Impacts of a warming climate on concentrations of organochlorines in a fasting high arctic marine bird: Direct vs. indirect effects?

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HIGHLIGHTS

- Organochlorines were measured in the blood of fasting High Arctic common eiders over 11 years at the point of hatching.
- The concentrations of HCB, p,p'-DDE and chlordanes increased over time whereas PCBs were stable.
- Body mass and clutch size were negatively associated to the concentrations of most OCs.
- Effective ambient temperature was positively associated to the concentrations of most OCs.
- Spring climate and primary production showed relatively weak relationships to concentrations of some OCs.

GRAPHICAL ABSTRACT
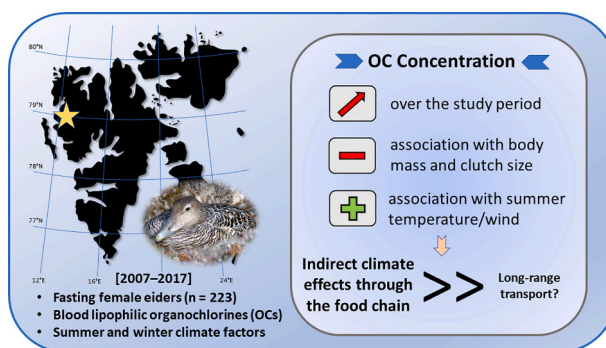
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ABSTRACT

The present study examined how climate changes may impact the concentrations of lipophilic organochlorines (OCs) in the blood of fasting High Arctic common eiders (*Somateria mollissima*) during incubation. Poly-chlorinated biphenyls (PCBs), 1-dichloro-2,2-bis (*p*-chlorophenyl) ethylene (p,p'-DDE), hexachlorobenzene (HCB) and four chlordane compounds (oxychlordane, *trans*-chlordane and *trans*- and *cis*-nonachlor) were measured in females at chick hatching ($n = 223$) over 11 years (2007–2017). Firstly, median HCB and p,p'-DDE concentrations increased ~75 % over the study period, whereas median chlordane concentrations doubled (except for oxy-chlordane). PCB concentrations, in contrast, remained stable over the study period. Secondly, both body mass and clutch size were negatively associated with OC levels, suggesting that females with high lipid metabolism redistributed more OCs from adipose tissue, and that egg production is an important elimination route for OCs.

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Thirdly, the direct climate effects were assessed using the mean effective temperature (ET: air temperature and wind speed) during incubation, and we hypothesized that a low ET would increase redistribution of OCs. Contrary to expectation, the ET was positively correlated to most OCs, suggesting that a warmer climate may lead to higher OCs levels, and that the impact of ET may not be direct. Finally, potential indirect impacts were examined using the Arctic Oscillation (AO) in the three preceding winters ($AO_{winter\ 1-3}$) as a proxy for potential long-range transport of OCs, and for local spring climate conditions. In addition, we used chlorophyll *a* (Chl*a*) as a measure of spring primary production. There were negative associations between $AO_{winter\ 1}$ and HCB, *trans*-chlordane and *trans*-nonachlor, whereas oxychlordane and *cis*-chlordane were negatively associated with Chl*a*. This suggests that potential indirect climate effects on eiders were manifested through the food chain and not through increased long-range transport, although these relationships were relatively weak.

1. Introduction

During the last decades, warming of the Arctic has occurred at a nearly four-fold rate compared to the global average (recently reviewed by Rantanen et al., 2022), and this has potentially severe consequences for wildlife species in the region (see also CAFF, 2013; Overland et al., 2019). In addition, the Arctic is a sink for different environmental contaminants, including lipophilic legacy organochlorines (OCs). Although most OCs, such as polychlorinated biphenyls (PCB) and 1-dichloro-2,2-bis (*p*-chlorophenyl) ethylene (*p,p′*-DDE) have declined strongly in wildlife since bans were introduced in the 1970s and 1980s, recent evidence suggests that climate change may directly or indirectly affect the OC concentrations in the physical environment and biota (Macdonald et al., 2005; Noyes et al., 2009; Bustnes et al., 2010a, 2022; Ma et al., 2016; Foster et al., 2019; Rigét et al., 2020; Borgå et al., 2022). Firstly, impacts on wildlife may be direct through changes in local conditions such as temperatures, wind, and precipitation. For example, many Arctic species depend on metabolizing stored lipid reserves which remobilize lipid-soluble OCs. Low temperatures leads to higher lipid metabolization and is thus expected to increase circulating concentrations of OCs and vice versa (van den Brink et al., 1998; Polischuk et al., 2002; Henriksen et al., 1998; Bustnes et al., 2010b, 2012, 2017). Secondly, impacts may be indirect through changes in winds and oceanic currents, which may alter the transport of OCs to remote locations, with subsequent biomagnification through food chains (Macdonald et al., 2005; Ma et al., 2016; Bustnes et al., 2010a; Foster et al., 2019; Borgå et al., 2022). There might also be climate-induced changes in food web structures that alter the diet, and thereby OC intake (Hebert et al., 2008; Bustnes et al., 2011; Borgå et al., 2022).

In the present study, we examined how climate variables were associated to accumulation of lipophilic OCs in High Arctic common eiders (*Somateria mollissima*). The common eider is a large-bodied marine duck that fasts during egg laying and incubation (3.5–4 weeks) and may lose 30–45 % of its initial body mass, primarily through lipid mobilization (Parker and Holm, 1990; Bolduc and Guillemette, 2003; Guillemette, 2001; Criscuolo et al., 2002). This leads to redistribution of lipophilic OCs, and blood concentrations of persistent PCBs, *p,p′*-DDE and hexachlorobenzene (HCB) have been shown to increase 2–8 fold over 15 days of incubation fast in High Arctic eiders (Bustnes et al., 2010b, 2012). Hence, there is a correspondence between the highest levels of OCs in the blood of female eiders and the time when they are in the poorest body condition, potentially making the birds more vulnerable to adverse effects of contaminants (Bustnes et al., 2010b).

We aimed to assess how blood OC concentrations of incubating common eiders may be influenced directly or indirectly by climate change, by measuring OCs in the blood of breeding females ($n = 223$), over 11 years (2007–2017) in the Norwegian High Arctic. Importantly, to standardize our data, we only used blood samples from females with hatching eggs. We firstly hypothesized that concentrations would decline because the investigated OCs have been banned for several decades. Secondly, we predicted that females in poor body conditions would have higher concentrations due to high lipid metabolism during incubation, or because of low initial body condition at the start of incubation (Bustnes et al., 2010b, 2012). We also hypothesized that clutch size would be negatively related to circulating levels of OCs since maternal transfer to eggs is an elimination route for OCs in birds (Bargar et al., 2001; Drouillard and Norstrom, 2001). Thirdly, we hypothesized that harsh climate conditions (low temperatures and strong winds) during incubation, would have direct effects on energy expenditure and lead to higher lipid metabolism and hence increased redistribution of OCs to the blood (Bustnes et al., 2012). Fourthly, we considered indirect climate impacts by assessing factors that may influence the long-range transport of OCs and the food chain of eiders, using the Arctic Oscillation (AO) in the preceding winters as proxies. The AO is a measurement of low-pressure activity and precipitation in the European Arctic and has previously proven useful in understanding the impacts of climate variability on contaminant pathways and trends in the Arctic (Borgå et al., 2022). A positive AO indicates high air transport towards the European Arctic, which predicts higher transport of OCs (Macdonald et al., 2005; Bustnes et al., 2010a; Rigét et al., 2013; Borgå et al., 2022). Hence, if variation in long-range transport affects the uptake of OCs in common eiders, we expected a positive relationship between OCs in spring and the prior winter AO. To account for potential longer time-lags in the accumulation of OCs, we also tested the effect of AO in the three winters prior to measurement ($AO_{winter\ 1-3}$: Bustnes et al., 2010a; Foster et al., 2019; Borgå et al., 2022). A negative relationship, however, would suggest that the impact of climate change may be manifested in the eiders through changes in the food chain (i.e. not as a result of increased long-range transport of OCs) since $AO_{winter\ 1}$ summarizes several local climate variables, such as sea surface temperature (SST), surface air temperature (SAT) and ice conditions prior to egg laying (Rigor et al., 2002; Wang et al., 2019; Borgå et al., 2022). These factors may strongly impact the Arctic benthic organisms that the common eiders feed on prior to nesting (Beuchel et al., 2006; Ambrose et al., 2006; Morata et al., 2015). Finally, to further assess potential indirect climate impacts through the food chain, we examined the effect of spring primary production using chlorophyll *a* (Chl*a*) measurements in the marine ecosystem. Alterations in the primary production is expected to have implications for the bioavailability of OCs entering the base of the food chain (Borgå et al., 2022), including the benthic system (van den Brink et al., 2011; Wagner et al., 2019) where eiders feed on prey such as bivalves, gastropods, and crustaceans (Lydersen et al., 1989). Previously, it has been shown that high Chl*a* was associated with high Hg concentrations in the blood of pelagic kittiwakes (*Rissa tridactyla*) in our study area (Tartu et al., 2022).

