Supporting Information:

Investigating the impact of climate change on PCB-153 exposure in Arctic seabirds with the Nested Exposure Model

Skogeng, Lovise Pedersen*[1,2], Blévin, Pierre[3], Breivik, Knut[1,4], Bustnes, Jan Ove[5], Eulaers, Igor[6], Sagerup, Kjetil[3,5], Krogseth, Ingjerd Sunde[1,2]

[1]The Climate and Environmental Research Institute – NILU, Tromsø, Norway
[2]Department of Arctic and Marine Biology, UiT – Arctic University of Norway, Tromsø, Norway
[3]Environmental Impacts, Akvaplan-niva, Tromsø, Norway
[4]Department of Chemistry, University of Oslo, Oslo, Norway
[5]Nowegian Institute for Nature Research, Tromsø, Norway
[6]Pollution and Marine Mammals, Norwegian Polar Institute, Tromsø, Norway

*Corresponding author, email: lpe050@uit.no

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SI.1. Parameterization of species included in the Nested Exposure Model

Following is a thorough description of the parameterization of the filter feeder and seabirds (common eider, black-legged kittiwake, and glaucous gull) included in the Nested Exposure Model (NEM). Parameters included as input to NEM have been underlined.

SI.1.1. Filter feeder

The filter feeder module in NEM is developed by adapting parameters from the filter feeder described by Krogseth *et al*[1] to data from blue mussels, where available. Following is a description of the parameters that have been changed from the original model. Parameters that have not been updated (e.g., due to lack of information from blue mussels specifically) are the proportionality constant β (which accounts for the absorption capacities of various media when assessing the biotic Z value); the assimilation efficiency of lipids, NLOM and water; the diet uptake efficiency; and filter feeder gill ventilation. Descriptions of these parameters can be found in the original filter feeder model by Krogseth *et al*[1] which was based on the model by Arnot and Gobas[2].

SI.1.1.1. Life cycle

Blue mussels generally breed from spring to late summer. Here, the filter feeder is assumed to be born August 1st. Observed maximum life span of blue mussels was 7 to 18 years, and Barents Sea populations were characterized by maximum life spans of 12.3 years.[3] Here, the maximum life span of the filter feeder is assumed to be 9 years.

SI.1.1.2. Biochemical composition

According to the Norwegian Food Composition Database, the inner (edible) part of blue mussels constitute on average 51% of the whole animal (by mass) and has an average lipid content of 1.4%.[4] Based on this, the lipid content of the filter feeder (whole organism = inner part and shell) was assumed to be 0.71%.

The water content of the inner part of blue mussels is on average 88%,[4] and as the inner part constitutes 51% of the whole organism, the water content of the filter feeder (whole organism) is assumed to be 44.9%.

Ash or inorganic content of the inner parts of blue mussels is 1.79%.[5] Non-lipid organic matter (NLOM), meaning what is not lipids, water, or inorganic material of the inner part of the filter feeder is hence 8.81%. NLOM is assumed to be 4.49% of the whole organism.

SI.1.1.3. Size and growth

In NEM, the growth of the filter feeder is described as Weight (g ww) = $Ax^3 + Bx^2 + Cx + D$, where A-D are constants and x is age (in days).[2]

Blue mussel larvae in last stage before becoming a mussel is on average 0.298 mm.[6] Using a weight-length relationship of Weight (g) = Length (mm) · 0.16 (g/mm) for blue mussels,[7] the weight is 0.05 g at age 0. After 2 years, blue mussels weight 10 g, and the maximum size is 100 mm,[7] or 16.7 g using the same weight-length relationship as before. From this, a growth curve is extrapolated, and when adding a third order polynomial trendline with intercept set to 0.05 (minimum weight), the following growth equation is assumed:

Weight (g ww) = $8\cdot10^{-10}x^3 - 7\cdot10^{-6}x^2 + 0.0194x + 0.05$ (R = 0.99), where x is age in days.

SI.1.1.4. Diet

The filter feeder scavenges nutrients by filtrating the seawater, and the scavenging efficiency is assumed to be 100%.

Blue mussels mainly feed on phytoplankton, but also on suspended particles and zooplankton when filtrating water.[7] The filter feeder is assumed to feed on phytoplankton and suspended particles, and the fractions of the two in the diet are assumed to be 50% and 50%, respectively.

For phytoplankton, lipids on average constitutes 10% and ash constitutes on average 44.8% of dry weigh, and phytoplankton consists of 90% water.[8] Here, we assume that the lipid content is 1% and the NLOM content is 4.5% of the total organism.

The concentration of suspended particles in Kongsfjorden 2.5 km away from the glacier front and below the surface water column was below 40 mg/L.[9] The concentration of suspended particles can vary with the season, as terrestrial runoff increases with more precipitation, and glacial runoff increases with melting glaciers. Through the summer season, the concentration of suspended particles did not vary considerably between May, June, and August, when the concentration was measured between 24.2±11.3 and 46.5±41.7 mg/L in surface and advected waters in Kongsfjorden.[10] Here, a concentration of suspended particles of $4\cdot10^{-2}$ g/L is assumed.

SI.1.2. Seabird assumptions

The seabird compartments in NEM are generally based on the Canada goose (*Branta canadensis*) model described by Binnington *et al*[11]. The three species included here are differentiated through their parameters but have several assumptions in common. To minimize repetition, these common assumptions are summarized here.

SI.1.2.1. Chick and duckling growth rate

The growth of seabird chicks and ducklings are described by the following equation for black-legged kittiwakes in Kongsfjorden:[12]

$$BBB = \frac{BBB_{max}}{1 + \left(\frac{BBB_{max}}{BBB_{chick}} - 1\right) * e^{-A*days}}$$

Where BW is the current body weight in grams, BW_{max} is the adult initial body weight pre seasonal change, BW_{chick} is the body weight of the chick/duckling at hatching, and A is the exponent chick growth constant, adapted to the different species in the corresponding paragraphs (see paragraphs SI.1.3.3, SI.1.4.3 and SI.1.5.3 for common eider ducklings, kittiwake chicks and glaucous gull chicks, respectively).

SI.1.2.2. Water uptake and elimination

To conserve mass balance, adult seabirds are assumed to drink and excrete water in the same rate. The water uptake is assumed to be seawater through their marine diet. In NEM, water uptake/elimination rate is scaled to the body weight of the seabird.

Incubating female common eiders with a mean body weight of 1438 g (*n* = 6) had a median water influx rate of 90.06 ml/day.[13] Scaled to the body weight BW_{max} of 2090 g (section 1.3.3), the water uptake and elimination rate for female and male common eiders was assumed to be $5.4 \cdot 10^{-6}$ $m^3 \cdot h^{-1}$. Gabrielsen *et al*[14] reported water uptake rates for black-legged kittiwakes, resulting in assumed water uptake and elimination rates of $5.86 \cdot 10^{-6}$ m^3h^{-1} and $5.02 \cdot 10^{-6}$ m^3h^{-1} for male and female kittiwakes, respectively. Due to a lack of information, the same water uptake and elimination rate is assumed for glaucous gulls as for black-legged kittiwakes but scaled to the body weights of male and female glaucous gulls. This gives uptake and elimination rates of $1.88 \cdot 10^{-5}$ m^3h^{-1} and $2.31 \cdot 10^{-5}$ m^3h^{-1} for female and male glaucous gulls, respectively.

SI.1.2.3. Energy need

The energy assimilation efficiency is assumed to be 85%.[11]

The energy need of the seabirds was parameterized and used to calculate the feeding rates in the same way as for the Canada goose model,[11] and based on the Avian Bioaccumulation Model (ABAM).[15]

The daily energy requirement (DER) for the seabird is calculated as the sum of the mean daily energy expenditure (DEE), which is entered into the model as the field metabolic rate (FMR) and the daily cost/benefit of lipid production/utilization (DEL). DER is used to calculate the feeding rate based on the dietary composition of the seabird (see the corresponding dietary composition paragraphs for each seabird species, paragraph SI.1.3.5, SI.1.4.5 and SI.1.5.5), the lipid content of the dietary species, and the energy content of lipids (assumed to be 39.3 kJ/g).[15] DEL is calculated based on the seabird's lipid dynamics (see section SI.1.3.3, SI.1.4.3 and SI.1.5.3) and an assumed energy content of lipids.[11] A specific energy demand for producing eggs (as in Binnington *et al*[11]) was not included here, as this was instead accounted for in the detailed field-based seasonal lipid dynamics incorporated for the female seabirds, and hence included in DEL.

