs. As eggs tend to lose water during incubation (Birkhead, 2016), this may impact the result.

Table 12: Mean concentration and SD (ng/g wet weight) of different OHCs detected in ivory gull eggs in this study and in eggs sampled in 2006-2007 reported by Miljeteig et al., (2007; 2009). Eggs from both studies are collected from various areas within the Norwegian (Svalbard) and Russian Arctic. Number of eggs in each location is indicated (n).

Area	**Year**	**Oxychlordane**	***p,p´*-DDE**	***p,p´*-DDT**	**HCB**	**b-HCH**	**PCB-153**	**PFUnDA**	**PFOS**
Svenskøya, Svalbard (n=10)	2007	156 ± 69	1510 ± 700	25.6 ± 12.5	62.1 ± 20.7	11.4 ± 3.5	957 ± 346	12.1 ± 5.2	72.6 ± 30.5
Nordaustlandet, Svalbard (n=3)	2021-2022	76 ± 48	1324 ± 632	9.5 ± 11.4	41.8 ± 12.7	6.9 ± 5.1	527 ± 150	14.5 ± 11.9	41.5 ± 26.2
Cape Klyuv, Russia (n=7)	2006	141 ± 34	1360 ± 340	39.9 ± 19.1	59.1 ± 17.4	15.4 ± 8.7	768 ± 172	10.8 ± 4.7	56.2 ± 29.4
Domashny, Russia (n=12)	2006	134 ± 71	1460 ± 1930	23.7 ± 7.31	62.4 ± 15.9	28.4 ± 6.9	610 ± 449	12.0 ± 5.2	66.5 ± 32.3
Nagurskoe, Russia, (n=6)	2006	287 ± 98	2910 ± 910	40.1 ± 5.7	97.4 ± 11.2	18.1 ± 6.9	1410 ± 420	12.9 ± 7.0	55.8 ± 23.6
Uyedineniya, Russia (n=10)	2019	113 ± 60	1043 ± 357	0.6 ± 0.4	47.2 ± 11.8	45.1 ± 27.1	579 ± 220	10.0 ± 4.3	38.7 ± 17.3

4.1.3 Inter-species comparison of contaminants

As predicted, the levels of OHCs differed between the species, with OC levels being over 21 times higher in ivory gull eggs compared to Brünnich's guillemot eggs (Table 10). Indeed, ivory gulls are among the most heavily contaminated species in the Arctic (Miljeteig et al., 2009). Both species had contaminant profiles dominated by ΣDDT and ΣPCB, although Σ_4DDT dominated the Brünnich's guillemot profiles and Σ_{26}PCB dominated the ivory gull profiles (Figure 7). Both groups of compounds are predominant in the Arctic (Borgå et al., 2007; Melnes et al., 2017; Norwegian Polar Institute, 2022a, 2022b). Furthermore, *p,p´*-DDE was the predominant compound in both species.

Also, PFASs varied between the species and were over 2.6 times higher in ivory gull eggs compared to Brünnich's guillemot eggs, even though PFASs accounted for a higher portion of all contaminants detected in the Brünnich's guillemot eggs (Table 10, Figure 8). The observed difference is supported by an earlier study which reported that the levels of PFASs in ivory gulls were comparable to those found in seabird species foraging at lower trophic levels (Miljeteig et al., 2009). In Brünnich's guillemot eggs, the predominant group of PFASs was Σ_6PFCA, with PFUnDA as the predominant compound. In ivory gull eggs, the predominant group of PFASs was Σ_3PFSA, with PFOS as the predominant compound. Overall PFUnDA and PFOS were the two dominating compounds of PFASs in both species.

The ivory gulls displayed higher levels of contaminants, likely because they feed at a higher trophic level. As predicted, δ^{15}N values in ivory gull eggs were significantly higher compared to Brünnich's guillemot eggs (Figure 7). As δ^{15}N displays an enrichment of 3-4 ‰ with each trophic level (Hobson & Welch, 1992), the species feed at two different trophic levels, with the difference between the two colonies measured at approximately 3.6 ‰. Accordingly, a previous study investigating the diet of Brünnich's guillemot and ivory gulls in the 1980s, reported that the diet of Brünnich's guillemots was dominated by the pelagic amphipod *Parathemisto*, while the diet of ivory gulls was dominated by polar cod (Mehlum & Gabrielsen, 1993). Ivory gulls exhibited higher levels of δ^{13}C compared to Brünnich's guillemots, linking the ivory gull to a more pelagic diet reflected by their habitat.

PFASs has been found to be deposited in ice cores, meltwaters and ponds in the Arctic, emphasising the role of meltwater in the distribution of PFASs (Hartz et al., 2023; Yeung et al.,

2017). The ivory gulls, who roam in ice-filled waters, could be exposed to these sources of PFASs, partly explaining their higher levels of PFASs compared to the Brünnich's guillemots.

The amount of lipid invested into the eggs differ between bird species, and gull species typically invest less lipids into their eggs (Drouillard & Norstrom, 2001). The present study confirmed that Brünnich's guillemots invested a higher proportion of lipid into their eggs compared to ivory gulls. As OCs are highly lipophilic, the degree of lipid % in the eggs and maternal transfer of contaminants could be linked. Furthermore, the two different species have different habitats, as the ivory gull ranges in higher latitudes than the Brünnich's guillemot (Anker-Nilssen et al., 2000). PCBs have shown a decrease with increasing latitude (Sobek & Gustafsson, 2004). Nevertheless, the ivory gull had notable higher concentrations of all analysed contaminant groups.