2. Materials and methods

2.1. Study area

The study was carried out between 2007 and 2017 at Storholmen in Kongsfjorden (78°55′N, 12°00′E), Svalbard. This island has a breeding population of 300–1000 pairs of common eiders, varying between years (Hanssen et al., 2013).

2.2. Data collection

Female eiders with hatching eggs were caught on their nest using a rod with a snare in the hatching period in late June or early July. A blood sample of ca. 10 mL was taken from the jugular vein with a syringe. The blood was centrifuged in the lab within a few hours (2–5 h) and the plasma was frozen at −20 °C until contaminant analysis. We recorded body mass using a spring balance and clutch size as the number of eggs in the nest at capture.

2.3. Environmental variables

We recorded various climate measurements (sea surface- and air temperature [SST and SAT], wind, precipitation, sea ice distribution, etc.) and then separated into different seasons and months (from the website of the Norwegian Meteorological Institute: MET). This created a lot of information, forcing us to make explicit a priori assumptions concerning what variables to include in the analyses. Furthermore, large-scale climate indexes often better predict variation in ecological processes than local climate (Stenseth et al., 2002; Hurrell et al., 2003). The AO index is an indicator of sea-level pressure variability for the Northern Hemisphere above 20°N, and its pattern has a dominant low-pressure region centered roughly over the Arctic Ocean. The asymmetries in the pressure pattern mean that cool winds sweep east-southeast across eastern Canada, and southwesterly North Atlantic storm tracks bring rain and mild temperatures to northern Europe. AO thus integrates, on a large scale, many climate variables and reflects variation in the basic transport pathways of persistent organic pollutants (POPs) (atmospheric transport), as it is a measure of airflow from temperate areas to the Arctic (Macdonald et al., 2005).

The environmental variables included in our statistical analyses were: 1) Effective temperature during the incubation period (26 days before hatching) for each female, based on the average daily recordings of wind (m s^{-1}) and temperature (°C, Norwegian Meteorological Institute). Effective temperature ('W': i.e., the wind chill index, which is how temperature 'feels like') was calculated according to the following formula:

$$W = 13.12 + 0.6215\,T - 11.37V^{0.16} + 0.3965\,T \times V^{0.16},$$

where 'T' is temperature (°C) and 'V' is wind speed (converted from m s^{-1} to km h^{-1}); MET: https://hjelp.yr.no/hc/no/articles/360001695513-Effektiv-temperatur-og-f%C3%B8les-som-;assessed11-03-2022); 2) the annual average of the monthly mean AO from November the previous year (t-1) to January (t; https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml); 3) chlorophyll-a concentrations in April (mg m^{-3}, a proxy for ocean productivity) extracted from the NASA OceanColor website (4 km MODIS Aqua satellites; https://oceandata.sci.gsfc.nasa.gov/) and spatially averaged over the area from 78° to 80°N and 10° and 12.6°E.

2.4. Contaminants analyses

Plasma was mixed with anhydrous sodium sulfate and ethanol (approximately 1:4 weight ratio). Samples were spiked with ^{13}C-labelled internal standards prior to being twice extracted with n-hexane under vortexing. Supernatant from each step was combined, and the combined supernatant was aliquoted into a pre-weighed vial for gravimetric lipid determination using a gentle stream of nitrogen gas. Samples were re-dissolved in 0.5 mL of n-hexane, and concentrated to 0.2 mL using a RapidVap.

The clean-up was performed using automated solid phase extraction, where the extract was eluted with 12 mL of 1:10 dichloromethane: hexane (v:v) through columns packed with 1 g of activated Florisil® (burnt at 450 °C for 8 h) and glass fiber frits on top and bottom. Iso-octane was added to the collected extract, which was evaporated to approximately 0.2 mL, quantitatively transferred to a GC vial and evaporated to 30 μL and spiked with a ^{13}C-labelled PCB-159 recovery standard.

Analysis of OCs in samples from 2012 to 2017 was performed by gas chromatography high-resolution accurate mass spectrometry (GC-HRAM) using a GC-Q-Exactive Orbitrap mass analyser (Thermo Scientific, UK). In brief, 1 μL of sample extract was injected into a split/splitless injector at 250 °C. Separation of analytes was performed on at TG-5SilMS GC (30 m × 0.25 mm ID × 250 μm) capillary column using helium as a carrier gas at a constant flow rate of 1 mL min^{-1}. The GC oven program utilized for separation was as follows: an initial temperature of 40 °C held for 1.5 min followed by a temperature ramp of 25 °C min^{-1} to 180 °C. Temperature was then increased at 5 °C min^{-1} to 280 °C followed by a final temperature ramp of 40 °C min^{-1} to 320 °C and held for 5 min. The analysis was performed using electron impact ionization (70 eV) in targeted single ion monitoring (TSIM) mode using an isolation window of 8 m:z at 60,000 mass resolution (full width at half maxima at 200 m:z). The quantification was performed using internal standard calibration with isotopic dilution. Data processing was performed using Tracefinder software v. 4.1 EFS. We analyzed blanks and standard reference materials (NIST 1957) with every 10 samples. Blanks were used to calculate the detection limits by using the equation LOD = average blank +3× STDEV, when no blanks were detected for some compounds 3 x S/N was used.

For further details on the OC analyses see Bustnes et al. (2010a, 2010b, 2012) and Fenstad et al. (2016).

Because of low concentrations of most OCs, the targeted OC-pesticides were limited to hexachlorobenzene (HCB), chlordanes (oxy-chlordane, *trans*-chlordane, *cis*-chlordane, *trans*-nonachlor and *cis*-nonachlor), and p,p'-DDE. In addition, the following key PCB-congeners were targeted: PCB118, PCB138, PCB153.

2.5. Statistical analyses

We conducted the statistical analyses and plotted results in R (R Core Team, 2021). All tests were two-tailed, and we rejected the null hypothesis at an α-level of 0.05. We used Wald statistics to test whether estimated parameters differed significantly from zero. Like Bustnes et al. (2017), we assessed multiple co-linearity among our a priori defined predictors of interest before any model fitting (Zuur et al., 2010; see also Næss et al., 2011 for an example of how to deal with this in practice). These predictors included continuous predictors: Effective temperature; AO; Chl$a$; year; clutch size; and female body mass. We rescaled and ranked each model in each analysis relative to the model with the lowest second-order Akaike's Information Criterion corrected for small sample sizes (AIC$_c$) value (Δ_i denotes this difference for model i). We selected the simplest model (judged by the models' estimated number of parameters) with a $\Delta_i \leq 1.5$ (e.g. Burnham and Anderson, 2002; Anderson, 2008) value using the AICcmodavg-package (Mazerolle, 2020: see SI Tables 1–8 for more details). We also examined the correlations between AO in the preceding winter and spring sea surface temperature (SST) ($r = 0.69$) and ice conditions in April ($r = 0.59$), confirming that AO was a good proxy for these variables.

Finally, like Bustnes et al. (2022), we treated the responses differently depending on the number of observations below or at the Limit of Detection (LOD). We created a rule of thumb based on the LOD for each contaminant (i.e., the percentage of minimum value for each response). If <15 % of samples were ≤LOD, we fitted linear models using the *lm* function (in the stats-package: see e.g., Fox, 2002; Zuur et al., 2009 for how we fitted these models to data). If between 15 and 50 % of the samples were ≤LOD, we fitted a tobit regression model using the vglm-function in the vgam-package (using the tobit-family and the contaminant-specific LOD as the lower-limit: see Yee and Moler (2020) for how these models were specified). Thomas et al. (2016) provide more details on the tobit-models we applied. We did not fit any models to responses where >50 % of the observations were ≤LOD.

3. Results and discussion

3.1. OC profile and temporal trends

The OC profile of the selected compounds in the common eider blood was dominated by HCB (mean = 29.8 %), *p,p′*-DDE (27.3 %) and PCBs (PCB118, PCB138 and PCB153: 33.7 %), whereas chlordanes made up 9.3 % (Fig. 1, Table 1).

Most compounds showed significant temporal trends over the 11 years, with PCBs as notable exceptions (Table 3). Due to many non-detects, PCB118 and PCB138 were not analyzed further, and we used PCB153 as indicator for PCBs. For HCB, the median concentration increased by 76 % between the first - and last three years of the study period (2007–2009 vs. 2015–2017), but the increase may have levelled off after 2015 (Table 2, Fig. 2). *Trans*-chlordane, *cis*- and *trans*-nonachlor also increased significantly over time (44.6 %, 99.1 % and 150.2 %, respectively), whereas oxychlordane decreased significantly (Tables 2, 3, Figs. 3–6). Moreover, the concentrations of *p,p′*-DDE also increased; the median concentration in the last three years was 74.4 % higher than in the first three years (Table 2, Fig. 7). Even though these chemicals have been banned for decades, the median overall ΣOC concentration increased by 49.4 % between the start and end years of our study period (Table 2), potentially increasing OC-related physiological stress.

