Universiteit Antwerpen

This item is the archived peer-reviewed author-version of:

Serum POP concentrations are highly predictive of inner blubber concentrations at two extremes of body condition in northern elephant seals

Reference:
Peterson Michael G., Peterson Sarah H., Debier Cathy, Covaci Adrian, Dirtu Alin, Govindan Malarvannan, Crocker Daniel E., Costa Daniel P..- Serum POP concentrations are highly predictive of inner blubber concentrations at tw o extremes of body condition in northern elephant seals
Environmental pollution - ISSN 0269-7491 - 218(2016), p. 651-663
Full text (Publisher's DOI): https://doi.org/10.1016/J.ENVPOL.2016.07.052
To cite this reference: https://hdl.handle.net/10067/1361890151162165141

uantwerpen.be
Institutional repository IRUA

Serum POP concentrations are highly predictive of inner blubber concentrations at two extremes of body condition in northern elephant seals

Michael G. Peterson[1*], Sarah H. Peterson[2], Cathy Debier[3], Adrian Covaci[4], Alin C. Dirtu[4,5], Govindan Malarvannan[4], Daniel E. Crocker[6], Daniel P. Costa[2]

[1]Department of Environmental Science, Policy and Management, University of California, Berkeley, 130 Mulford Hall #3114, Berkeley, CA 94720, USA

[2]Department of Ecology and Evolutionary Biology, University of California, Santa Cruz, 100 Shaffer Road, Santa Cruz, CA 95060, USA

[3]Institut des Sciences de la Vie, Université catholique de Louvain, Croix du Sud 2/L7.05.08, 1348 Louvain-la-Neuve, Belgium

[4]Toxicological Center, Universiteit Antwerpen, Universiteitsplein 1, 2610 Wilrijk, Belgium

[5]Department of Chemistry, "Al. I. Cuza" University of Iasi, Carol I Bvd, No. 11, 700506 Iasi, Romania

[6]Department of Biology, Sonoma State University, 1801 East Cotati Ave, Rohnert Park, CA 94928, USA

* corresponding author: petersmg@berkeley.edu

ABSTRACT

Long-lived, upper trophic level marine mammals are vulnerable to bioaccumulation of persistent organic pollutants (POPs). Internal tissues may accumulate and mobilize POP compounds at different rates related to the body condition of the animal and the chemical characteristics of individual POP compounds. Collection of samples from multiple tissues is a major challenge to ecotoxicology studies of free-ranging marine mammals, yet the ability to predict POP concentrations in one tissue from another tissue remains rare. Northern elephant seals (*Mirounga angustirostris*) forage on mesopelagic fish and squid for months at a time in the northeastern Pacific Ocean, interspersed with two periods of fasting on land, which results in dramatic seasonal fluctuations in body condition. Using northern elephant seals, we examined commonly studied tissues in mammalian toxicology to describe relationships and determine predictive equations among tissues for a suite of POP compounds, including ΣDDTs, ΣPCBs, Σchlordanes, and ΣPBDEs. We collected paired blubber (inner and outer) and blood samples from adult female and male seals in 2012 and 2013 at Año Nuevo State Reserve (California, USA). For females (N = 24), we sampled the same seals before (late in molting fast) and after (early in breeding fast) their approximately seven month foraging trip. For males, we sampled different seals before (N = 14) and after (N = 15) their approximately four month foraging trip. We observed strong relationships among tissues for many, but not all compounds. Serum POP concentrations were strong predictors of inner blubber POP concentrations for both females and males, while serum was a more consistent predictor of outer blubber for males than females. The ability to estimate POP blubber concentrations from serum, or vice versa, has the potential to enhance toxicological assessment and physiological modeling. Furthermore, predictive equations may illuminate commonalities or distinctions in bioaccumulation across marine mammal species.

Keywords: pinniped, marine mammal, tissue-correlation, predictive-equations, fasting, partitioning coefficients

Capsule: Relationships among serum and blubber layers in elephant seals, after fasting and foraging periods, can enhance contaminant studies and enable comparisons among species.

HIGHLIGHTS

- Serum was a strong predictor of inner blubber for DDTs, PCBs, CHLs, and PBDEs
- Relationships between serum and outer blubber were stronger for males than females
- Higher blubber/serum partitioning coefficients in early breeding than late molting
- Predictive equations provided for seals at two extremes of body condition

INTRODUCTION

Persistent organic pollutants (POPs) are lipophilic environmental contaminants that are pervasive in marine food webs and bioaccumulate in organisms, which presents particular concern for long-lived, upper trophic level marine mammals. Although close proximity to POP sources can result in higher POP concentrations (Frouin et al. 2011), even foraging strategies that place animals far from contaminant sources do not insulate them from POP exposure (Peterson et al. 2015). Elevated concentrations of POPs are associated with endocrine, immune, and reproductive effects in marine and terrestrial wildlife (Tanabe 2002, Debier et al. 2005, Desforges et al. 2016). Among marine mammals, pinnipeds and odontocetes are vulnerable to biomagnification of POPs due to their high trophic position, and therefore are often the target species for POP biomonitoring efforts (Weijs et al. 2010, Yordy et al. 2010b, Lopez et al. 2012).