The mean daily energy expenditure (DEE) of resting non-incubating female common eiders with mean weight of 1600 g at thermoneutrality was 649.4 $kJ \cdot day^{-1}$,[13] which gives an assumed field metabolic rate of <u>$0.017\ kJ \cdot (g \cdot h)^{-1}$</u>, assumed for all seasons, ages and both sexes of common eiders. Lower energy needs for female common eiders during incubation has been reported by Parker and Holm[16] (490 $kJ \cdot day^{-1}$) and Gabrielsen *et al*[13] (604 $kJ \cdot day^{-1}$). The FMR is assumed to be <u>$0.078\ kJ(g \cdot h)^{-1}$</u> for all ages, seasons and both sexes of black-legged kittiwakes.[17] For glaucous gulls, the FMR was calculated from the average of measurements from Gabrielsen and Mehlum[18], Scholander *et al*[19] and Verreault *et al*[20]. This was <u>$0.024\ kJ(g \cdot h)^{-1}$</u>, assumed for all seasons and ages, and for both sexes of glaucous gulls.

SI.1.2.4. Biotransformation

Due to a lack of species-specific biotransformation rates for PCB-153 in seabirds, biotransformation rates for PCB-153 in seabirds, as used as input to NEM, were quantified by allometrically scaling the assumed biotransformation rate for PCB-153 in humans[21, 22] to the maximum body weight of the organisms, following Binnington *et al*[11] and Arnot and Gobas.[2] For common eiders with a maximum body weight of 2090 g, this gives an assumed biotransformation rate for PCB-153 of <u>$1.36 \cdot 10^{-5}\ h^{-1}$</u> (half-life of 5.8 years). Scaling this to a kittiwake with body weight of 400 g gives an assumed biotransformation rate for PCB-153 of <u>$2.05 \cdot 10^{-5}\ h^{-1}$</u> (half-life of 3.9 years). For glaucous gulls, scaling the biotransformation rate to a glaucous gull with body weight of 1752 g (male) gives an assumed biotransformation rate for PCB-153 of <u>$1.42 \cdot 10^{-5}\ h^{-1}$</u> (half-life of 5.6 years).

SI.1.2.5. Mother-egg ratio

In NEM, a mother-egg-ratio is used to calculate transfer of contaminants from the seabird to the egg, following Binnington *et al*[11] and Norstrom *et al*[15]. A mother-egg ratio for PCB-153 in Herring gull (*Larus argentatus*)[11] of 0.48 is assumed for all seabirds.

The age distribution of reproducing seabirds (see sections SI.1.3.2, SI.1.4.2 and SI.1.5.2 for eiders, kittiwakes and glaucous gulls, respectively) is used to calculate f and Z values for eggs.

SI.1.3. Common eider (*Somateria mollissima*)

SI.1.3.1. Body temperature

The average core body temperature of nesting females was 40 °C (n = 18).[13]

SI.1.3.2. Life span and reproduction

The average life expectancy for common eiders was found to be 26 years,[23] and here, a maximum age of 20 years was assumed. Eiders start breeding from they are 2 years old,[23] and they lay on average 5 eggs.[24] The age distribution of breeding female eiders is based on field experience and shown in Table SI.1.

Table SI.1: Age distribution of breeding female common eiders in the Nested Exposure Model (NEM), assuming they start breeding when they are 2 years old and live until they are 20 years old.

Age group (years)	Fraction (sum = 1)
0-2	0
2-4	0.1
4-6	0.2
6-8	0.1
8-10	0.1
10-12	0.1
12-14	0.1
14-16	0.1
16-18	0.1
18-20	0.1

Common eider eggs weigh on average 98 g,[13] have an assumed average lipid content of 20.82%,[25] and an assumed water content of 71%. The eggs in Kongsfjorden are assumed to be laid June 19th,[26] and are on average incubated for 25 days,[13] which means that they are assumed to hatch July 14th.

SI.1.3.3. Body weight and body composition

Ducklings: At hatching, the ducklings weigh on average 58.9 g,[27] and they reach adult weight after approximately 9 weeks.[28] Adapting the growth curve BW = 178.23 · (age in weeks)$^{1.04}$ by Hawkins *et al*,[28] and to how the ducklings reach adult weight after 9 weeks,[28] to the growth equation for chicks and ducklings by Moe *et al*[12] (see paragraph SI.1.2.1), the exponent chick growth constant A is 0.11 for common eider ducklings.

Adults: In the breeding season, reproducing female common eiders undergo large variations in body weight and body composition. The initial body weight (BW_{max}) is 2090 g (mean weight, n = 10)[29] and has a lipid content of 12.6% (average, n = 2)[16]. For 4-5 weeks before breeding, the female feeds heavily in the nesting area and increases her body weight by approximately 20%.[16] Here, the period of feeding and weight increase is assumed to last for 28 days, after which the maximum pre-breeding body weight ($BW_{Pre\text{-}breeding}$) is on average 2442 g,[13] with an average lipid content of 28.5%.[16] Following is the egg production period which is assumed to last for 7 days. After egg laying, the body weight of the female common eider is on average 2106 g,[13] and the female is left by her partner to incubate the eggs. The female do not feed during this period, and undergo a median weight loss of 30 g/day.[13] The expression for this weight loss is:

$$y(\text{loss}) = 2114.5 - 52.188x + 1.064x^2 + 0.006x^3$$

Where x is the days of incubation.[13] When the eggs hatch, the female common eider has an assumed minimum body weight (BW_{min}) of 1357 g[13] with an average assumed lipid content of 9.6%.[16] From the BW_{min} and the body weight of female common eiders caught 7-14 days after hatching (on average 1713 g),[16] it was assumed a weight gain of 25.4 g/day and that it would take a total of 29 days for the female to reach the initial body weight of 2090 g. Water content is assumed to be constant at 71%.

Male common eiders are also included in NEM but are not evaluated due to lack of both biometric data and measurement data for contaminants. The parameterization of the male is therefore done assuming that they have the same body weight and composition as an adult female outside of the breeding period, with no seasonal change.

SI.1.3.4. Respiration

The mean resting metabolic rate (oxygen uptake for non-incubating females) was 0.86 ml $O_2(g\cdot h)^{-1}$.[13] Assuming 21% oxygen in air, this translates to a respiration rate of $4.1\cdot10^{-6}$ $m^3(g\cdot h)^{-1}$. Scaled to the BW_{max} of 2090 g, gives an assumed respiration rate of $8.56\cdot10^{-3}$ $m^3\cdot h^{-1}$ for both male and female (non-incubating) common eiders. Female common eiders slow down their breathing when they are incubating their eggs,[13] but this is not included in NEM as it is assumed that respiration has a negligible effect on the total uptake of contaminants compared to other processes.

SI.1.3.5. Dietary composition

Of 35 different prey items found in the digestive system of common eiders in northern Norway, more than 50% were blue mussels (*Mytilus edulis*) and other epifauna bivalves.[30] The common nomenclature for the mussels used in this context is *filter feeders* (see SI.1.1). Amphipods and small fractions of predatory deposit feeders (snails and crabs) have also been identified as an important part of the diet of common eiders in Svalbard.[31]

Here, the dietary composition for the common eider was assumed to be 80% filter feeder and 20% amphipods, with no seasonal variations.

Common eiders are selective feeders on epifauna, and will select bigger and more meat rich mussels when given the opportunity.[30] Here, it is assumed that the common eiders mainly feed on older (and thus bigger) filter feeders, and the assumed age distribution of filter feeders in the common eider's diet is shown in Table SI.2.

Table SI.2: Assumed age distribution between the three age groups of filter feeders in the common eider's diet in NEM.

Age group (years)	Fraction (sum = 1)
0-3	0.2
3-6	0.4
6-9	0.4

SI.1.4. Black-legged kittiwake (*Rissa tridactyla*)

SI.1.4.1. Body temperature

Black-legged kittiwake is assumed to have a core temperature of 40°C.[32, 33]

SI.1.4.2. Life span and reproduction

The maximum life expectancy for the kittiwake is assumed to be 20 years, and the kittiwake is assumed to reproduce annually from age 4 by laying on average 2 eggs annually until the end of life (field experience). The assumed age distribution of reproducing kittiwakes is shown in Table SI.3.

*Table SI.3: Assumed age distribution of reproducing black-legged kittiwakes (*Rissa tridactyla*) that live for 20 years and starts reproducing from age 4.*

Age groups (years)	Fraction (sum = 1)
0-2	0
2-4	0
4-6	0.2
6-8	0.2
8-10	0.1
10-12	0.1
12-14	0.1
14-16	0.1
16-18	0.1
18-20	0.1

The eggs are assumed to have an average weight of 40 g,[34] and consist of 71% water and 7% lipids.[25] The eggs are assumed to hatch July 11th in Kongsfjorden, Svalbard,[35] after being incubated for 28 days.