HCB is an important byproduct of the manufacturing of chlorinated compounds and its industrial or combustion processes, and has great transport potential (Barber et al., 2005). Hence it is often found in relatively high concentrations in remote regions such as the Arctic. In recent years, HCB concentrations have increased in the atmosphere in our study area (Hung et al., 2016; Platt et al., 2022), and hence the increase in common eiders may not be surprising. Moreover, recent evidence suggests that in Kongsfjorden, deposition of HCB on the seabed has increased more than predicted from atmospheric input, pointing to a recent increase in glacial run-off as a potential source of HCB (Pouch et al., 2018). This supports increased HCB levels in benthos-feeding

eiders in the area. Increasing *p,p′*-DDE and some chlordanes may also have resulted from melting glaciers (Morselli et al., 2014). However, in some regions of the world, the production and use of DDT have continued for human disease vector control, and the global production of DDT increased somewhat between 2003 and 2007, with a 30 % decline in 2008 (van den Berg et al., 2017). Moreover, there is probably a considerable time lag between the production and use of DDT to potential measurable increases of the main DDT metabolite *p,p′*-DDE in Arctic wildlife. However, the scale of this process is difficult to assess.

3.2. Individual traits: body mass and clutch size

Several studies of Arctic marine birds have shown that the metabolism of stored lipids results in increased circulating levels of lipophilic OCs (Henriksen et al., 1998; Bustnes et al., 2010b, 2012, 2017). We predicted a negative relationship between blood OCs and body mass as eiders fast for nearly four weeks during incubation. Thus, it was not surprising that the selected statistical models for the dominant compounds included body mass (Table 3, Figs. 2–8); exceptions were *trans*-chlordane, *cis*- and *trans*-nonachlor. Hence, eider females with low lipid reserves at the start of incubation or with high lipid metabolism during incubation redistributed more of the dominating OCs from their lipid stores to the blood. However, although significant, the effect of body mass was relatively weak compared to the impact of clutch size. Egg laying is a well-known route for eliminating OCs from female birds (Bargar et al., 2001; Drouillard and Norstrom, 2001), and we predicted that females with large clutches would have lower circulating OC levels, which was found for all measured OCs, except for oxychlordane (Table 3, Figs. 2–8). Life-history theory predicts that differences among individuals regarding reproductive output and longevity to some extent is genetically determined (Stearns, 1992; Wilson and Nussey, 2010). A proximate reason for differences in OC concentrations between females might thus be the individual ability (i.e. individual quality) to gain body reserves prior to breeding. Hence, individual quality may be an
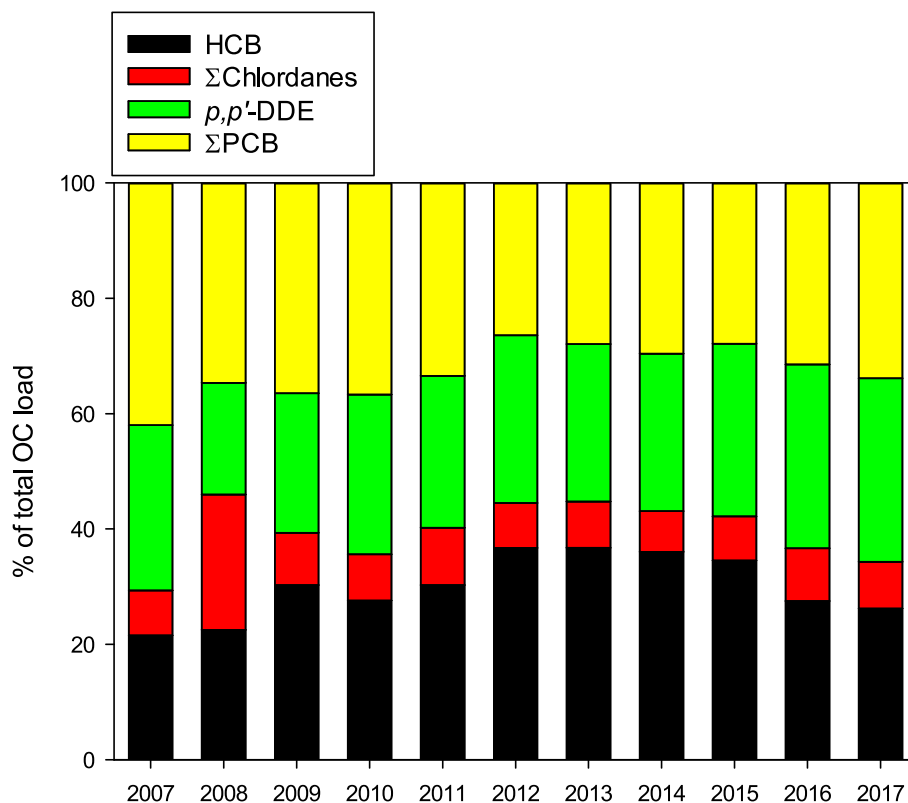

Fig. 1. Mean annual composition of organochlorine load in the blood of incubating common eider females (*n* = 223). Data from Kongsfjorden, Svalbard, 2007–2017.

Table 1

Summary of concentrations (pg g^{-1}, wet weight) of different organochlorines in the blood of common eider females at hatching in Kongsfjorden, Svalbard, 2007–2017.

Compound	LOD	Number detected	% detection	Concentrations					% of total
				Mean	Median	SE	Min	Max	
HCB		223	100	890.6	769.0	32.2	99.4	2754.7	29.8
Oxychlordane	50.3	159	71.3	129.3	93.4	9.0	25.2	769.7	4.3
trans-chlordane	2.3	201	90.1	27.9	16.4	2.2	1.2	210.8	0.8
Trans-nonachlor	1.8	212	95.1	101.2	71.1	6.8	0.9	758.7	2.8
cis-nonachlor	2.4	216	96.7	48.9	30.8	3.7	1.2	318.0	1.4
p,p′-DDE	126.9	217	97.3	984.4	738.0	59.1	63.5	6304.1	27.3
PCB118	181.1	78	35	186.1	90.7	14.6	90.7	2061.0	5.6
PCB138	124.4	188	84.3	381.0	277.6	26.2	62.2	3178.0	10.4
PCB153	136.9	215	96.4	605.5	482.6	35.1	68.5	4113.0	17.7
$\sum$PCB				1172.6	859.3	73.5	221.3	9352.0	33.7
$\sum$OC				3354.9	2689.1	166.6	422.1	19,174.8	

Table 2

Concentrations (pg g^{-1}, wet weight) of different organochlorines in the blood of common eider females at hatching in Kongsfjorden, Svalbard, in two time periods (2007–2009, $N = 79$ and 2015–2017, $N = 36$).