4.2 Eggshell thickness

We reported no correlation between eggshell thickness and contaminants in either of the species. Although this was expected for the Brünnich's guillemot eggs based on their historical lower OHC concentrations, this contradicted our prediction of contaminant-induced eggshell thinning in ivory gulls. In the latter species, an eggshell thinning of 7-17 % has previously been recorded as well as associations between eggshell thickness and several PCBs and OCPs (Miljeteig et al., 2012). The contaminant levels measured in this study may be below the thresholds to induce eggshell thinning. The Brünnich's guillemot is likely not vulnerable to contaminant induced eggshell thinning due to their notable lower concentrations of contaminants, and contaminant levels measured in ivory gull eggs in this study were lower than those previously reported by Miljeteig et al (2007; 2009).

When handling the ivory gull eggs, several eggs appeared fragile. Both oxychlordane and Σ_3PFSA showed notable negative associations with eggshell thickness, although the correlations were not significant (Figure 9). Oxychlordane has previously been linked to eggshell thinning (Wiemeyer et al., 1984), while studies on associations between PFASs and eggshell thinning are scarce. However, Miljeteig et al. (2012) found no evidence of a relationship between PFASs and eggshell thickness in ivory gulls. Finally, the thickness of

eggshells did not correlate with any egg measurements (i.e., width and length in Brünnich's guillemots, and weight of frozen eggs in ivory gulls) nor stable isotopes.

Across various studies reporting eggshell thickness in different species, there are methodological inconsistencies regarding the removal of the membranes. Eggs have two membranes, the outer membrane that is in contact with the eggshell, and the inner membrane that is in contact with the content of the egg. While some studies measure the thickness of eggshells with both membranes still attached (less time-consuming), others remove the inner membrane or both membranes, as done in the current study to provide the most accurate measurements. Differences in methodologies could therefore contribute to inconsistencies between studies. However, although Miljeteig et al. (2012) reported eggshell thickness of ivory gulls with the outer membrane and we reported thickness of bare shells, our results support some degree of eggshell recovery in this species as we estimated the outer membrane to be about 0.04 – 0.08 thick in the species (data not shown) (Table 13).

Table 13: Mean and SD of equatorial eggshell thickness (mm) measured in ivory gull eggs in this study and in eggs sampled in 2006-2007 reported by Miljeteig et al., (2012). Eggs from both studies are collected from various areas within the Norwegian (Svalbard) and Russian Arctic. Number of eggs in each location is indicated (n). The eggshell measurements from Nordaustlandet and Uyedineniya is performed on eggshell only, while eggshell measurements from Svenskøya, Cape Klyuv, Domashny and Nagurskoe are performed on eggshells with outer membranes.

Area	**Year**	**Eggshell thickness**
Svenskøya, Svalbard (n=10)	2007	0.25 ± 0.02
Nordaustlandet, Svalbard (n=3)	2021-2022	0.24 ± 0.03
Cape Klyuv, Russia (n=7)	2006	0.26 ± 0.05
Domashny, Russia (n=12)	2006	0.25 ± 0.01
Nagurskoe, Russia, (n=6)	2006	0.23 ± 0.01
Uyedineniya, Russia (n=10)	2019	0.23 ± 0.02

Eggshell thinning of 17-20 % has been linked to population declines (Hickey & Anderson, 1968; Walker et al., 2012). The ivory gull has been experiencing rapid population declines

(Gilchrist & Mallory, 2005; Strøm et al., 2020), and although studies on percentage eggshell thinning leading to population declines for gull species are scarce, eggshell thinning in the species has been hypothesized to partly explain the population declines (Miljeteig et al., 2012). This study reported high levels of OHCs in the ivory gull, and the observed fragile eggshells of the species may impose challenges for the species. While decreasing contaminant concentrations and a potential recovery in eggshell thickness offer better perspectives for the ivory gull, the ongoing warming of the Arctic and decreasing sea ice are threatening the habitat of the ivory gull (Spencer et al., 2014; Vinnikov et al., 1999).

5 Conclusion

This study reported the concentrations and patterns of OCs and PFASs in eggs of Brünnich's guillemots and ivory gulls. While Brünnich's guillemots showed regional differences in several contaminant groups between two colonies within the Norwegian Arctic, ivory gulls exhibited fewer regional differences between two colonies in the Norwegian and Russian Arctic. As predicted, the ivory gull eggs had levels of OCs and PFASs over 21 and 2.6 times higher than the levels reported in Brünnich's guillemot eggs, respectively. The contaminant profiles in both species were dominated by OCs, with ΣDDT and ΣPCBs as predominant contaminant groups. Furthermore, *p,p´*-DDE was the predominant compound. Among PFASs, PFUnDA and PFOS were the dominating compounds in both species.

The interspecies differences in contaminant concentrations were likely explained by their diet, as the ivory gull exhibited elevated values of $\delta^{15}N$, positioning them higher up in the food chain compared to Brünnich's guillemots. Variations in $\delta^{13}C$ values among the two species indicated that the ivory gull is more connected to the pelagic ecosystem.