SI.1.4.3. Body weight and body composition

Chicks: At hatching, the kittiwake chick is assumed to weight 30 g. The body weight increase daily according to measurements from northern Norway by Barrett and Runde.[36] Adapted to the growth equation for chicks and ducklings by Moe *et al*[12] (see section SI.1.2.1), the exponent chick growth constant A is 0.181 for kittiwake chicks.

Adults: For the rest of the kittiwake's lifetime, the body weight is assumed to be constant, with the exception of an imposed seasonality in body weight during breeding season.[12] The body weight (BW_{max}) for adult female and male kittiwakes is assumed to be on average 380 g and 443 g, respectively.[12]

During the 28 days of incubation, the body weight of the female kittiwake is assumed to increase with $0.93\ g \cdot day^{-1}$.[12] The body weight of the male is assumed to not increase during incubation. After the eggs hatch, an intense chick rearing period lasting 40 days follows, where the female and male kittiwake are assumed to experience body weigh decrease of $4\ g \cdot day^{-1}$ and $3.6\ g \cdot day^{-1}$, respectively.[12] After chick rearing, the adult kittiwake's body weight is assumed to increase for 45 days until BW_{max} is regained. For the rest of the year, the body weight is assumed to be constant for both sexes of kittiwakes.

Based on Golet and Irons,[37] whole-body lipid content is assumed to be 9.5% during non-chick rearing periods, and 7.4% during chick-rearing periods. This is adapted to the BW-equations, by letting the lipid content decrease linearly during the intense chick-rearing period, stay constant for the remainder of the chick rearing period, and increase linearly during the body weight build-up period. No increase in lipid content is assumed for females during incubation.

Water content of kittiwakes is assumed to be constant at 71%.

SI.1.4.4. Respiration

Blévin *et al*[32] reported an average oxygen consumption rate for resting adult kittiwakes, resulting in assumed respiration rates of $0.0028\ m^3h^{-1}$ and $0.0033\ m^3h^{-1}$ for females and males, respectively (assuming 21% oxygen in air).

SI.1.4.5. Dietary composition

Here, it is assumed that the kittiwakes feed on polar cod (*Boreogadus saida*), capelin (*Mallotus villosus*), herring (*Clupea harengus*), krill and amphipods. The dietary composition is based on research by Vihtakari *et al*[38] in Kongsfjorden during the breeding season and is shown in Table SI.4. Due to lack of information from other seasons, the composition is assumed to be constant throughout the year.

The amphipods in NEM are based on carnivorous pelagic species (*Themisto abyssorum, T. libellula*),[39] but the contaminant load in pelagic and ice-dependent amphipods are comparable, and the variance is more influenced by the diet than by the habitat.[40] The amphipods in NEM are thus assumed to also represent ice-dependent amphipods.

A changing climate reduces the availability of sea ice and allows Atlantic species to venture into the Arctic ocean, changing the availability of common prey species. For the purpose of testing different climate scenarios on the bioaccumulation of PCB-153 in kittiwakes, two alternative diets (future scenarios, FS) were constructed. FS1 hypothesises that polar cod will be replaced with Atlantic cod (*Gadus morhua*), while FS2 hypothesises all ice-dependent species (polar cod, capelin and amphipods) to be replaced with herring and krill (Table SI.4).

*Table SI.4: The assumed dietary composition of black-legged kittiwake (*Rissa tridactyla*) in the Nested Exposure Model (NEM), based on Vihtakari* et al. [38] *The sum of the fractions in each diet sum to 1. Due to a lack of information, the composition is assumed to be constant for all seasons. Also included are two hypothesised future scenarios (FS), where polar cod has been replaced by Atlantic cod (FS1), and where all polar species are virtually replaced by krill (FS2).*

Prey	**Base**	**FS1**	**FS2**
Polar Cod	0.55	0.00	0.00
Capelin	0.13	0.13	0.00
Herring	0.05	0.05	0.08
Krill	0.22	0.22	0.92
Amphipods	0.05	0.05	0.00
Atlantic cod	0.00	0.55	0.00

The assumed age distribution of the fish species in the diet of the black-legged kittiwake is shown in Table SI.5. The age distribution is also based on Vihtakari *et al*,[38] and is assumed constant throughout the year.

Table SI.5: The assumed age distribution of the fish species (polar cod, capelin and herring) in the diet of the black-legged kittiwake in the Nested Exposure Model. The fraction of each specie adds up to 1.

	Age group (years)									
Prey	**0-1**	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**	**7-8**	**8-9**	**9-10**	**sum**
Polar cod	0.01	0.60	0.32	0.07	0	0	0	0	0	0	**1**
Capelin	0.00	0.64	0.29	0.06	0.01	0	0	0	0	0	**1**
Herring	0.40	0.60	0	0	0	0	0	0	0	0	**1**
Atlantic cod	1	0	0	0	0	0	0	0	0	0	**1**

SI.1.5. Glaucous gull (*Larus hyperboreus*)

SI.1.5.1. Body temperature

Body temperature of 40°C is assumed, based on research on black-legged kittiwakes.[32]

SI.1.5.2. Life span and reproduction

The highest known age for a glaucous gull ring marked in the Norwegian Arctic is 19 years.[41] Here, the gull is assumed to live for 20 years. It is assumed that the glaucous gull starts reproducing when they are 4 years old (field experience) by laying on average 3 eggs annually[42, 43] until they are approximately 17 years old (field experience). The assumed age distribution of reproducing glaucous gulls is shown in Table SI.6.

*Table SI.6: Assumed age distribution of reproducing glaucous gulls (*Larus hyperboreus*) in the Nested Exposure Model (NEM).*

Age group (years)	Fraction (sum = 1)
0-2	0
2-4	0
4-6	0.1
6-8	0.2
8-10	0.2
10-12	0.2
12-14	0.1
14-16	0.1
16-18	0.1
18-20	0

Based on unpublished field measurements from Kongsɳorden, Svalbard between 2011 and 2021 (*n* = 193), the median egg hatching date (with success) was June 22nd. The incubation period was assumed to last for 28 days.[43]

Mean weight of glaucous gull eggs was on average 108 g,[43] and eggs are assumed to contain 10.45% lipids[25] and 71% water.

SI.1.5.3. Body weight and body composition

Chicks: The body mass of hatching chicks is on average 81 g.[44, 45] Chick growth measurements from Kongsɳorden, Svalbard reported by Sagerup *et al*[44] were adapted to the growth equation for chicks and ducklings (see section SI.1.2.1), which gave the exponent chick growth constant A as 0.120 for glaucous gull chicks.

Adults: The body weights (BW_{max}) of female and male glaucous gulls are assumed to be 1428 g and 1752 g, respectively. These are averages of unpublished field data from Kongsɳorden, Svalbard from 2008 to 2021 (*n* = 158 for females and *n* = 79 for males). The capture of glaucous gulls is more complicated than for the common eider and black-legged kittiwake. Usually, a glaucous gull can only be captured once per breeding season, during the incubation, and the gull will learn how to avoid being caught again (field experience). This means that there is only one measurement done per breeding season, and no measurements for glaucous gulls outside of the breeding season. A constant body weight with no seasonal change is thus assumed, even if it is reasonable to expect some body weight change during incubation and chick rearing.

Glaucous gulls contain on average 4.61% lipids (n = 10, whole body analysis in gulls from Kongsfjorden),[46] and no seasonal change is assumed due to a lack of data. Water content is assumed to be constant at 71%.

SI.1.5.4. Respiration

Mass-specific oxygen consumption rates of 1.21 ml $O_2(g\cdot h)^{-1}$ for males and 1.33 $O_2(g\cdot h)^{-1}$ for females were reported by Verreault *et al*.[20] This converts to respiration rates of $0.009\ m^3h^{-1}$ and $0.010\ m^3h^{-1}$ for females and males, respectively (assuming 21% oxygen in the air).