Compound	2007–2009					2015–2017					% change of median	t	Df	*p*-Value
	Mean	Median	SE	Min	Max	Mean	Median	SE	Min	Max				
HCB	620.4	578.0	36.1	99.4	1888.0	1066.6	1017.2	81.8	145.3	2434.5	75.0	−4.88	64.5	0.00001
Oxychlordane	182.6	136.0	20.8	25.2	769.7	74.5	56.3	8.9	25.2	192.6	−58.8	3.48	97.3	0.00076
trans-chlordane	27.3	15.7	4.4	1.2	210.8	40.4	22.7	6.5	4.5	138.0	44.6	−3.23	94.7	0.0017
trans-nonachlor	65.8	48.2	8.7	0.9	529.0	129.9	120.6	12.8	23.9	303.1	150.2	−5.75	112.5	<0.00001
cis-nonachlor	38.3	21.5	6.0	1.2	318.0	57.4	42.8	7.3	5.0	198.4	99.1	−3.83	97.9	0.00023
p,p′-DDE	825.6	605.0	90.6	63.5	4964.9	1155.7	1054.9	102.2	139.7	2521.5	74.4	−3.68	95.9	0.00039
PCB118	164.7	90.7	16.5	90.7	822.7	189.0	136.8	23.7	90.7	776.3	50.8	−1.34	66.7	0.185
PCB153	382.5	267.0	43.7	62.2	2004.4	358.6	346.3	37.3	62.2	1107.2	29.7	−1.13	93.0	0.261
PCB138	640.2	494.0	62.2	68.5	2928.0	564.0	532.8	48.1	68.5	1335.3	7.9	−0.46	95.6	0.644
$\sum$PCB	1187.4	876.6	116.4	221.3	4947.5	1111.6	1054.2	104.6	221.3	2942.2	20.3	−0.58	87.0	0.564
$\sum$OC	2947.4	2356.6	258.5	422.1	12,888.4	3636.1	3520.8	279.2	565.1	6809.4	49.4	−1.84	84.5	0.07
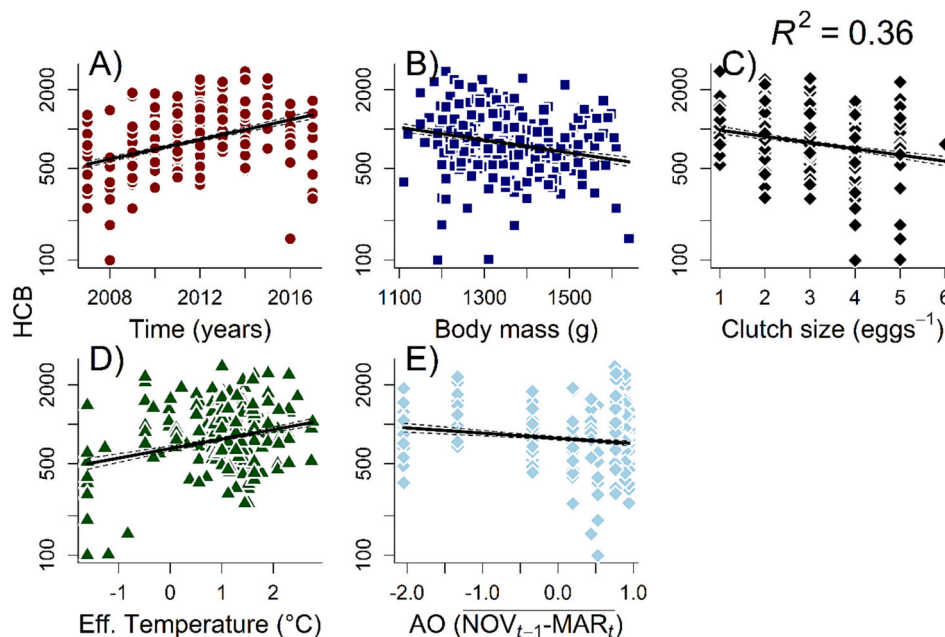
Fig. 2. Relationships between HCB concentrations (pg g^{-1}, wet weight) in the blood of incubating common eider females and Year (A), Body mass (B), Clutch size (C), Effective temperature (D) and Arctic Oscillation in preceding winter (E). Each sub-plot shows the underlying data (scatter), and model predictions, including their precision ($\pm$ 1 SE), keeping all the other variables at their estimated average values (see Table 3 for model details). Data from Kongsfjorden, Svalbard, 2007–2017.

Table 3
Estimated effects, including their precision [± Standard Error (SE)] for the selected models for different OCs in the blood of incubating common eider females ($n = 223$) in Kongsfjorden, Svalbard, (2007–2017). The type of model (Model Type) ran for each analysis was dictated by our rule of thumb on how we dealt with the percentage of observation below of equaling the Limit of Detection LOD; see main text for details: 1) Linear models (LM); and 2) Tobit regression model (VGLM).

Compound	Modell type	Parameter	Estimate	SE	t/z-value	p-Value
HCB	LM	Intercept	6.996	0.095	73.918	<0.00001
	LM	Year	0.086	0.011	8.185	<0.00001
	LM	Body mass	−0.001	0.000	−4.137	0.00005
	LM	Clutch size	−0.109	0.028	−3.908	0.00013
	LM	Effective temperature	0.167	0.035	4.806	<0.00001
	LM	AO winter	−0.091	0.033	−2.771	0.0061
		R^2	0.357			
Oxychlordane	VGLM	Intercept 1	4.944	0.243	20.313	<0.00001
	VGLM	Intercept 2	0.130	0.055	2.350	0.019
	VGLM	Year	−0.075	0.028	−2.694	0.0071
	VGLM	Body mass	−0.002	0.001	−2.248	0.025
	VGLM	Clutch size	−0.223	0.072	−3.090	0.002
	VGLM	Effective temperature	−0.196	0.087	−2.265	0.023
	VGLM	ChlorophyllA April	1.409	0.378	3.723	0.0002
	VGLM	R^2	0.147			
trans-chlordane	LM	Intercept	3.625	0.228	15.875	<0.00001
	LM	Year	0.104	0.025	4.168	0.00004
	LM	Clutch size	−0.278	0.067	−4.139	0.00005
	LM	AO winter	−0.258	0.077	−3.331	0.001
	LM	R^2	0.180			
trans-Nonachlor	LM	Intercept	4.768	0.232	20.547	<0.00001
	LM	Year	0.164	0.025	6.443	<0.00001
	LM	Clutch size	−0.202	0.068	−2.951	0.0035
	LM	AO winter	−0.166	0.079	−2.107	0.036
	LM	R^2	0.204			
cis-Nonachlor	LM	Intercept	4.056	0.200	20.289	<0.00001
	LM	Year	0.071	0.022	3.198	0.0016
	LM	Clutch size	−0.194	0.059	−3.292	0.0012
	LM	ChlorophyllA April	0.637	0.310	2.053	0.041
	LM	R^2	0.111			
p,p′-DDE	LM	Intercept	7.261	0.149	48.827	<0.00001
	LM	Year	0.061	0.017	3.667	0.00031
	LM	Body mass	−0.001	0.000	−2.769	0.0061
	LM	Clutch size	−0.211	0.044	−4.813	<0.00001
	LM	Effective temperature	0.226	0.053	4.263	0.00003
	LM	R^2	0.226			
PCB153	LM	Intercept	6.755	0.135	49.916	<0.00001
	LM	Year	−0.001	0.015	−0.039	0.969
	LM	Body mass	−0.001	0.000	−3.596	0.0004
	LM	Clutch size	−0.190	0.040	−4.765	<0.00001
	LM	Effective temperature	0.182	0.048	3.762	0.00022
	LM	R^2	0.193			

important determining factor for the concentrations of OCs in the blood of eiders, as low-quality individuals may start breeding with low body reserves.

3.3. Direct climate effects: effective temperature

By measuring OCs in the blood of incubating eiders twice during incubation (15 days apart), Bustnes et al. (2012) found evidence that ambient temperature played a role in the redistribution of OCs, i.e. in cold years females burned more lipids and OC concentrations increased more than in mild years. This predicts that exposure to harsh conditions with low temperatures during incubation would result in a higher redistribution of OCs compared to higher temperatures. In addition, Hilde et al. (2016) found that wind was a very potent factor in increasing incubation costs, and hence lipid metabolism, of common eiders in our study area. Accordingly, we predicted that OC concentrations would be negatively related to effective temperature (see methods). However, HCB, *p,p′*-DDE and PCB153 were positively associated with effective temperature, contrary to our predictions, whereas oxychlordane showed a negative relationship to effective temperature, albeit relatively weak (Table 3, Figs. 2–8). This suggests that the impact of effective temperature, for most OCs, is not directly on the individual eider females, but rather indirectly. Hence, benign conditions, such as higher temperatures and low wind seem to increase redistribution of the dominating OCs to

the blood of the eiders suggesting that a warmer Arctic climate will lead to higher levels of OCs in their most vulnerable period. This counter-intuitive result may also have different explanations. For example, it may indicate that the birds adjust their reproductive investments. That is, relatively high temperatures suggest a higher chance of reproductive success leading to increased incubation effort (e.g., higher incubation temperature through increased lipid metabolism) or females staying more on the nest to avoid nest predation (Bjørn and Erikstad, 1994; Bårdsen et al., 2018). Moreover, females experiencing harsher conditions may be more likely to start feeding during incubation to ensure their own survival at the expense of reproduction. Hence, OCs in the blood at hatching may originate partly from ingested food leading to lower concentrations than if OCs originated from endogenous lipids only. Finally, the positive relationship between OCs and effective temperature may be an indirect impact, i.e. since the temperature in June (when eiders incubate) was highly correlated to temperature in April ($r = 0.74$) it might be a carry-over effect from the spring, i.e. warm spring weather may speed up the transport and transmission of OCs in the food chain (Noyes and Lema, 2015; Borgå et al., 2022), leading to eiders ingesting higher loads.