There was no evidence of statistically significant correlations between eggshell thickness and contaminants in either of the species, although oxychlordane and Σ_3PFSA displayed negative associations with eggshell thickness in the ivory gull. In Brünnich's guillemots, the contaminant levels are likely below the threshold for contaminant-induced eggshell thinning. In the ivory gulls on the other hand, high levels of OHCs were detected, and the lack of evidence of eggshell thinning could be due to the low sample size, as eggshell thinning has been reported in the species in earlier studies (Miljeteig et al., 2012). However, when comparing eggshell thickness reported in this study to Miljeteig et al., 2012, there are indications of some degree of recovery in eggshell thickness. Eggshell thickness in ivory gulls needs to be investigated further to confirm the potential recovery. Additionally, the relationship between eggshell thinning and PFASs should also be investigated further.

Both species showed declines in several major OHCs over the last decade, although PFASs have increased in the Brünnich's guillemots. As the Brünnich's guillemot and the ivory gull have had population declines over the last decades, the OHCs declines are a positive development for the species. Climate change and a warming Arctic is threatening the habitat of

the Arctic seabird species, and contaminants add to the multiple stressors experienced by these species.

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Appendix

Appendix A: OHC concentrations in Brünnich's guillemot eggs

***Table A1**: Mean, standard deviation (SD), median and range (Min-Max) of OHC concentrations (ng/g ww) in Brünnich's guillemot eggs collected from Bjørnøya (Svalbard) in 2018 (n=5), and from Kongsfjorden (Svalbard) in 2020, 2021 and 2022 (n=15). OHCs detected in under 75 % of the samples are designated by ND (not detected), and NA refers to not analysed. Compounds below detection limit for included OHCs are assigned half the value of LOD. *Not included in sum (Σ) of contaminant group.*

	Bjørnøya			**Kongsfjorden**		
	Mean ± SD	**Median**	**Min-Max**	**Mean ± SD**	**Median**	**Min-Max**
cis-Chlordane	0.09 ± 0.06	0.07	0.04 – 0.18	0.08 ± 0.04	0.07	0.04 – 0.19
trans-Chlordane	ND	ND	ND	ND	ND	ND
Heptachlor	0.008 ± 0.002	0.008	0.006 – 0.011	0.007 ± 0.004	0.008	0.001 – 0.015
Mirex	1.18 ± 0.38	1.28	0.77 – 1.69	1.81 ± 0.70	1.76	0.94 – 3.51
cis-Nonachlor	0.66 ± 0.28	0.82	0.33 – 0.90	1.00 ± 0.54	0.77	0.38 – 1.93
trans-Nonachlor	0.09 ± 0.06	0.06	0.04 – 0.17	0.09 ± 0.06	0.08	0.04 – 0.28
Oxychlordane	3.11 ± 0.80	3.16	2.09 – 4.02	5.54 ± 2.61	4.86	2.29 – 10.03
ΣCHLOR	5.14 ± 1.35	4.94	3.32 – 6.86	8.54 ± 3.40	7.47	3.71 – 13.37
o,p´-DDD	ND	ND	ND	ND	ND	ND
p,p´-DDD	ND	ND	ND	ND	ND	ND
o,p´-DDE	0.10 ± 0.02	0.11	0.08 – 0.12	0.16 ± 0.05	0.15	0.11 – 0.31
p,p´-DDE	62.96 ± 16.00	61.46	43.65 – 84.79	82.64 ± 18.28	77.01	59.64 – 128.51
o,p´-DDT	0.030 ± 0.017	0.025	0.012 – 0.053	0.023 ± 0.018	0.016	0.002 – 0.073
p,p´-DDT	0.05 ± 0.03	0.03	0.03 – 0.09	0.05 ± 0.03	0.05	0.01 – 0.11
ΣDDT	63.14 ± 15.98	61.67	43.87 – 84.95	82.88 ± 18.33	77.33	59.85 – 128.84
HCB	30.55 ± 4.04	30.77	25.88 – 36.05	32.67 ± 8.01	32.18	16.42 – 47.12
a-HCH	0.06 ± 0.01	0.07	0.04 – 0.07	0.06 ± 0.02	0.06	0.03 – 0.09
b-HCH	1.32 ± 0.20	1.25	1.11 – 1.61	2.36 ± 0.75	2.31	1.42 – 4.42
g-HCH	ND	ND	ND	ND	ND	ND
ΣHCH	1.38 ± 0.20	1.32	1.15 – 1.66	2.42 ± 0.75	2.37	1.48 – 4.48
PCB 18	ND	ND	ND	NA/ND	NA/ND	NA/ND
PCB 28/31	1.72 ± 0.20	1.67	1.45 – 1.97	2.11 ± 0.58	2.14	1.33 – 3.71
PCB 47	0.93 ± 0.24	0.88	0.63 – 1.25	1.36 ± 0.34	1.25	0.98 – 2.28
PCB 52	0.10 ± 0.05	0.09	0.05 – 0.18	0.10 ± 0.05	0.08	0.03 – 0.17
PCB 66	2.38 ± 0.64	2.22	1.70 – 3.30	3.35 ± 0.88	3.11	2.35 – 5.81
PCB 74	1.67 ± 0.32	1.55	1.31 – 2.12	2.33 ± 0.64	2.19	1.63 – 4.10
PCB 99	3.53 ± 1.03	3.37	2.21 – 4.91	5.60 ± 1.44	5.37	3.81 – 8.93
PCB 101	0.26 ± 0.02	0.26	0.23 – 0.28	0.27 ± 0.15	0.28	0.05 – 0.57
PCB 105	2.18 ± 1.13	2.06	0.55 – 3.57	3.03 ± 0.74	2.91	2.12 – 5.05
PCB 118	7.17 ± 2.28	6.84	4.27 – 10.15	10.23 ± 2.74	9.82	7.27 – 17.25
PCB 123	0.12 ± 0.04	0.11	0.07 – 0.18	0.17 ± 0.04	0.17	0.13 – 0.25
PCB 128	0.88 ± 0.51	0.91	0.03 – 1.32	1.34 ± 0.45	1.22	0.83 – 2.18
PCB 138	6.88 ± 3.23	7.28	1.75 – 10.19	11.25 ± 3.59	10.25	6.75 – 18.57
PCB 141	0.016 ± 0.008	0.013	0.008 – 0.030	0.014 ± 0.009	0.013	0.003 – 0.036
PCB 149	0.18 ± 0.04	0.16	0.15 – 0.25	0.19 ± 0.07	0.19	0.12 – 0.32
PCB 153	12.06 ± 4.26	11.99	5.82 – 16.80	18.17 ± 5.59	16.66	11.97 – 30.68
PCB 156	1.00 ± 0.28	0.83	0.77 – 1.39	1.14 ± 0.28	1.08	0.79 – 1.84
PCB 157	0.22 ± 0.07	0.20	0.14 – 0.32	0.26 ± 0.06	0.26	0.19 – 0.38
PCB 167	0.49 ± 0.17	0.48	0.26 – 0.71	0.68 ± 0.18	0.66	0.45 – 1.05
PCB 170	1.52 ± 0.63	1.50	0.62 – 2.21	2.16 ± 0.62	2.05	1.43 – 3.43
PCB 180	3.31 ± 1.24	3.43	1.44 – 4.58	5.12 ± 1.67	4.69	3.04 – 8.87
PCB 183	0.69 ± 0.18	0.60	0.52 – 0.95	0.83 ± 0.23	0.81	0.57 – 1.33
PCB 187	4.22 ± 0.72	4.47	3.11 – 4.88	5.99 ± 2.00	6.16	3.65 – 10.63
PCB 189	0.11 ± 0.03	0.12	0.08 – 0.13	0.10 ± 0.03	0.10	0.08 – 0.17
PCB 194	0.52 ± 0.14	0.60	0.36 – 0.67	0.52 ± 0.13	0.47	0.37 – 0.82
PCB 206	0.16 ± 0.05	0.18	0.11 – 0.21	0.17 ± 0.04	0.15	0.12 – 0.26