SI.1.5.5. Dietary composition

Glaucous gulls are opportunistic feeders and may feed on chicks and eggs and young from other seabirds, as well as on polar cod, capelin, amphipods, and krill, and scavenge on carcasses from adult seabirds, seals, or other species.[41] Eggs and ducklings/chicks from common eider and black-legged kittiwake is an important contribution to the glaucous gull's diet during the breeding season in Kongsfjorden. Analysis of regurgitate pellets collected at two different seabird colonies (inland and shore) at the Bear Island, Barents Sea identified the composition of key dietary species in the glaucous gull's diet.[47] The opportunistic nature of the glaucous gull's feeding makes it difficult to accurately predict the possible fraction of seal or whale carcasses in the diet, and these species are therefore excluded for now. The dietary composition for the gulls in the colony closest to the sea from Bustnes *et al*,[47] combined with field experience from the glaucous gull in Kongsfjorden, resulted in the assumed dietary composition shown in Table SI.7. Note that there is a seasonal change in the diet, where the glaucous gull scavenges on common eider and black-legged kittiwake during the breeding season (when eggs and chicks are available), while the rest of the year has no seasonal change. In NEM, the eggs are exclusively available to be eaten by the glaucous gull during incubation, i.e. from egg-laying to hatching (see section SI.1.3.2 and SI.1.4.2 for eiders and kittiwakes, respectively). Ducklings and chicks are assumed to be available to the glaucous gull for the first 10 days after hatching, up until they weight about 200 g (field experience). The sex ratio of ducklings and chicks in the diet is assumed to be 1:1. The age distribution of the fish species in the glaucous gull's diet is shown in Table SI.8.

Table SI.7: Assumed dietary composition of glaucous gulls in Kongsfiorden used as input to NEM. The sum of the fractions in each season adds up to 1. The composition is based on field experience and research done on glaucous gull colonies close to the shore on Bear Island.[47]

Prey	Spring	Summer	Autumn	Winter
Polar cod	0.28	0.2	0.28	0.28
Capelin	0.28	0.2	0.28	0.28
Kittiwake (eggs + chicks)	0	0.15	0	0
Eider (eggs + ducklings)	0	0.15	0	0
Krill	0.22	0.15	0.22	0.22
Amphipods	0.22	0.15	0.22	0.22

Table SI.8: Assumed age distribution of polar cod and capelin in the diet of the glaucous gull.

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
Polar cod	0.01	0.6	0.32	0.07	0	0	0	0	0	0
Capelin	0	0.64	0.29	0.06	0.01	0	0	0	0	0

SI.2. Supporting figures and tables

SI.2.1. Tables

Table SI.9: Measured concentrations of PCB-153 in biota used for the evaluation of newly added species in NEM.

Target NEM compartment	Species (*scientific name*)	Year(s)	*n*	Reference
Filter feeder	Blue mussel (*Mytilus edulis)*	1993-1997, 1999-2007, 2009, 2012-2019	89	Norwegian Environment Agency[48]
	Bathyarca glacialis, Ciliatocardium ciliatum	2016	6	Evenset *et al*[49]
Seabird: Common eider	Common eider (*Somateria mollissima*)	2007-2017	223	Bustnes *et al*[50]
	Common eider (*Somateria mollissima*)	2017-2021	58	Norwegian Environment Agency[48]
Seabird EGG: Common eider eggs	Common eider (*Somateria mollissima*)	2015	17	Rodvelt (MSc thesis)[25]
	Common eider (*Somateria mollissima*)	2017-2021	75	Norwegian Environment Agency[48]
Seabird: Black-legged kittiwake	Black-legged kittiwake (*Rissa tridactyla*)	2007-2011, 2015, 2017-2021	347	NPI (NPDC)[51]
Seabird EGG: Black-legged kittiwake eggs	Black-legged kittiwake (*Rissa tridactyla*)	1995	5	Berrett *et al*[52]
	Black-legged kittiwake (*Rissa tridactyla*)	2008	10	Miljeteig and Gabrielsen[53]
	Black-legged kittiwake (*Rissa tridactyla*)	2013-2014	10	Norwegian Environment Agency[48]
	Black-legged kittiwake (*Rissa tridactyla*)	2015	11	Rodvelt (MSc thesis)[25]
Seabird:	Glaucous gull	2008-2021	216	NPI (NPDC)[51]

Glaucous gull	(*Larus hyperboreus*)			
Seabird EGG: Glaucous gull eggs	Glaucous gull (*Larus hyperboreus*)	2012-2013, 2020	15	NPI (NPDC)[51]
	Glaucous gull (*Larus hyperboreus*)	2015	5	Rodvelt (MSc thesis)[25]

*Table SI.10: Comparison between modelled and measured concentrations of PCB-153 in blue mussels (*Mytilus edulis*) in four non-consecutive grid cells along the coast of Northern Norway. The comparable parameters are the estimate-measurement ratio (EMR), the model bias (MB) and the root mean square error of the log transformed concentrations ($RMSE_{log}$).*

Grid cell	Coordinates of upper left corner (Lat, Long)	EMR median (range)	MB	$RMSE_{log}$
9	75°N, 25°E	0.14 (0.029 – 0.50)	0.14	10
10	75°N, 30°E	0.16 (0.0077 – 0.39)	0.13	9.4
12	70°N, 15°E	1.1 (0.14 – 2.9)	0.86	3.7
15	70°N, 30°E	0.36 (0.019 – 0.45)	0.21	8.1
Overall	-	0.24 (0.0077 – 2.9)	0.26	7.8

Table SI.11: Comparison between modelled and measured concentrations of PCB-153 in seabird species in Kongsfjorden. The comparable parameters are the estimate-measurement ratio (EMR), the model bias (MB) and the root mean square error of the log transformed concentrations ($RMSE_{log}$).

Specie		EMR median (range)	MB	$RMSE_{log}$
Common eider	Female	0.87 (0.030 – 7.3)	0.79	4.2
	Egg	0.56 (0.18 – 1.6)	0.53	3.3
Black-legged kittiwake	Female	0.85 (0.48 – 1.4)	0.85	7.2
	Male	0.87 (0.60 – 1.2)	0.87	6.0
	Egg	0.45 (0.12 – 1.4)	0.44	4.5
Glaucous gull	Female	0.36 (0.039 – 3.8)	0.36	6.0
	Male	0.23 (0.061 – 1.6)	0.253	6.9
	Egg	0.23 (0.085 – 0.57)	0.22	6.8

Table SI.12: Linear regression of the measured and modelled time trends of PCB-153 for the seabird species common eider (CE), black-legged kittiwake (KW) and glaucous gull (GG), divided in female (F) and male (M). The table gives the rate constant for decline (k) and environmental half-lives ($t_{1/2}$) of the measured and modelled time trends. The analysis approach is further detailed in Krogseth et al.[39]

	Specie	CE	KW	KW	GG	GG
	Sex	F	F	M	F	M
	Time period	2007 - 2021	2007 - 2021	2007 - 2021	2008 - 2021	2008 - 2021
Measured	**n (birds)**	281	158	186	151	77
	k (year-1)	0.0563	-0.0077	0.0326	-0.0373	0.0288
	95%CI low.	0.0309	-0.0424	0.0071	-0.0737	-0.0140
	95%CI up.	0.0817	0.0269	0.0581	-0.0009	0.0716
	p	0.00002	0.7	0.01	0.04	0.2
	t1/2 (years)	12	-90	21	-19	24
Modelled	**n (age groups)**	9	8	8	8	8
	k (year-1)	0.077	0.080	0.080	0.076	0.079
	95%CI low.	0.076	0.079	0.079	0.074	0.076
	95%CI up.	0.078	0.081	0.081	0.079	0.082
	p	0.00001	0.00001	0.00001	0.00001	0.00001
	t1/2 (years)	9.0	8.7	8.6	9.1	8.8

SI.2.2. Figures

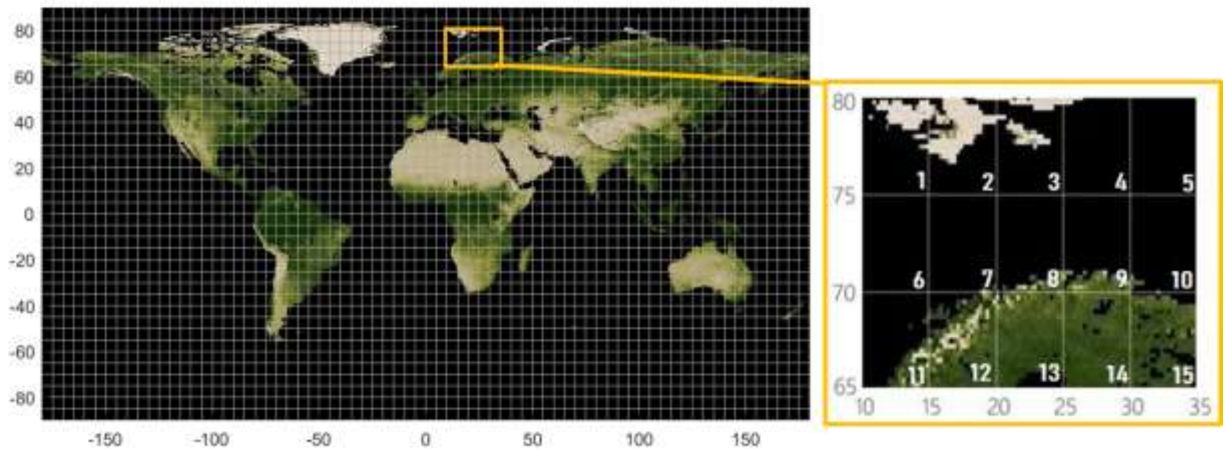


Figure SI.1: The modelled spatial domain included in the present study for the physical environment (the globe) and for the biota (yellow square), covering Svalbard (grid cell 1) and the coast of northern Norway where the measurement data from filter feeders were sampled (grid cells 9, 10, 12 and 15).