3.4. Indirect climate impacts

Indirect climate impacts were defined as effects related to the long-
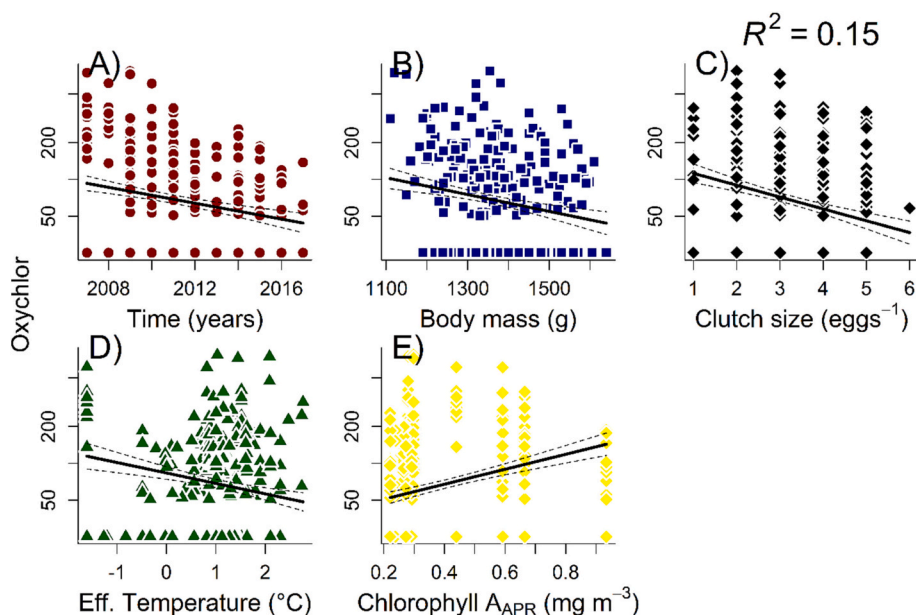
Fig. 3. Relationships between Oxychlordane concentrations (pg g^{-1}, wet weight) in the blood of incubating common eider females and Year (A), Body mass (B), Clutch size (C), Effective temperature (D) and Spring chlorophyll *a* (E). See legends under Fig. 2 for technical details. Data from Kongsfjorden, Svalbard, 2007–2017.

range transport of OCs, or effects that are manifested by altering the bioavailability or biomagnification through the food chain. To assess the potential impact of long-range transport we used the Arctic Oscillation in the three preceding winters (AO$_{winter\ 1}$, AO$_{winter\ 2}$, AO$_{winter\ 3}$: to account for potential time-lags) (see Macdonald et al., 2005; Bustnes et al., 2010a; Borgå et al., 2022). We hypothesized positive relationships with OCs, but there were no significant positive associations between the AO variables, and the selected models included no time-lagged AO variables (Table 3), except for a weak positive effect of AO$_{winter\ 3}$ on *cis*-nonachlor ($P = 0.02$; results not shown). Hence, the present study found very little support for direct relationships between variation in potential atmospheric transport of OCs and the concentrations in eider blood, as have been found for some other Arctic seabirds (Bustnes et al., 2010a; Foster et al., 2019).

Indirect impacts of climate may be reflected in changes in the food chain, and as eiders arrive in Kongsfjorden in April (Hanssen et al., 2016), they prepare for breeding by building up large body reserves for egg laying and incubation locally and depend on the availability of large quantities of benthic prey species (Guillemette, 2001). Hence, does variation of the spring climate lead to variation in the bioavailability of OCs to the eiders? AO$_{winter\ 1}$ is a good proxy for spring climate since it summarizes several important climate indexes (SST, SAT, ice conditions etc.: see Methods). These factors, and in particular the effects that AO has on the marine environment, may strongly impact the arctic benthic organisms that the common eiders feed on prior to nesting (Beuchel et al., 2006; Ambrose et al., 2006; Morata et al., 2015). In addition, to further assess potential food chain impacts, we examined the effect of spring primary production using Chl*a* measurements in the marine system. Alterations in the primary production is expected to have implications for the bioavailability of OCs entering the base of the food chain (Borgå et al., 2010, 2022), including the benthic system (van den Brink et al., 2011; Wagner et al., 2019). There were significant, but negative, relationships between AO$_{winter\ 1}$ and HCB, *trans*-chlordane and *trans*-nonachlor, whereas for PCB153 and *p,p'*-DDE, there were no relationships (Table 3). For oxychlordane and *cis*-nonachlor, Chl*a* was significantly and positively related (Table 3). High primary production in the fjord may depend on an influx of water masses high in nutrients and possibly also OCs, predicting a positive relationship between Chl*a* and OCs. Hence, for the relatively volatile HCB and chlordane compounds, spring conditions, i.e., low AO$_{winter\ 1}$ and high Chl*a*

corresponded to high concentrations of OCs in Kongsfjorden and input to the benthic food chain. Our observations might also be related to glacial melting (Morselli et al., 2014), although a time lag would be expected for this effect since eiders build up their body reserves prior to the annual ice melt.

Although, recent assessments concluded that the use and regulation of OCs is still the most important driver for the temporal trends seen in both the abiotic environment and biota (Hung et al., 2022), the present study suggests that a warming climate will have consequences for the remobilization to OCs in high arctic common eiders at the point in time when they are in poor body condition and most vulnerable to physiological stress. However, these relationships are complex and individual traits of females, such as body mass and especially clutch size (included in the selected models for all 7 compounds), play a role in the determination of circulating OCs, i.e. low body condition and small clutch size were associated to high OC concentrations. Furthermore, over the last decades, the Arctic has warmed at a very high rate, much faster than in temperate areas, and concurrent with this warming several OCs, such as HCB and *p,p'*-DDE have increased in eider blood. This might come about through increased transport of OCs to the Arctic, redistribution of OCs already present, and/or remobilization of deposited OCs by glacial melting. Moreover, relatively strong positive relationship between concentrations of the dominant OCs and effective temperature suggests that a warming climate may increase the exposure to OCs. This was contrary to our expectations, and there may be several explanations for these relationships, including individual reproductive investment and more indirect effects relating to OC intake prior to breeding. As such, this temperature effect may not be considered a direct impact on the individual, but rather an indirect effect. Finally, the study suggests that the spring conditions, proxied by AO$_{winter\ 1}$, and primary production were significant factors for HCB and most chlordanes, and that climate has some indirect effects for some compounds, and this seems to be manifested through changes in the food chain. However, such indirect climate impacts were relatively weak, and more research is needed to establish such links.

CRediT authorship contribution statement

Jan Ove Bustnes: *Conceptualization, analyses, writing*.
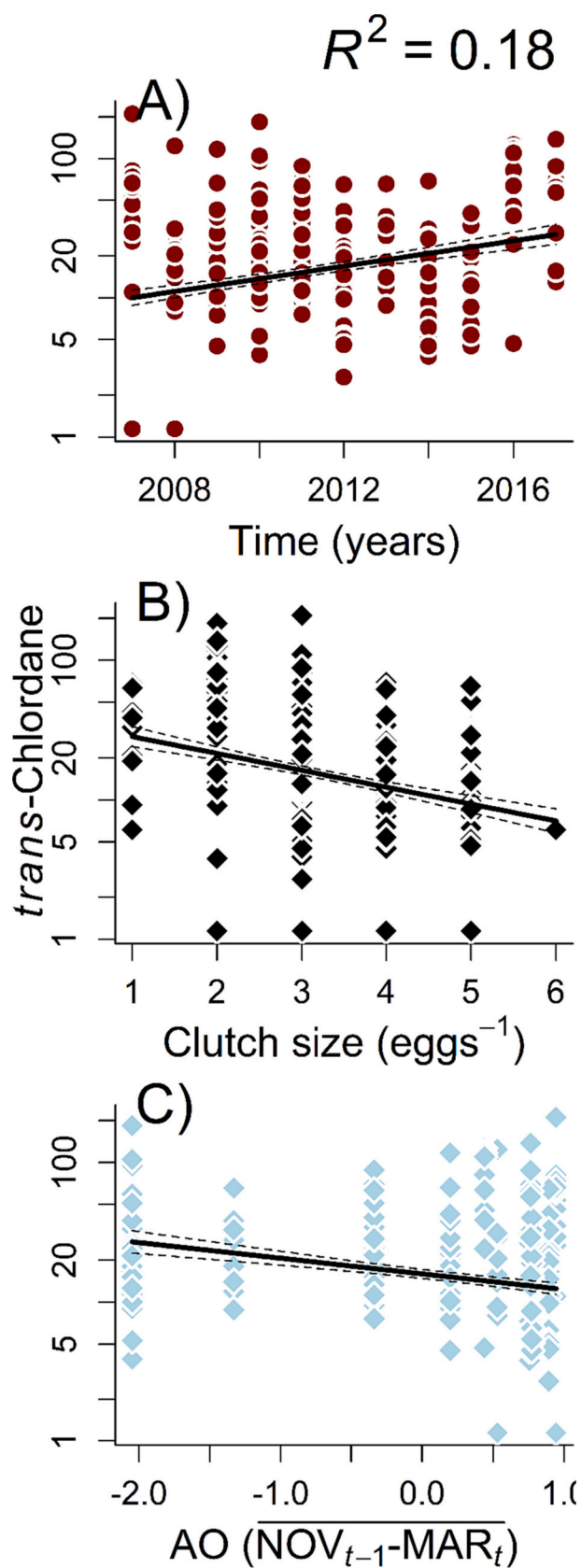Bård-Jørgen Bårdsen: *Conceptualization, statistical analyses,*