PCB 209	0.19 ± 0.06	0.20	0.12 – 0.27	0.15 ± 0.03	0.14	0.11 – 0.21
ΣPCB	52.52 ± 16.42	51.00	30.31 – 72.18	76.66 ± 21.31	73.24	51.76 – 122.47
PFPeA	ND	ND	ND	ND	ND	ND
PFHxA	ND	ND	ND	ND	ND	ND
PFHpA	ND	ND	ND	ND	ND	ND
PFOA	0.71 ± 0.48	0.47	0.38 – 1.55	0.08 ± 0.05	0.08	0.02 – 0.24
PFNA	2.10 ± 0.62	1.96	1.52 – 3.06	1.12 ± 0.38	0.98	0.58 – 2.05
PFDA	2.13 ± 0.34	2.26	1.56 – 2.39	1.51 ± 0.56	1.66	0.65 – 2.71
PFUnDA	13.66 ± 2.58	13.21	10.71 – 16.80	8.30 ± 2.77	8.74	3.96 – 14.14
PFDoDA	2.79 ± 0.57	2.71	2.10 – 3.43	1.96 ± 0.60	1.93	1.07 – 2.98
PFTrDA	ND	ND	ND	ND	ND	ND
PFTeDA	1.44 ± 0.35	1.60	1.01 – 1.79	0.69 ± 0.18	0.73	0.36 – 0.92
PFHxDA	ND	ND	ND	ND	ND	ND
PFODcA	ND	ND	ND	ND	ND	ND
ΣPFCA	22.83 ± 3.43	22.58	17.68 – 26.84	13.66 ± 4.14	14.38	6.78 – 22.04
4:2 FTS	±	ND	ND	±	ND	ND
6:2 FTS	±	ND	ND	±	ND	ND
8:2 FTS	±	ND	ND	±	ND	ND
10:2 FTS	±	ND	ND	±	ND	ND
PFBS	±	ND	ND	±	ND	ND
PFPS	±	ND	ND	±	ND	ND
PFHxS	±	ND	ND	±	ND	ND
PFHpS	±	ND	ND	±	ND	ND
PFOSlin*	11.88 ± 6.16	10.68	5.95 – 22.02	7.07 ± 2.03	6.14	4.73 – 11.72
sum PFOS	12.68 ± 6.59	11.32	6.28 – 23.55	7.58 ± 2.17	6.81	4.96 – 12.65
PFNS	±	ND	ND	±	ND	ND
PFDS	±	ND	ND	±	ND	ND
FOSA	±	ND	ND	±	ND	ND
ΣPFSA	12.68 ± 6.59	11.32	6.28 – 23.55	7.58 ± 2.17	6.81	4.96 – 12.65