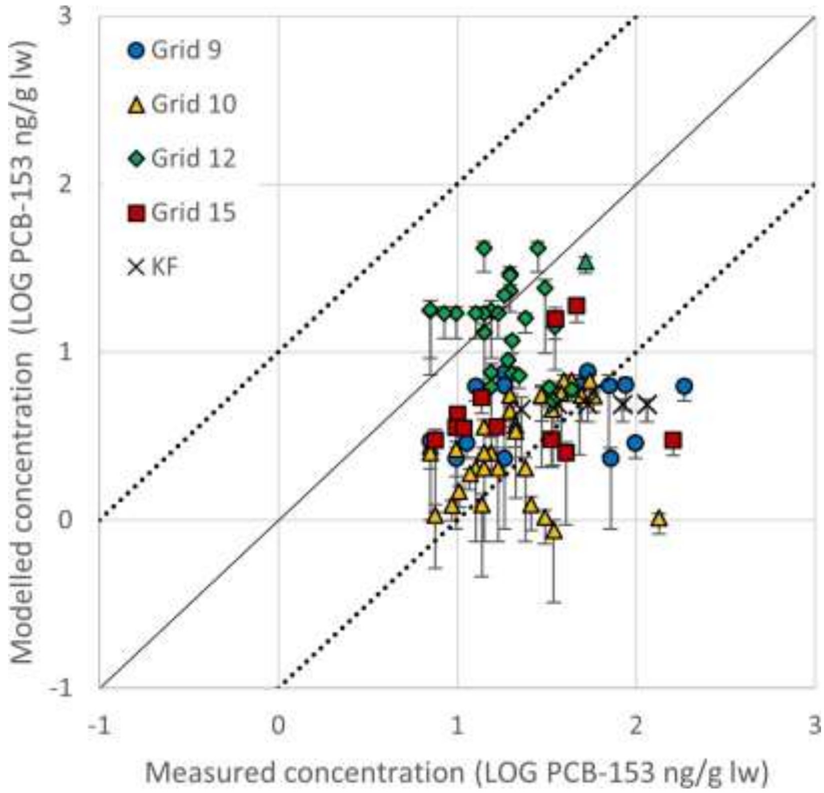


Figure SI.2: Measured PCB-153 concentrations in blue mussels from four grid cells along the Northern Norwegian coast were compared to modelled concentrations (median of all age groups, the error bars represent the span in these concentrations) in the same spatial and temporal domain (grid cells 9, 10, 12 and 15). Measured concentrations of PCB-153 in two mussel species sampled in Kongsfiorden are also included (KF). Modelled and measured concentrations are on a logarithmic scale to facilitate comparison, and the solid line represents a 1:1 fit between modelled and measured concentrations. The dotted lines represent a fit within one order of magnitude.

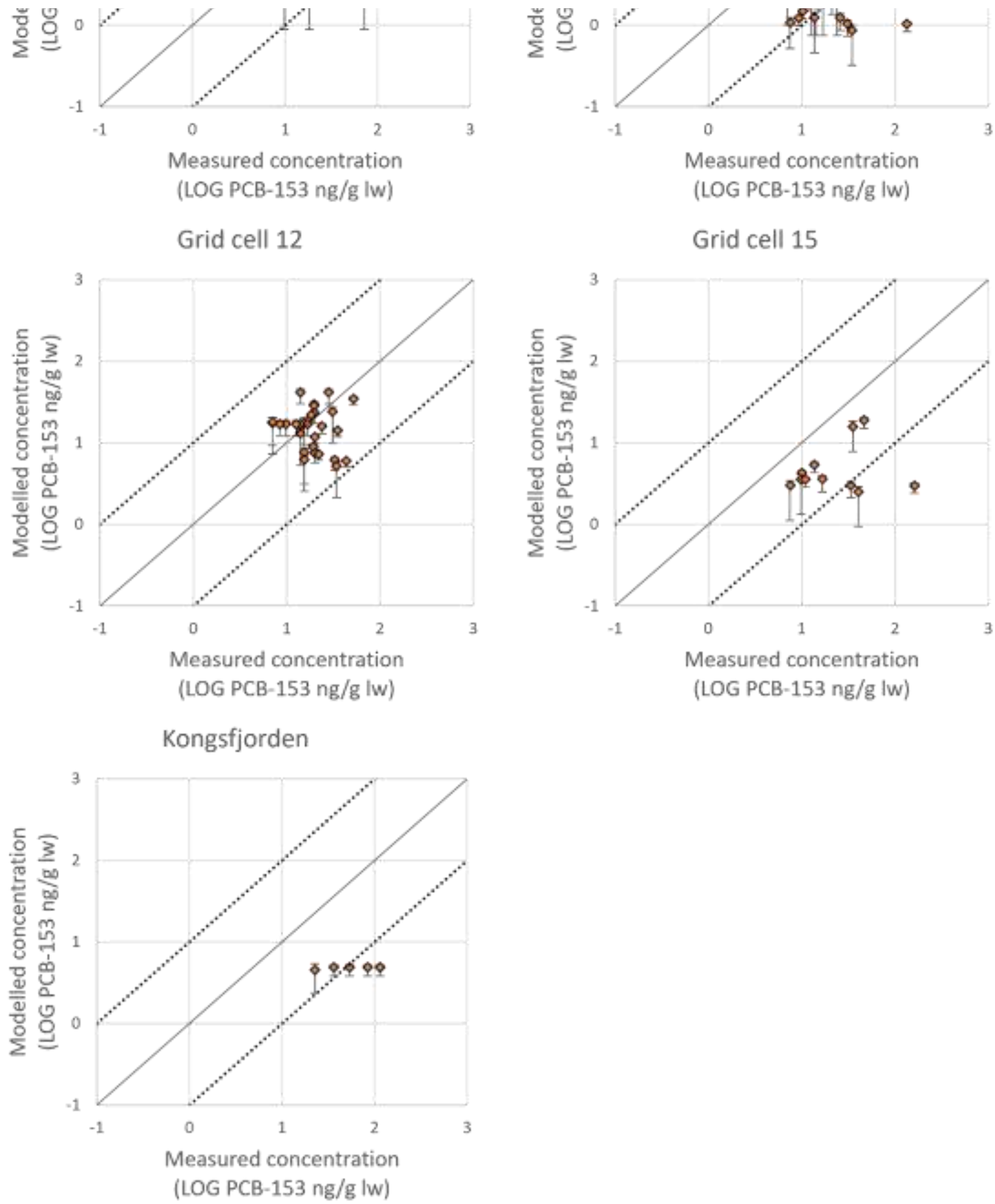


Figure SI.3: Measured concentrations of PCB-153 in **blue mussels** sampled along the coast of Norway, spanning over four non-consecutive grid cells (numbered 9, 10, 12 and 15) plotted against NEM modelled concentrations of PCB-153 in the filter feeder compartment in the same grid cells. Also included are measurements from two species of mussels sampled in Kongsfjorden compared to modelled concentrations in the same area and time. The modelled concentrations are medians of concentrations in the three age groups of the filter feeder, and the error bars represent the span in these concentrations. Modelled and measured concentrations are on a logarithmic scale to facilitate comparison, and the solid line represents a 1:1 fit between modelled and measured concentrations, meaning data point closer to this line is better. The dotted lines represent a fit within one order of magnitude.