Fig. 4. Relationships between *trans*-chlordane concentrations (pg g^{-1}, wet weight) in the blood of incubating common eider females and Year (A), Clutch size (B), and Arctic Oscillation in preceding winter (C). See legends under Fig. 2 for technical details. Data from Kongsfjorden, Svalbard, 2007–2017.
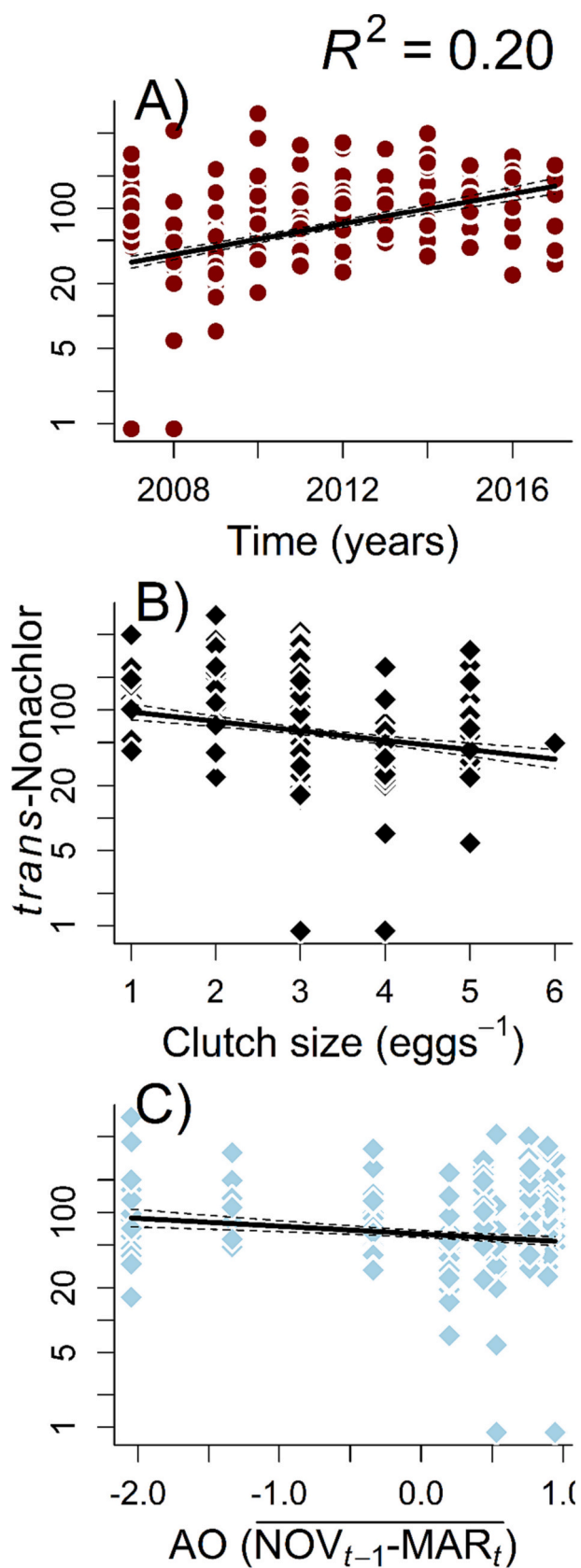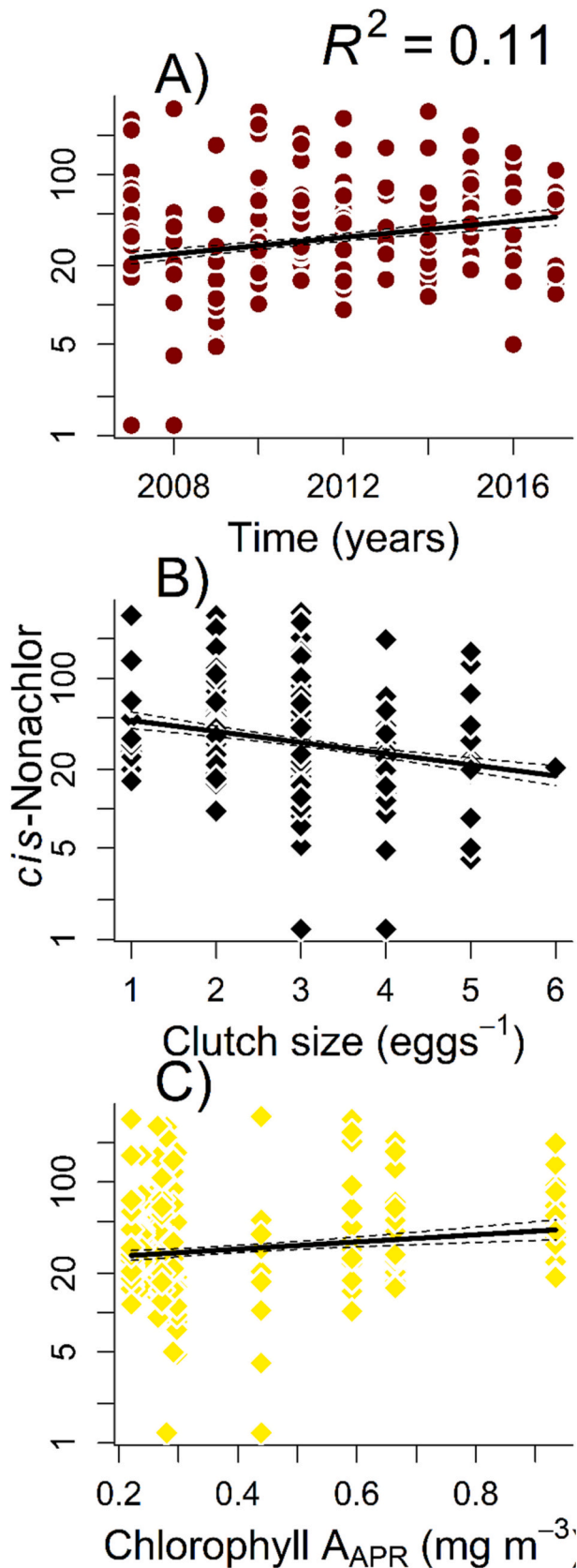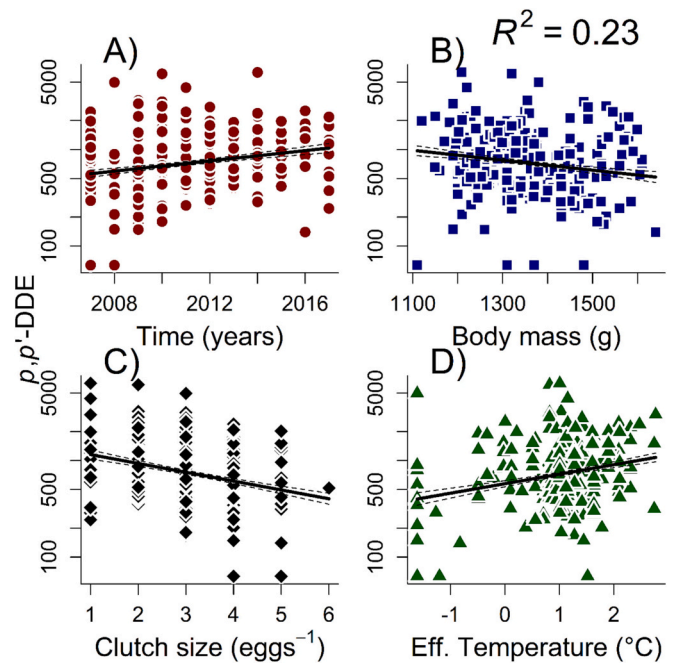
Fig. 5. Relationships between *trans*-nonachlor concentrations (pg g^{-1}, wet weight) in the blood of incubating common eider females and Year (A), Clutch size (B), and Arctic Oscillation in preceding winter (C). See legends under Fig. 2 for technical details. Data from Kongsfjorden, Svalbard, 2007–2017.
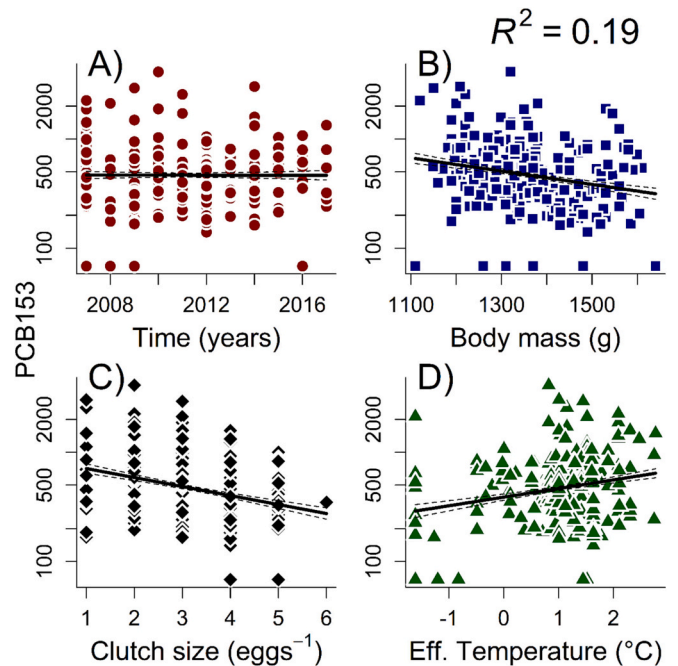
Fig. 6. Relationships between *cis*-nonachlor concentrations (pg g^{-1}, wet weight) in the blood of incubating common eider females and Year (A), Clutch size (B), and Spring chlorophyll (C). See legends under Fig. 2 for technical details. Data from Kongsfjorden, Svalbard, 2007–2017.