Appendix B: OHC concentrations in ivory gull eggs

***Table A2**: Mean, standard deviation (SD), median and range (Min-Max) of OHC concentrations (ng/g ww) in ivory gull eggs collected from Nordaustlandet (Svalbard) in 2021-2022 (n=3), and from Uyedineniya (Russia) in 2019 (n=10). OHCs detected in under 75 % of the samples are designated by ND (not detected). Compounds below detection limit for included OHCs are assigned half the value of LOD. *Not included in sum (Σ) of contaminant group.*

	Nordaustlandet			**Uyedineniya**		
	Mean ± SD	**Median**	**Min-Max**	**Mean ± SD**	**Median**	**Min-Max**
cis-Chlordane	2.63 ± 2.05	1.90	1.05 – 4.95	1.64 ± 0.79	1.79	0.46 – 2.82
trans-Chlordane	ND	ND	ND	ND	ND	ND
Heptachlor	0.05 ± 0.04	0.03	0.028 – 0.10	0.13 ± 0.6	0.12	0.05 – 0.22
Mirex	28.56 ± 10.80	22.93	21.73 – 41.00	27.07 ± 10.03	26.18	8.70 – 43.14
cis-Nonachlor	20.25 ± 21.44	8.34	7.41 – 45.00	8.28 ± 5.35	7.80	1.36 – 21.03
trans-Nonachlor	151.40 ± 169.36	54.38	52.86 – 346.95	74.44 ± 56.76	60.92	12.81 – 223.18
Oxychlordane	76.01 ± 48.45	53.08	43.27 – 131.67	113.25 ± 60.16	95.35	35.34 – 248.35
ΣCHLOR	278.90 ± 251.90	139.81	127.21 – 569.67	224.81 ± 129.25	191.82	58.73 – 538.74
o,p´-DDD	0.26 ± 0.32	0.16	0.01 – 0.62	0.03 ± 0.02	0.02	0.005 – 0.06
p,p´-DDD	27.25 ± 38.73	9.4	0.65 – 71.89	0.23 ± 0.12	0.23	0.08 – 0.43
o,p´-DDE	0.52 ± 0.41	0.31	0.26 – 0.99	0.55 ± 0.21	0.52	0.13 – 0.86
p,p´-DDE	1324.39 ± 632.06	1106.77	829.89 – 2036.51	1042.77 ± 357.29	1084.53	368.99 – 1667.012
o,p´-DDT	0.40 ± 0.48	0.23	0.03 – 0.94	0.06 ± 0.03	0.05	0.03 – 0.12
p,p´-DDT	9.46 ± 11.40	5.22	0.79 – 22.38	0.65 ± 0.44	0.61	0.20 – 1.69
ΣDDT	1362.28 ± 680.42	1108.51	845.22 – 2133.11	1044.29 ± 357.82	1086.16	369.60 – 1669.42
HCB	41.76 ± 12.73	38.53	30.96 – 55.80	47.19 ± 11.75	49.27	20.82 – 61.64
a-HCH	0.06 ± 0.04	0.05	0.02 – 0.10	0.05 ± 0.03	0.04	0.03 – 0.13
b-HCH	6.86 ± 5.13	3.92	3.86 – 12.78	45.14 ± 27.12	38.75	12.99 – 94.78
g-HCH	0.08 ± 0.07	0.04	0.04 – 0.16	0.07 ± 0.03	0.07	0.02 – 0.12
ΣHCH	6.99 ± 5.24	3.99	3.95 – 13.04	45.25 ± 27.16	38.83	13.04 – 94.95
PCB 18	ND	ND	ND	ND	ND	ND
PCB 28/31	2.16 ± 0.77	2.05	1.46 – 2.98	5.69 ± 1.7	6.15	1.61 – 7.82
PCB 47	8.86 ± 5.17	6.22	5.54 – 14.81	10.67 ± 4.75	10.87	2.96 – 21.28
PCB 52	10.83 ± 14.86	3.74	0.83 – 27.90	2.49 ± 1.27	2.11	1.15 – 5.00
PCB 66	6.81 ± 1.66	5.94	5.76 – 8.73	15.77 ± 6.75	15.01	4.05 – 27.03
PCB 74	8.40 ± 2.70	6.91	6.78 – 11.51	20.38 ± 7.60	20.96	5.65 – 34.30
PCB 99	105.78 ± 45.18	90.86	69.95 – 156.53	131.09 ± 48.70	140.50	40.35 – 216.45
PCB 101	7.78 ± 8.70	3.46	2.09 – 17.80	5.42 ± 2.15	4.94	1.79 – 8.21
PCB 105	20.73 ± 4.25	21.36	16.20 – 24.63	36.87 ± 16.32	33.60	9.78 – 66.53
PCB 118	87.21 ± 23.57	81.43	67.08 – 113.14	131.21 ± 54.24	125.26	34.99 – 230.99
PCB 123	1.24 ± 0.60	1.01	0.79 – 1.93	1.59 ± 0.56	1.59	0.40 – 2.35
PCB 128	42.30 ± 15.69	37.75	29.40 – 59.77	29.03 ± 12.90	26.93	8.48 – 53.56
PCB 138	324.04 ± 106.02	296.26	234.67 – 441.19	288.61 ± 108.55	289.61	84.40 – 456.30
PCB 141	0.28 ± 0.20	0.26	0.08 – 0.49	0.28 ± 0.16	0.25	0.07 – 0.66
PCB 149	31.08 ± 39.23	10.55	6.37 – 76.32	8.62 ± 6.46	7.28	1.81 – 25.97
PCB 153	526.55 ± 150.24	494.48	394.93 – 690.24	578.96 ± 219.95	574.04	176.98 – 881.55
PCB 156	10.89 ± 1.34	10.44	9.84 – 12.40	16.99 ± 6.73	16.69	4.86 – 27.02
PCB 157	2.88 ± 0.18	2.94	2.68 – 3.01	4.53 ± 1.85	4.34	1.40 – 7.32
PCB 167	5.22 ± 0.68	5.03	4.65 – 5.97	5.72 ± 2.38	5.33	1.66 – 9.56
PCB 170	80.34 ± 20.95	73.99	63.30 – 103.73	57.70 ± 25.70	58.66	18.13 – 110.94
PCB 180	232.48 ± 56.53	215.79	186.18 – 295.48	157.25 ± 72.42	153.96	47.69 – 312.94
PCB 183	45.08 ± 12.01	41.58	35.21 – 58.46	32.74 ± 13.43	30.44	10.20 – 56.86
PCB 187	78.52 ± 48.43	60.64	41.56 – 133.35	40.03 ± 18.68	33.88	10.67 – 74.99
PCB 189	2.14 ± 0.35	2.13	1.79 – 2.50	1.47 ± 0.92	1.34	0.42 – 3.73
PCB 194	24.50 ± 7.29	22.03	18.76 – 32.71	14.93 ± 9.69	14.03	4.45 – 38.61
PCB 206	4.54 ± 1.36	4.03	3.51 – 6.09	2.67 ± 1.61	2.54	0.78 – 6.06
PCB 209	2.50 ± 0.99	1.97	1.89 – 3.64	1.42 ± 0.83	1.38	0.38 – 3.01
ΣPCB	1673.16 ± 562.14	1495.19	1221.55 – 2302.74	1602.14 ± 619.62	1601.17	475.11 – 2528.31