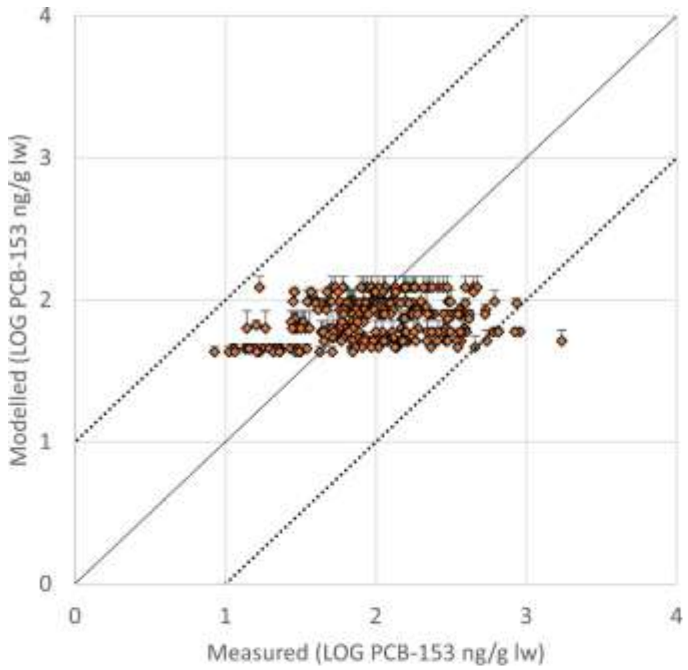


*Figure SI.4: Measured concentrations of PCB-153 in whole blood from female **common eiders** breeding in Kongsfiorden (2007-2021) compared to NEM modelled concentrations in the same grid cell and time. The modelled concentrations are medians of concentrations in the age groups of where the eider is assumed to be breeding (2-20 years). The error bars represent the span in these concentrations, and only the positive error bars are visible due to the median = the minimum value. Modelled and measured concentrations are on a logarithmic scale to facilitate comparison, and the solid line represents a 1:1 fit between modelled and measured concentrations. The dotted lines represent a fit within one order of magnitude.*

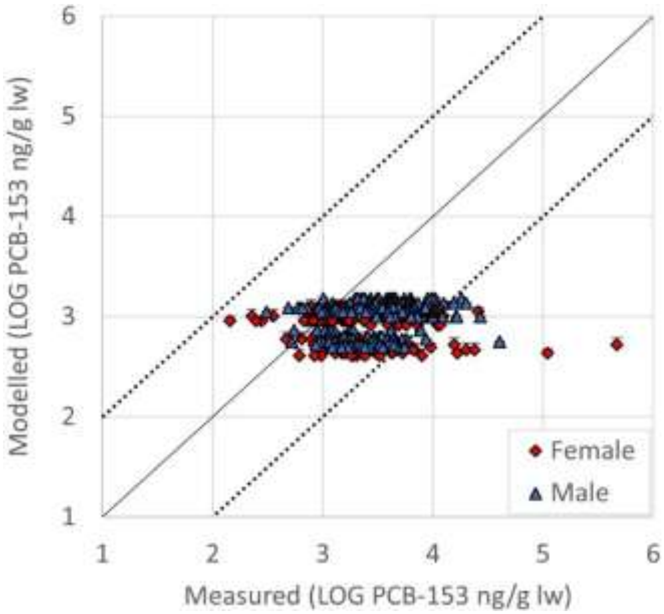


Figure SI.5: Measured concentrations of PCB-153 in female (diamond) and male (triangle) black-legged kittiwakes (Rissa tridactyla) sampled in Kongsfiorden (2007-2011, 2015, and 2017-2021) compared to NEM modelled concentrations from the same grid cell and time. The modelled concentrations are medians of concentrations in the age groups (n=8) of where the kittiwake is assumed to be breeding (4-20 years). The error bars represent the span in these concentrations, and only the positive error bars are visible due to the median = the minimum value. Additionally, only the female has a span in the concentrations due to contaminant elimination through egg-laying. Modelled and measured concentrations are on a logarithmic scale to facilitate comparison, and the solid line represents a 1:1 fit between modelled and measured concentrations. The dotted lines represent a fit within one order of magnitude. The modelled concentrations appear to be divided into two groups, due to a hiatus in the sampling period between 2011 and 2015.

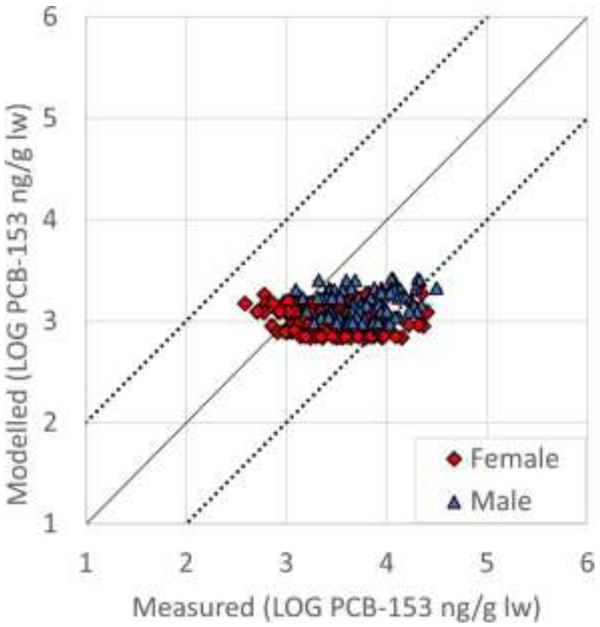
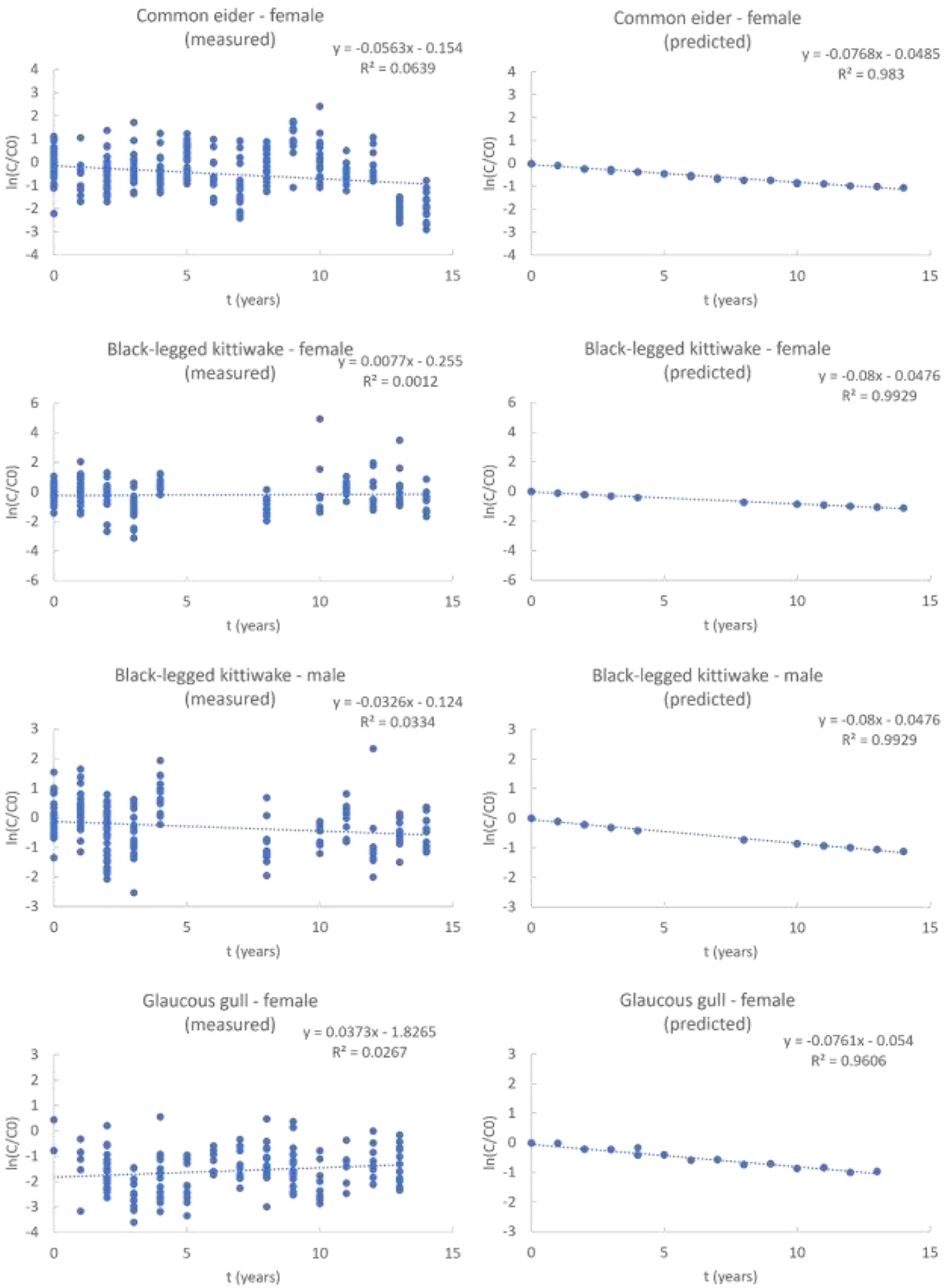


Figure SI.6: Measured concentrations of PCB-153 in female (diamond) and male (triangle) glaucous gulls (Larus hyperboreus) sampled in Kongsfiorden (2008-2021) compared to NEM modelled concentrations from the same grid cell and time. The modelled concentrations are medians of concentrations in the age groups of where the gull is assumed to be breeding (4-20 years). Modelled and measured concentrations are on a logarithmic scale to facilitate comparison, and the solid line represents a 1:1 fit between modelled and measured concentrations. The dotted line represents a fit within one order of magnitude.