Fig. 7. Relationships between *p,p′*-DDE concentrations (pg g^{-1}, wet weight) in the blood of incubating common eider females and Year (A), Body mass (B), Clutch size (C), Effective temperature (D). See legends under Fig. 2 for technical details. Data from Kongsfjorden, Svalbard, 2007–2017.

Fig. 8. Relationships between PCB153 concentrations (pg g^{-1}, wet weight) in the blood of incubating common eider females and Year (A), Body mass (B), Clutch size (C), Effective temperature (D).
See legends under Fig. 2 for technical details. Data from Kongsfjorden, Svalbard, 2007–2017.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168096.

References

Ambrose, W.G., Carroll, M.L., Greenacre, M., Thorrold, S.R., McMahon, K.W., Thorrold, S.R., 2006. Variation in *Serripes groenlandicus* (Bivalvia) growth in a Norwegian high-Arctic fjord: evidence for local- and large-scale climatic forcing. Glob. Chang. Biol. 12, 1595–1607.

Anderson, D.R., 2008. Model Based Inference in the Life Sciences: A Primer on Evidence. Springer-Verlag, Berlin, Germany.

Barber, J.L., van Wijk, D., Jones, K.C., 2005. Hexachlorobenzene in the global environment: emissions, levels, distribution, trends and processes. Sci. Total Environ. 349, 1–44.

Bårdsen, B.J., Hanssen, S.A., Bustnes, J.O., 2018. Multiple stressors in a sub-arctic marine bird: modelling the effect of pollution, climate change and predation on demography and population viability. Ecosphere 9, e02342.

Bargar, T.A., Scott, G.I., Cobb, G.P., 2001. Maternal transfer of contaminants: case study of the excretion of three polychlorinated biphenyl congeners and technical-grade endosulfan into eggs by white leghorn chickens (*Gallus domesticus*). Environ. Toxicol. Chem. 20, 61–67.

Beuchel, F., Gulliksen, B., Carroll, M.L., 2006. Long-term patterns of rocky bottom macrobenthic community structure in an Arctic fjord (Kongsfjorden, Svalbard) in relation to climate variability (1980–2003). J. Mar. Syst. 63, 35–48.

Bjørn, T.H., Erikstad, K.E., 1994. Patterns of intraspecific nest parasitism in the high arctic common eider (*Somateria mollissima borealis*). Can. J. Zool. 72, 1027–1034.

Bolduc, F., Guillemette, M., 2003. Incubation constancy and mass loss in the common eider *Somateria mollissima*. Ibis 145, 329–332.

Borgå, K., Saloranta, T.M., Ruus, A., 2010. Simulating climate change-induced alterations in bioaccumulation of organic contaminants in an Arctic marine food web. Environ. Toxicol. Chem. 29, 1349–1357.

Borgå, K., McKinney, M.A., Routti, H., Fernie, K.J., Giebichenstein, J., Hallanger, I., Muir, D.C.G., 2022. The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs. Environ. Sci.-Process. Imp. 10, 1544–1576.

Burnham, K.P., Anderson, D.R., 2002. Model Selection and Multimodel Inference. A Practical Information-Theoretic Approach. Springer-Verlag, New York, p. 2002.

Bustnes, J.O., Gabrielsen, G.W., Verreault, J., 2010a. Climate variability and temporal trends of persistent organic pollutants in the Arctic: a study of glaucous gulls. Environ. Sci. Technol. 44, 3155–3161.

Bustnes, J.O., Moe, B., Herzke, D., Hanssen, S.A., Nordstad, T., Sagerup, K., Gabrielsen, G.W., Borgå, K., 2010b. Strongly increasing blood concentrations of lipid-soluble organochlorines in high arctic common eiders during incubation fast. Chemosphere 79, 320–325.

Bustnes, J.O., Yoccoz, N., Bangjord, G., Herzke, D., Ahrens, L., Skaare, J.U., 2011. Impacts of climate and feeding condition on the annual accumulation (1986–2009) of persistent organic pollutants in a terrestrial raptor. Environ. Sci. Technol. 45, 7542–7547.

Bustnes, J.O., Moe, B., Herzke, D., Hanssen, S.A., Nordstad, T., Fenstad, A., Borgå, K., Gabrielsen, G.W., 2012. Temporal dynamics of circulating persistent organic pollutant in a fasting seabird under different environmental conditions. Environ. Sci. Technol. 46, 10287–10294.

Bustnes, J.O., Bårdsen, B.J., Moe, B., Herzke, D., Hanssen, S.A., Sagerup, K., Beck, C., Nordstad, T., Chastel, O., Tartu, S., Gabrielsen, G.W., 2017. Temporal variation in circulating concentrations of organochlorine pollutants in a pelagic seabird breeding in the High Arctic. Environ. Toxicol. Chem. 36, 442–448.

Bustnes, J.O., Bårdsen, B.-J., Herzke, D., Bangjord, G., Bollinger, E., Bourgeon, S., Schulz, R., Fritsch, C., Eulaers, I., 2022. The impact of climate sensitive factors on the exposure of organohalogenated contaminants in an aquatic bird exploiting both freshwater and marine environments. Sci. Total Environ. 850, 157667.

CAFF, 2013. Arctic Biodiversity Assessment. Status and Trends in Arctic Biodiversity. Conservation of Arctic Flora and Fauna, Akureyri.

Criscuolo, F., Gabrielsen, G.W., Gendner, J.P., Le Maho, Y., 2002. Body mass regulation during incubation in female common eiders *Somateria mollissima*. J. Avian Biol. 33, 83–88.

Drouillard, K.G., Norstrom, R.J., 2001. Quantifying maternal and dietary sources of 2,2′,4,4′,5,5′-hexachlorobiphenyl deposited in eggs of the ring dove (*Streptopelia risoria*). Environ. Toxicol. Chem. 20, 561–567.

Fenstad, A.A., Jenssen, B.M., Gabrielsen, K.M., Öst, M., Jaatinen, K., Bustnes, J.O., Hanssen, S.A., Moe, B., Herzke, D., Krøkje, Å., 2016. Persistent organic pollutant levels and the importance of source proximity in Baltic and Svalbard breeding common eiders. Environ. Toxicol. Chem. 35, 1526–1533.

Foster, K.L., Braune, B.M., Gaston, A.J., Mallory, M.L., 2019. Climate influence on legacy organochlorine pollutants in Arctic seabirds. Environ. Sci. Technol. 53, 2518–2528.

Fox, J., 2002. An R and S-PLUS Companion to Applied Regression. Sage Publications, London, UK and Thousand Oak, USA.

Guillemette, M., 2001. Foraging before spring migration and before breeding in Common Eiders: does kyperphagia occur? Condor 103, 633–638.

Hanssen, S.A., Moe, B., Bårdsen, B.J., Hanssen, F., Gabrielsen, G.W., 2013. A natural antipredation experiment: predator control and reduced sea ice increases colony size in a long-lived duck. Ecol. Evol. 3, 3554–3564.

Hanssen, S.A., Gabrielsen, G.W., Bustnes, J.O., Bråthen, V.S., Skottene, E., Fenstad, A., Strøm, H., Bakken, V., Phillips, R.A., Moe, B., 2016. Migration strategies of common eiders from Svalbard: implications for bilateral conservation management. Polar Biol. 39, 2179–2188.

Hebert, C.E., Weseloh, D.V.C., Idrissi, A., Arts, M.T., O'Gorman, R., Gorman, O.T., Locke, B., Madenjian, C.P., Roseman, E.F., 2008. Restoring piscivorous fish populations in the Laurentian Great Lakes causes seabird dietary change. Ecology 89, 891–897.

Henriksen, E.O., Gabrielsen, G.W., Skaare, J.U., 1998. Validation of the use of blood samples to assess tissue concentrations of organochlorines in glaucous gull *Larus hyperboreus*. Chemosphere 37, 2627–2643.

Hilde, C.H., Pelabon, C., Guery, L., Gabrielsen, G.W., Decamps, S., 2016. Mind the wind: microclimate effects on incubation effort of an arctic sebird. Ecol. Evol. 6, 1914–1921.