PFPeA	ND	ND	ND	ND	ND	ND
PFHxA	ND	ND	ND	ND	ND	ND
PFHpA	ND	ND	ND	ND	ND	ND
PFOA	0.08 ± 0.02	0.08	0.05 – 0.09	0.15 ± 0.08	0.13	0.03 – 0.29
PFNA	2.33 ± 1.67	2.15	0.76 – 4.09	2.53 ± 1.24	2.01	0.91 – 4.22
PFDA	3.52 ± 3.13	2.89	0.75 – 6.91	2.75 ± 1.23	2.19	1.57 – 5.47
PFUnDA	14.53 ± 11.91	13.53	3.15 – 26.90	10.04 ± 4.33	8.14	5.76 – 19.50
PFDoDA	3.66 ± 2.58	3.30	1.27 – 6.40	1.70 ± 0.62	1.55	0.89 – 2.74
PFTrDA	10.27 ± 4.63	7.63	7.56 – 15.61	3.97 ± 2.65	4.11	0.10 – 9.05
PFTeDA	1.92 ± 0.64	1.93	1.28 – 2.55	0.85 ± 0.30	0.82	0.48 – 1.40
PFHxDA	ND	ND	ND	ND	ND	ND
PFODcA	ND	ND	ND	ND	ND	ND
Σ PFCA	36.30 ± 23.98	30.76	15.57 – 62.56	21.99 ± 9.23	19.62	9.73 – 42.55
4:2 FTS	ND	ND	ND	ND	ND	ND
6:2 FTS	ND	ND	ND	ND	ND	ND
8:2 FTS	ND	ND	ND	ND	ND	ND
10:2 FTS	ND	ND	ND	ND	ND	ND
PFBS	ND	ND	ND	ND	ND	ND
PFPS	ND	ND	ND	ND	ND	ND
PFHxS	0.53 ± 0.51	0.29	0.18 – 1.11	0.47 ± 0.27	0.41	0.08 – 0.91
PFHpS	0.23 ± 0.17	0.18	0.09 – 0.42	0.27 ± 0.15	0.25	0.05 – 0.48
PFOSlin*	39.61 ± 25.14	43.48	12.76 – 62.59	36.52 ± 16.08	33.96	18.21 – 67.94
sum PFOS	41.49 ± 26.20	45.76	13.41 – 65.29	38.70 ± 17.25	36.24	18.72 – 71.46
PFNS	ND	ND	ND	ND	ND	ND
PFDS	ND	ND	ND	ND	ND	ND
FOSA	ND	ND	ND	ND	ND	ND
Σ PFSA	42.25 ± 26.79	46.23	13.69 – 66.83	39.44 ± 17.65	36.97	18.85 – 72.86

Appendix C: Quality control of methodological differences in OC analysis

***Table A3**: Concentrations of OCs (ng/g wet weight) for two Brünnich's guillemot eggs (collected from Kongsfjorden in 2020) analysed in 2020-2021 and in 2023.*