Common eider - female
(measured)
y = -0.0563x - 0.154
R² = 0.0639
ln(C/C0)
t (years)
Common eider - female
(predicted)
y = -0.0768x - 0.0485
R² = 0.983
ln(C/C0)
t (years)
Black-legged kittiwake - female
(measured)
y = 0.0077x - 0.255
R² = 0.0012
ln(C/C0)
t (years)
Black-legged kittiwake - female
(predicted)
y = -0.08x - 0.0476
R² = 0.9929
ln(C/C0)
t (years)
Black-legged kittiwake - male
(measured)
y = -0.0326x - 0.124
R² = 0.0334
ln(C/C0)
t (years)
Black-legged kittiwake - male
(predicted)
y = -0.08x - 0.0476
R² = 0.9929
ln(C/C0)
t (years)
Glaucous gull - female
(measured)
y = 0.0373x - 1.8265
R² = 0.0267
ln(C/C0)
t (years)
Glaucous gull - female
(predicted)
y = -0.0761x - 0.054
R² = 0.9606
ln(C/C0)
t (years)

(continued)

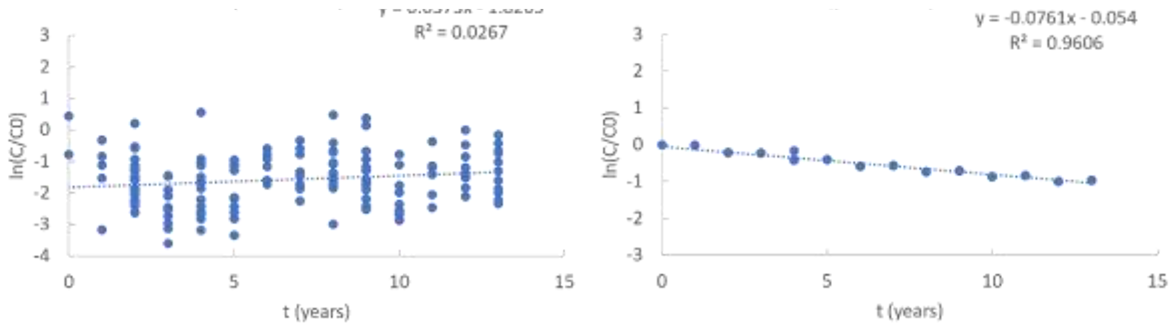


Figure SI.7: Linear regression of time trends for the measured (left) and predicted (right) concentrations of PCB-153 in the common eider (female), the black-legged kittiwake (female and male), and the glaucous gull (female and male). The measurements and model predictions are from Kongsfiorden, Svalbard, in 2007-2021. The time trends are represented by the natural logarithm of the concentration (C) over the median concentration from the first year of measurements (C_0), t years after the first year of measurements. The slope of the curve is used to derive the half-life ($t_{1/2}$) of PCB-153 in the time trend, given in Table SI.11.

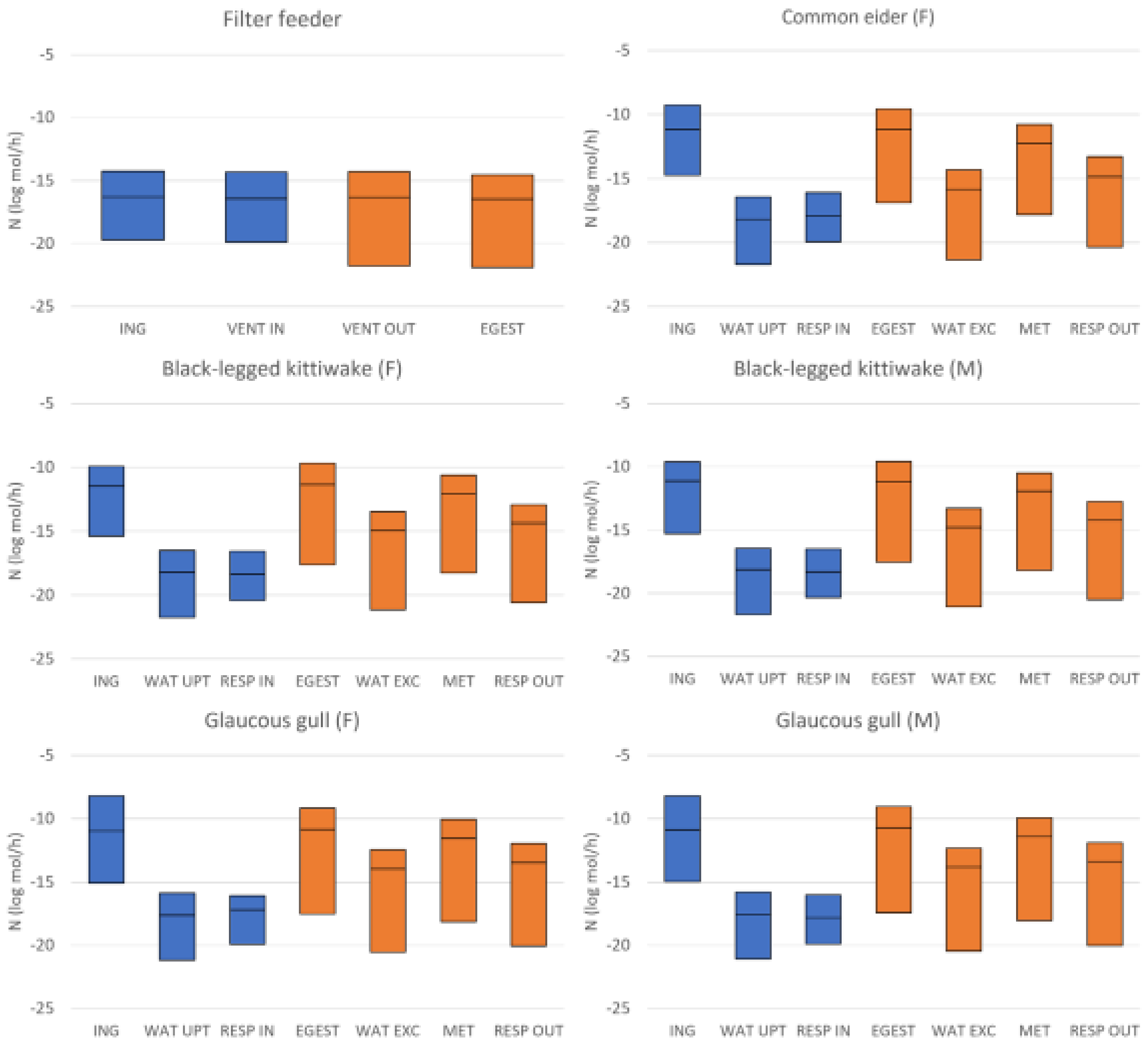


Figure SI.8: Range (min, median and max) of transport rates (N) in mol/h for each uptake (blue) and elimination (orange) process for PCB-153 in the filter feeder and seabirds in NEM: Ingestion (ING), ventilation in/out (VENT IN/VENT OUT), egestion (EGEST), water uptake/excretion (WAT UPT/WAT EXC), respiration in/out (RESP IN/RESP OUT), and metabolism

(MET). The seabirds are divided in female (F) and male (M). The N values are on a logarithmic scale to facilitate comparison between the different processes in each species. Reproduction/egg laying for female seabirds has not been included.*