The internal tissues of marine mammals accumulate and mobilize POPs at varying rates, which presents challenges for interpretation. Blood and blubber are commonly studied tissue compartments because they can be sampled non-lethally and are relatively accessible to researchers. Blood is advantageous for study because it is in direct contact with internal tissues of toxicological concern, including the liver and other organs, and it is responsive to recent foraging (De Swart et al. 1996) or fasting (Louis et al. 2014). Therefore, blood can serve as a relevant indicator of recent contaminant exposure or a reflection of changes in physiological state that may liberate contaminants from storage tissues into circulation. Blood collection from live pinnipeds is generally less invasive than blubber collection, and many studies may store blood samples long term, often the serum or plasma compartments, that could be utilized to compare contaminant exposure over time; however, the relationship between blood and blubber layers may be inconsistent (Lyderson et al. 2002). In contrast, blubber is a lipid-rich tissue used for energy storage in both pinnipeds and odontocetes (Koopman et al. 1996, Strandberg et al. 2008). Within the vertical profile of the blubber layer, metabolic activity and fatty-acid mobilization vary, with inner blubber more metabolically active than outer (Strandberg et al. 2008, Fowler et al. 2014). While recent events such as foraging or fasting may impact contaminant concentrations in blood and inner blubber (Louis et al. 2014), outer blubber or full thickness blubber cores may provide a more relevant indicator of longer-term bioaccumulation (Randhawa et al. 2015). Blubber is often collected in pinnipeds and cetaceans, and in some cases it is the only tissue available to study (*e.g.*, Barón et al. 2015, Hunt et al. 2015).

Northern elephant seals (*Mirounga angustirostris*) are upper trophic level predators that bioaccumulate POPs as they forage in the northeastern Pacific Ocean (Peterson et al. 2015). The life history of northern elephant seals includes two foraging migrations per year interspersed

96 with fasting periods for breeding and molting on land, which makes them relatively accessible
97 for study among marine mammals (Robinson et al. 2012). Additionally, foraging and fasting life-
98 history phases create dramatically different seasonal body conditions. For example, during the
99 molting fast females spend roughly 4-6 weeks fasting and lose approximately 25% of their mass,
100 of which 41% comes from fat stores (Worthy et al. 1992). Females then go to sea and forage for
101 approximately 7 months, during which time they undergo a 95% mean mass gain (Robinson et
102 al. 2012). At the end of their foraging trip, females return to land and undergo a breeding fast,
103 lasting approximately 4-6 weeks, which occurs as they give birth to a pup and lactate, and results
104 in loss of approximately 40% of their body mass and 57% of their fat stores (Costa et al. 1986,
105 Crocker et al. 2001). After breeding, females once again return to sea for a shorter 2-3 month
106 foraging trip, which ends when they return to land for molting (Robinson et al. 2012). Males
107 undergo a similar proportional loss of body mass (34-41%) and fat stores (54-59%) while on
108 shore for fasting (Deutsch et al. 1990, Crocker et al. 2012). The male breeding fast is longer than
109 females, lasting approximately 2-3 months, while the male molting fast is approximately 4-6
110 weeks in duration (Le Boeuf et al. 2000). The two male foraging trips at sea each year are similar
111 to each other in duration, lasting approximately 4 months each (Le Boeuf et al. 2000). Because
112 body condition is an important determinant of POP concentrations in blood and blubber
113 (Peterson et al. 2014), effective toxicological risk assessment relies upon understanding POP
114 concentrations at extremes in body condition.
115 The naturally occurring extremes of body condition of northern elephant seals present an
116 opportunity to examine how body condition impacts the relationships of contaminant
117 concentrations among tissues. We examined commonly studied tissues with higher (serum, inner
118 blubber) and lower (outer blubber) metabolic activity to describe relationships and determine

predictive equations among tissues for POPs in northern elephant seals. Our primary focus was to investigate relationships for polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT) and metabolites of DDT, chlordanes (CHLs), and polybrominated diphenyl ethers (PBDEs), although we also included hexachlorobenzene (HCB), hexachlorocyclohexane (α-HCH and β-HCH), and the naturally produced 6-MeO-BDE 47. Specifically, our objectives were to 1) assess serum POP concentrations as a predictor of inner and outer blubber POP concentrations, and inner blubber POP concentrations as a predictor of outer blubber POP concentrations at two body condition extremes, 2) compare serum to blubber relationships between males and females, and 3) use partitioning coefficients to compare blubber/serum POPs and inner blubber/outer blubber POPs relationships between females and males at two naturally occurring extremes of elephant seal body condition.

METHODS

Animal Sampling

We collected paired blubber and blood samples from adult female and male northern elephant seals in 2012 and 2013 at Año Nuevo State Reserve (California, USA, 37.11° N, 122.33° W). The same known-age females (N = 24), ranging in age from four to twelve years, were sampled before (late in the molting fast) and after (early in the breeding fast) an approximately seven month long foraging trip. Due to the challenges associated with repeatedly sampling males, blubber cores and blood samples were collected from 29 unique male northern elephant seals at two points in their life history: 14 seals were sampled at the end of the molting fast and 15 seals were sampled approximately four months later at the start of the breeding fast.