Egg ID	**BG-20-3**		**BG-20-4**	
Year of analysis	**2020-2021**	**2023**	**2020-2021**	**2023**
cis-Chlordane	0.1221	0.1127	0.0652	0.0557
Heptachlor	0.0201	0.0052	0.0011	0 0048
Mirex	2.5735	2.4935	1.1745	1.0238
cis-Nonachlor	1.8906	1.7731	0.7370	0.6752
trans-Nonachlor	0.1308	0.1068	0.0765	0.0574
Oxychlordane	12.1998	5.3177	7.5807	2.8160
o,p´-DDE	0.2110	0.1863	0.1280	0.1290
p,p´-DDE	118.5510	99.6493	74.8620	62.6086
o,p´-DDT	0.0390	0.0279	0.0023	0.0141
p,p´-DDT	0.0810	0.0756	0.0310	0.0293
HCB	47.5971	30.4918	44.1582	29.7247
a-HCH	0.1040	0.0857	0.0550	0.0450
b-HCH	2.9590	2.5037	1.9790	1.7130
PCB 28/31	2.5820	2.3485	2.3072	2.0849
PCB 47	1.9555	1.6015	1.3254	1.1023
PCB 52	0.1850	0.1476	0.0960	0.0712
PCB 66	4.5104	3.8052	3.2552	2.9571
PCB 74	3.2509	2.6581	2.2135	1.9823
PCB 99	8.6955	7.3359	4.7047	4.6464
PCB 101	0.1900	0.5685	0.0937	0.2545
PCB 105	4.1235	3.6732	2.7282	2.4386
PCB 118	14.4475	13.4678	7.9529	7.4909
PCB 123	0.2344	0.2601	0.1397	0.1206
PCB 128	2.2007	2.1577	0.9714	0.8838
PCB 138	20.1971	16.9381	8.8336	7.2921
PCB 141	0.0248	0.0232	0.0108	0.0078
PCB 149	0.3325	0.3165	0.1637	0.1495
PCB 153	32.4139	28.9505	13.2337	11.7441
PCB 156	1.5911	1.4555	0.9696	0.8783
PCB 157	0.3992	0.3521	0.2346	0.2084
PCB 167	1.1343	0.9731	0.5703	0.4616
PCB 170	3.5154	3.3451	1.6001	1.5292
PCB 180	9.3471	8.4026	3.5977	3.3141
PCB 183	1.2034	1.2609	0.6127	0.6178
PCB 187	8.6484	8.7952	3.6195	3.6784
PCB 189	0.1503	0.1357	0.0899	0.0802
PCB 194	0.7734	0.7500	0.4612	0.4604
PCB 206	0.2817	0.2357	0.1604	0.1309

PCB 209	0.2373	01743	0.1532	0.1105

Appendix D: Limits of detection (LOD) for OHCs

Limits of detection (LOD) for OCs

Table A4*: LOD (in ng/g wet weight) for OCs detected in Brünnich's guillemot eggs (collected in 2018, 2020, 2021 and 2022) and ivory gull eggs (collected in 2021 and 2022). Compounds that were not analysed are denoted with NA.*

Year of analysis	**Br. guillemot (2020)** **2020-2021**	**Br. guillemot (2018, 2021, 2022)** **Ivory gull (2021, 2022)** **2023**
cis-Chlordane	0.01	0.001
trans-Chlordane	0.01	0.002
Heptachlor	0.01	0.002
Mirex	0.01	0.003
cis-Nonachlor	0.01	0.0004
trans-Nonachlor	0.01	0.009
Oxychlordane	0.03	0.02
o,p´-DDD	0.02	0.001
p,p´-DDD	0.04	0.002
o,p´-DDE	0.005	0.001
p,p´-DDE	0.07	0.001
o,p´-DDT	0.02	0.004
p,p´-DDT	0.01	0.002
HCB	0.42	0.50
a-HCH	0.01	0.009
b-HCH	0.002	0.004
g-HCH	0.09	0.04
PCB 18	NA	0.02
PCB 28/31	0.08	0.02
PCB 47	0.08	0.007
PCB 52	0.05	0.009
PCB 66	0.01	0.004
PCB 74	0.08	0.06
PCB 99	0.01	0.01

PCB 101	0.03	0.006
PCB 105	0.04	0.003
PCB 118	0.01	0.0101
PCB 123	0.01	0.0004
PCB 128	0.01	0.004
PCB 138	0.03	0.002
PCB 141	0.01	0.0007
PCB 149	0.01	0.004
PCB 153	0.04	0.04
PCB 156	0.01	0.0007
PCB 157	0.01	0.0005
PCB 167	0.01	0.001
PCB 170	0.01	0.003
PCB 180	0.02	0.008
PCB 183	0.01	0.002
PCB 187	0.01	0.003
PCB 189	0.01	0.0002
PCB 194	0.01	0.0008
PCB 206	0.01	0.0005
PCB 209	0.05	0.0093

Limit of detection (LOD) for PFASs

Table A5*: LOD (in ng/g wet weight) for PFASs detected in Brünnich's guillemot eggs (collected in 2018, 2020, 2021 and 2022) and ivory gull eggs (collected in 2021 and 2022). LOD values that were not available are denoted with na.*

Year of analysis	**Brunnichs guillemot (2018, 2020, 2021, 2022)** **Ivory gull (2021, 2022)** **2022**
PFPeA	0.09
PFHxA	0.10
PFHpA	0.05
PFOA	0.05
PFNA	na
PFDA	na
PFUnDA	na

PFDoDA	na
PFTrDA	0.20
PFTeDA	na
PFHxDA	0.10
PFODcA	0.15
4:2 FTS	0.10
6:2 FTS	0.10
8:2 FTS	0.10
10:2 FTS	0.10
PFBS	0.02
PFPS	0.05
PFHxS	0.02
PFHpS	0.05
PFOSlin	na
sum PFOS	na
PFNS	0.10
PFDS	0.10
FOSA	0.10