Hung, H., Brorstrom-Lunden, E., Olafsdottir, K., Aas, W., Breivik, K., Bohlin-Nizzetto, P., Sigurdsson, A., Hakola, H., Bossi, R., Skov, H., Sverko, E., Barresi, E., Fellin, P., Wilson, S., 2016. Temporal trends of persistent organic pollutants (pops) in arctic air: 20 years of monitoring under the Arctic Monitoring and Assessment Programme (AMAP). Environ. Pollut. 217, 52–61.

Hung, H., Halsall, C., Ball, H., Bidleman, T., Dachs, J., De Silva, A., Hermanson, M., Kallenborn, R., Muir, D., Suhring, R., Wang, X.P., Wilson, S., 2022. Climate change influence on the levels and trends of persistent organic pollutants (POPs) and chemicals of emerging Arctic concern (CEACs) in the Arctic physical environment - a review. Environ. Sci.- Process. Imp. 24, 1577–1615.

Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M., 2003. The North Atlantic Oscillation: climate significance and environmental impact. Geophys. Monogr. Ser. 134 (279 pp.).

Lydersen, C., Gjertz, I., Weslawsik, J.M., 1989. Stomach contents of autumn-feeding marine vertebrates from Hornsund. Svalbard. Polar Records 25, 107–114.

Ma, J.M., Hung, H., Macdonald, R.W., 2016. The influence of global climate change on the environmental fate of persistent organic pollutants: a review with emphasis on the Northern Hemisphere and the Arctic as a receptor. Glob. Planet. Chang. 146, 89–108.

Macdonald, R.W., Harner, T., Fyfe, J., 2005. Recent climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. Sci. Total Environ. 342, 5–86.

Mazerolle, M.J., 2020. AICcmodavg: Model Selection and Multimodel Inference Based on (Q)AIC(c).

Morata, N., Michaud, E., Włodarska-Kowalczuk, M., 2015. Impact of early food input on the Arctic benthos activities during the polar night. Polar Biol. 38, 99–114.

Morselli, M., Semplice, M., Villa, S., Di Guardo, A., 2014. Evaluating the temporal variability of concentrations of POPs in a glacier-fed stream food chain using a combined modeling approach. Sci. Total Environ. 493, 571–579.

Næss, M.W., Bårdsen, B.-J., Pedersen, E., Tveraa, T., 2011. Pastoral herding strategies and governmental management objectives: predation compensation as a risk buffering strategy in the Saami reindeer husbandry. Hum. Ecol. 39, 489–508.

Noyes, P.D., Lema, S.C., 2015. Forecasting the impacts of chemical pollution and climate change interactions on the health of wildlife. Curr. Zool. 61, 669–689.

Noyes, P.D., McElwee, M.K., Miller, H.D., Clark, B.W., van Tiem, L.A., Walcott, K.C., Erwin, K.N., Levin, E.D., 2009. The toxicology of climate change: environmental contaminants in a warming world. Environ. Int. 35, 971–986.

Overland, J.E., Hanna, E., Hanssen-Bauer, I., Kim, S.-J., Walsh, J.E., Wang, M., Bhatt, U. S., Thoman, R.L., Ballinger, T.J., 2019. Surface air temperature. In: Richter-

Menge, J., Druckenmiller, M.L., Jeffries, M. (Eds.), Arctic Report Card. http://www.artic.noaa.gov/Repor-Card.

Parker, H., Holm, H., 1990. Patterns of nutrient and energy expenditure in female common eiders nesting in the high Arctic. Auk 107, 660–668.

Platt, S.M., Hov, Ø., Berg, T., Breivik, K., Eckhardt, S., Eleftheriadis, K., Evangeliou, N., Fiebig, M., Fisher, R., Hansen, G., Hansson, H.-C., Heintzenberg, J., Hermansen, O., Heslin-Rees, D., Holmén, K., Hudson, S., Kallenborn, R., Krejci, R., Krognes, T., Larssen, S., Lowry, D., Lund Myhre, C., Lunder, C., Nisbet, E., Nizzetto, P.B., Park, K.-T., Pedersen, C.A., Aspmo Pfaffhuber, K., Röckmann, T., Schmidbauer, N., Solberg, S., Stohl, A., Ström, J., Svendby, T., Tunved, P., Tørnkvist, K., van der Veen, C., Vratolis, S., Yoon, Y.J., Yttri, K.E., Zieger, P., Aas, W., Tørseth, K., 2022. Atmospheric composition in the European Arctic and 30 years of the Zeppelin Observatory, Ny-Ålesund. Atmos. Chem. Phys. 22, 3321–3369. https://doi.org/10.5194/acp-22-3321-2022.

Polischuk, S.C., Norstrom, R.J., Ramsay, M.A., 2002. Body burdens and tissue concnetartions of organochlorines in polar bears (*Ursus maritimus*) vary during seasonal fast. Environ. Pollut. 118, 29–39.

Pouch, A., Zaborska, A., Pazdro, K., 2018. The history of hexachlorobenzene accumulation in Svalbard fjords. Environ. Monit. Assess. 190, 360.

R Core Team, 2021. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rantanen, M., Karpechko, A.Y., Lipponen, A., Nordling, K., Hyvärinen, O., K., Vihma, T., Laaksonen, A., 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Commun. Earth. Environ. 3, 168. https://doi.org/10.1038/s43247-022-00498-3.

Rigét, F., Vorkamp, K., Hobson, K.A., Muir, D.C.G., Dietz, R., 2013. Temporal trends of selected POPs and the potential influence of climate variability in a Greenland ringed seal population. Environ. Sci.-Proc. Imp. 15, 1706–1716.

Rigét, F., Vorkamp, K., Eulaers, I., Dietz, R., 2020. Influence of climate and biological variables on temporal trends of persistent organic pollutants in Arctic char and ringed seals from Greenland. Environ. Sci.-Proc. Imp. 22, 993–1005.

Rigor, I.G., Wallace, J.M., Colony, R.L., 2002. Response of sea ice to the Arctic oscillation. J. Clim. 15, 2648–2663.

Stearns, S.C., 1992. The Evolution of Life Histories. Oxford University Press, Oxford.

Stenseth, N.C., Mysterud, A., Ottersen, G., Hurrell, J.W., Chan, K.-S., Lima, M., 2002. Ecological effects of climate fluctuations. Science 297, 1292–1296.

Tartu, S., Blevin, P., Bustamante, P., Angelier, F., Bech, C., Bustnes, J.O., Gabrielsen, G. W., Guotte, A., Moe, B., Sauser, C., Sire, J., Barbraud, C., Chastel, O., 2022. U-turn for mercury concentrations over 20 years: how do environmental conditions affect exposure in Arctic seabirds? Environ. Sci. Technol. 56, 2443–2454.

Thomas, M.G., Næss, M.W., Bårdsen, B.-J., Mace, R., 2016. Smaller Saami herding groups cooperate more in a public goods experiment. Hum. Ecol. 44, 633–642.

van den Berg, H., Manuweera, G., Konradsen, F., 2017. Global trends in the production and use of DDT for control of malaria and other vector-borne diseases. Malar. J. 16, 401.

van den Brink, N.W., van Franeker, J.A., de Ruiter-Dijkman, E.M., 1998. Fluctuating concentrations of organochlorine pollutants during a breeding season in two Antarctic seabirds: adélie penguin and southern fulmar. Environ. Toxicol. Chem. 17, 702–709.

van den Brink, N.W., Riddle, M.J., van den Heuvel-Greve, M., van Franeker, J.A., 2011. Contrasting time trends of organic contaminants in Antarctic pelagic and benthic food webs. Mar. Pollut. Bull. 6, 128–132.

Wagner, C.C., Amos, H.M., Thackray, C.P., Zhang, C.P., Lundgren, E.W., Forget, G., Friedman, C.L., Selin, N.E., Lohmann, R., Sunderland, E.M., 2019. A global 3-D ocean model for PCBs: Benchmark compounds for understanding the impacts of global change on neutral persistent organic pollutants. Glob. Biogeochem. Cycles 33, 469–481.

Wang, Y., Haibo, B.I., Huang, H., Liu, Y., Liu, Y., Liang, X., Fu, M., Zhang, Z., 2019. Satellite-observed trends in the Arctic sea ice concentration for the period 1979–2016. J. Ocean. Limno. 37, 18–37. https://doi.org/10.1007/s00343-019-7284-0.

Wilson, A.J., Nussey, D.H., 2010. What is individual quality? An evolutionary perspective. Trends Ecol. Evol. 25, 207–214.

Yee, T., Moler, C., 2020. VGAM: Vector Generalized Linear and Additive Models.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology With R. Springer, New York, USA.

Zuur, A.F., Ieno, E.N., Elphick, C.S., 2010. A protocol for data exploration to avoid common statistical problems. Methods Ecol. Evol. 1, 3–14.