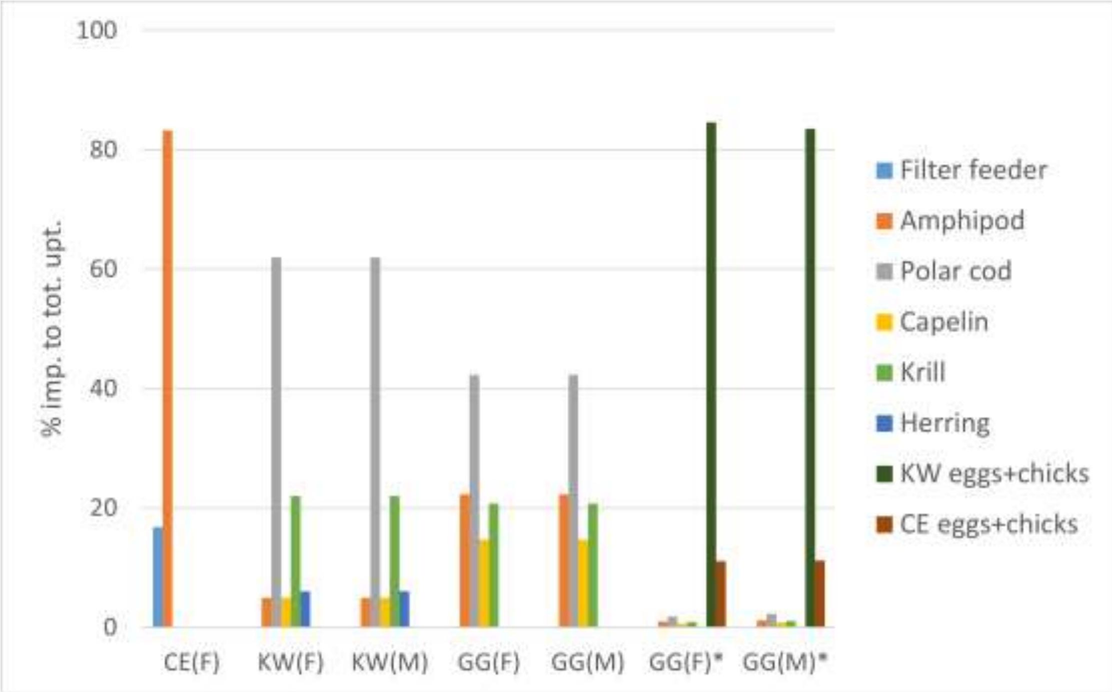


Figure SI.9: Importance of dietary species for the uptake of PCB-153, as a percentage of the total uptake through ingestion (N, mol/h) of the contaminant in the female (F) common eider (CE), female and male (M) black-legged kittiwake (KW), and female and male glaucous gull (GG) in Kongsfiorden, Svalbard, modelled in the Nested Exposure Model (NEM). For the glaucous gulls, two parts are shown: diets when eggs and chicks of KW and CE are included (*), and diets for the rest of the year excluding eggs and chicks.

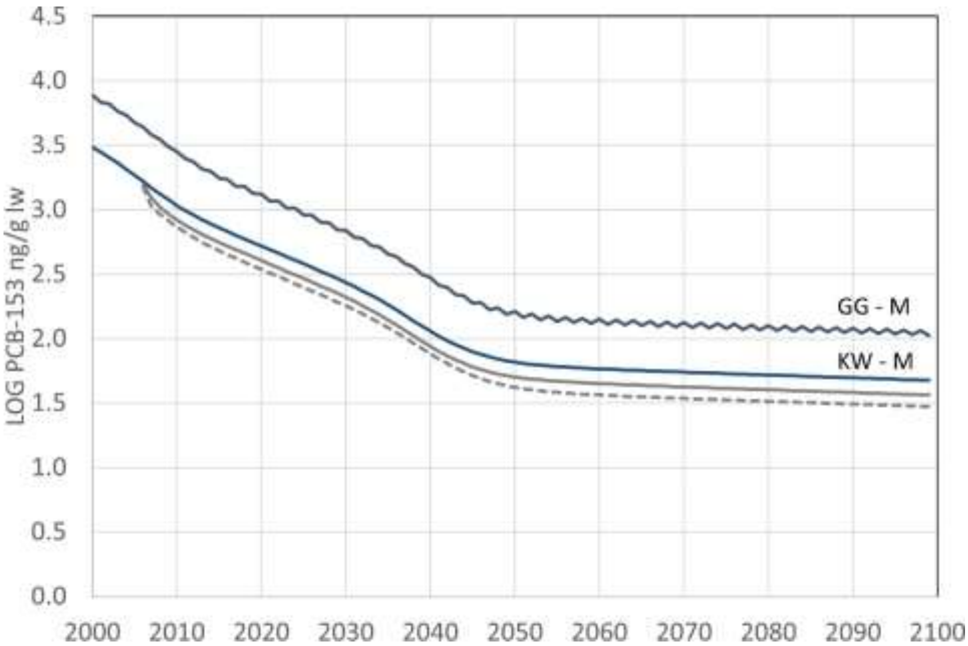


Figure SI.10: Modelled time trend of PCB-153 concentrations in female (red) and male (blue) eiders (CE), kittiwakes (KW) and glaucous gulls (GG) in Kongsfiorden from 2000 to 2100 given estimated global emissions from Breivik et al.[54] *Also included are the modelled time trends given two dietary scenarios for kittiwakes starting in 2006,[38] where polar cod has been replaced by Atlantic cod (FS1, grey stippled line), and all ice-dependent species have been replaced (FS2, grey unbroken line); and a ambient temperature driven scenario for the female eider, where a warmer climate has led to changed lipid* dynamics during reproduction (grey dotted line). The concentrations are log-scaled to facilitate comparison among species and sexes.*

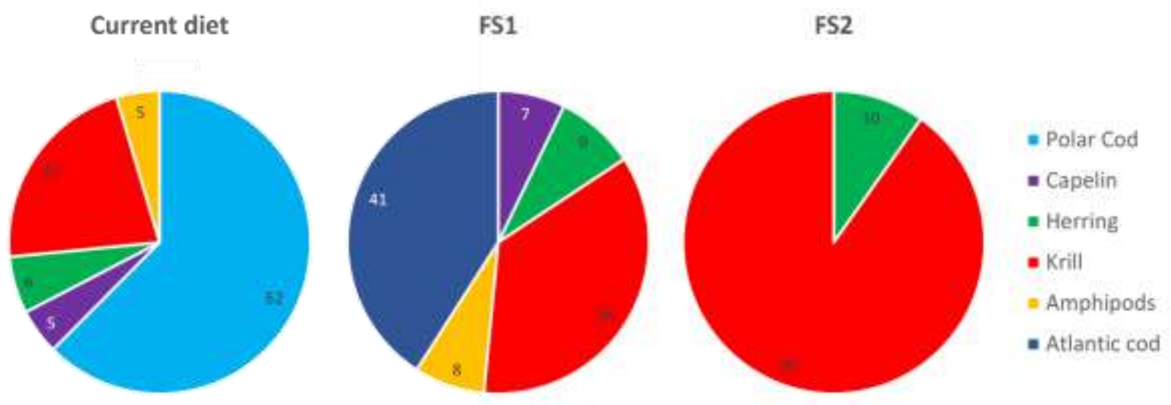


Figure SI.11: Importance (%) of the species to the total dietary uptake of PCB-153 in kittiwakes, at three different diets: The current diet consisting of a range of species typically found in the Arctic food web, and two future scenarios (FS), where a polar specie have been replaced by an Atlantic specie (FS1), and where all ice-dependent species are removed from the diet (FS2).

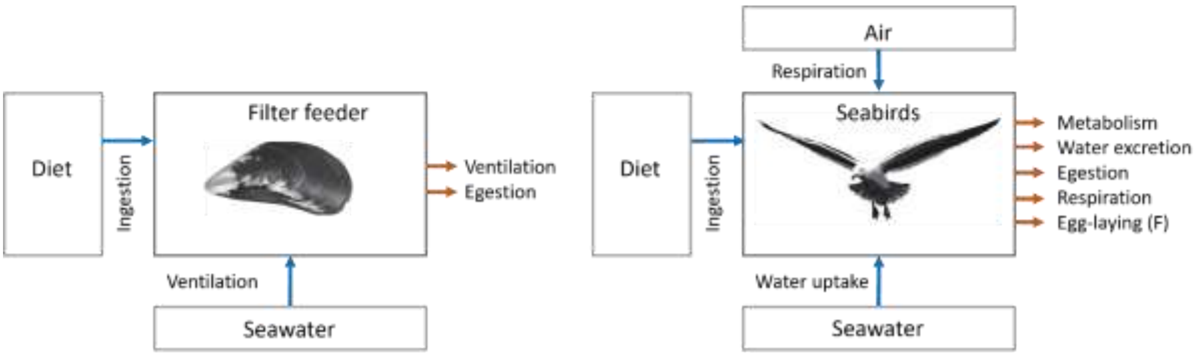


Figure SI.12: Schematic representation of the uptake (blue arrows) and elimination (red arrows) of PCB-153 in filter feeders and seabirds in NEM. Each organism in NEM is treated as single compartments. The uptake from the physical environment includes ventilation of seawater for the filter feeder, and water uptake from seawater and respiration of air for the seabirds. The dietary composition for each organism is found under section SI.1.

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