Appendix E: Variances in OHC concentrations between sampling years

Variances in contaminant concentration between sampling years were assessed for the Brünnich's guillemot eggs collected from Kongsfjorden in 2020, 2021 and 2023. Kruskal-Wallis tests followed by pairwise Mann-Whitney U tests were performed for this purpose. The analysis included Σ_6CHLOR (*cis*-Chlordane, heptachlor, mirex, *cis*-Nonachlor, *trans*-Nonachlor and oxychordane), Σ_4DDT (*o,p´*-DDE, *p,p´*-DDE, *o,p´*-DDT and *p,p´*-DDT), Σ_2HCH (a-HCH and b-HCH), Σ_{26}PCB (PCB-28/31, -47, -52, -66, -74, -99, -101, -105, -118, -123, -128, -138, -141, -149, -153, -156, -157, -167, -170, -180, -183, -187, -189, -194, -206 and -209), Σ_6PFCA (PFOA, PFDA, PFNA, PFUnDA, PFDoDA, and PFTeDA) and Σ_1PFSA (sumPFOS). The analysis was performed on contaminant groups in ng/g wet weight, as lipid % did not vary significantly between the years (Kruskal-Wallis test, $p > 0.5$).

Across the different sampling years of Brünnich's guillemot eggs from Kongsfjorden, only the levels of HCB varied significantly (Kruskal-Wallis test, $p < 0.01$). The levels of HCB decreased from 2020 to 2022 and varied significantly between 2020 and 2021 (Mann-Whitney U test, $p < 0.01$), as well as between 2020 and 2022 (Mann-Whitney U test, $p < 0.01$).

As all Brünnich's guillemot eggs from Bjørnøya were sampled from the same year, no such analysis was performed on these eggs. Nor was the relationship between contaminant concentrations and sampling year assessed in ivory gull eggs, as all 10 eggs from Uyedineniya were sampled in 2019, while the three eggs from Nordaustlandet were sampled in 2021 and 2022.

Appendix F: Eggshell thickness for different colonies of Brünnich's guillemots and ivory gulls

Table A6*: Mean, SD and range (Min-Max) of eggshell thickness (mm) at the blunt end and the equator in eggs of Brünnich's guillemots from two different colonies on Svalbard. Eggs were sampled from Bjørnøya in 2018, and from Kongsfjorden in 2020, 2021 and 2022. Number of eggs (n) used for each measurement is indicated.*

	Bjørnøya		**Kongsfjorden**	
	Mean ± SD	**Min-Max**	**Mean ± SD**	**Min-Max**
Blunt end	0.33 ± 0.03	0.28 – 0.36	0.38 ± 0.05	0.31 – 0.44
n	4		13	
Equator	0.48 ± 0.03	0.45 – 0.51	0.49 ± 0.04	0.43 – 0.54
n	5		12	

Table A7*: Mean, SD and range (Min-Max) of eggshell thickness (mm) at the blunt end and the equator in eggs of ivory gulls from a colony on Svalbard and a colony in the Russian Arctic. Eggs were sampled from Nordaustlandet in 2021 and 2022, and from Uyedineniya in 2019. Number of eggs (n) used for each measurement is indicated.*

	Nordaustlandet		**Uyedineniya**	
	Mean ± SD	**Min-Max**	**Mean ± SD**	**Min-Max**
Blunt end	0.20 ± 0.02	0.18 – 0.22	0.19 ± 0.02	0.17 – 0.24
n	3		9	
Equator	0.24 ± 0.03	0.20 – 0.26	0.23 ± 0.02	0.20 – 0.25
n	3		9	

Appendix G: Standards for OHC analysis

Internal standards - OCs

DDT I

Component
13C alpha-HCH
13C beta-HCH
13C gamma-HCH
13C delta-HCH
13C p.p.DDE
13C o.p.DDD
13C p.p.DDT

PBDE I

Component
13C PBDE-28
13C PBDE-47
13C PBDE-99
13C PBDE-153
13C PBDE-183
13C PBDE-197
13C PBDE-206
13C PBDE-209

PCB I

Component
13C PeCB
13C HCB
13C PCB- 28
13C PCB- 52
13C PCB- 101
13C PCB- 105
13C PCB- 114
13C PCB- 118
13C PCB- 123
13C PCB- 138
13C PCB- 153
13C PCB- 156
13C PCB- 157
13C PCB- 167
13C PCB- 180
13C PCB- 189
13C PCB- 209

PEST I

Component
13C tr.Nonachlor
13C Cis-NonaChlor

13C tr.Chlordane
13C Cis-Chlordane
13C Oxychlordane
13C Heptachlor epoxid
13C HeptaChlor
13C Dieldrin
13C Mirex
13C Endosulfan I
13C Endosulfan II
13C Endosulfan Sulfate
d14 Trifluralin (di-n-propyl)
13C Endrin
13C Aldrin
13C Isodrin

Internal standards – PFASs

Component
13C4 PFBA
13C5 PFPeA
13C5 PFHxA
13C4 PFHpA
13C4 PFOA
13C5 PFNA

13C6 PFDA
13C7 PFUnDA
13C2 PFDoDA
13C2 PFTeDA
13C2 PFHxDA
13C3 PFBS
13C3 PFHxS
13C4 PFOS
13C8 FOSA
13C2 6:2 FTS
13C2 8:2 FTS