We used standard procedures for chemical immobilization and collection of blubber and

blood from northern elephant seals (Le Boeuf et al. 2000, Robinson et al. 2012), and these procedures have been described previously in Peterson et al. (2015). In brief, a full-thickness blubber core was collected from the lateral pelvic area of each seal from a sterile scalpel incision with a 6 mm biopsy punch (Miltex, Inc., York, Pennsylvania, USA) and stored in aluminum foil. Blood samples were collected from the extradural vein and stored on ice in the field. Upon return to the lab within several hours, samples were centrifuged and serum aliquots were transferred to glass vials. Blubber cores and serum samples were stored at -20°C until analysis.

Laboratory analysis

We targeted 29 PCB congeners (IUPAC numbers: CB 28, 49, 52, 74, 95, 99, 101, 105, 110, 118, 128, 138, 146, 149, 153, 156, 170, 171, 174, 177, 180, 183, 187, 194, 196/203, 199, 206, and 209), seven PBDE congeners (IUPAC numbers: BDE 28, 47, 99, 100, 153, 154, and 183), three DDTs (*p,p'*-DDD, *p,p'*-DDE, *p,p'*-DDT), five chlordanes (CHLs: OxC (oxychlordane), CC (*cis*-chlordane), TC (*trans*-chlordane), TN (*trans*-nonachlor), CN (*cis*-nonachlor)), hexachlorobenzene (HCB), hexachlorocyclohexane (α-HCH, β-HCH), and the naturally-produced methoxylated PBDE, 6-MeO-BDE 47, in all samples.

Extraction, clean-up, and concentration measurement methods for blubber and serum followed protocols described in Vanden Berghe et al. (2012) and Peterson et al. (2015). In brief, for blubber analyses, the skin layer and hair (Schwarz et al. 2015), was removed from the outer portion of the biopsy core, and the remaining blubber layer was cut into inner and outer segments of approximately equal mass. Inner and outer blubber segments were analyzed separately due to differences in metabolic activity and stratification in fatty acid profiles among layers (Strandberg et al. 2008, Fowler et al. 2014). Serum samples were split for separate determination of target

contaminants and lipids. Four lipid classes in serum (total cholesterol, phospholipids, triacylglycerides, and non-esterified fatty acids) were determined with enzyme kits from Diasys Diagnostic Systems (Holzheim, Germany) and Wako Chemicals (Neuss, Germany), with the concentrations of each lipid class calculated on the basis of standard equivalents. Total lipid concentrations were calculated as the sum of the four lipid classes (Debier et al. 2006, Vanden Berghe et al. 2012). All POP concentrations in serum were lipid-normalized before statistical analyses.

PBDEs, MeO-PBDEs, CHLs, HCB, and HCHs were measured by gas chromatography-electron capture negative ion/mass spectrometry (GC-ECNI/MS) on a 30 m × 0.25 mm × 0.25 µm DB-5 column (J&W Scientific, Folsom, CA, USA) by monitoring two ions *m/z* = 79 and 81 (for PBDEs and MeO-PBDEs) and two specific ions for each pesticide. DDTs and PCBs were measured by gas chromatography-electron ionization/mass spectrometry (GC-EI/MS) on a 25 m × 0.22 mm × 0.25 µm HT-8 column (SGE, Zulte, Belgium) by monitoring 2 ions for each homologue group.

Quality control

For quality control (QC), we randomly analyzed procedural blanks, solvent blanks, and standards throughout the extraction process. Recoveries for individual PCB and PBDE congeners ranged between 75 and 104% (RSD < 12%). For each analyte, the mean procedural blank value was used for subtraction to determine final analyte concentrations. After blank subtraction, the limit of quantification (LOQ) was set at 3 × SD of the procedural blank. For analytes that were not detected in procedural blanks, LOQs were calculated for a ratio S/N (signal to noise) equal to 10. A standard reference material SRM 1945 (PCBs, OCPs, and PBDEs in whale blubber) was

188 used to test the accuracy of the method. Measured values did not deviate more than 15% from
189 the certified values.
190
191 ***Statistical analysis***
192 We examined the relationship between each pair of tissues (inner blubber:serum, outer
193 blubber:serum, outer blubber:inner blubber) individually for each class of contaminants (ΣDDTs,
194 ΣPCBs, ΣCHLs, and ΣPBDEs), for individual contaminants (HCB, α-HCH, β-HCH), and the
195 naturally-produced 6-MeO-BDE 47, before elephant seals left for a foraging trip (late in the
196 molting fast), and upon return from foraging (early in the breeding fast). In order to quantify the
197 relationships between concentrations of POPs in paired tissues, we used general linear models in
198 the statistical program R, version 3.0.2 (R Development Core Team 2012). We first ran a global
199 model for each pair of tissue POP concentrations with sex as a factor and an interaction between
200 the predictor tissue POP concentration × sex. If the interaction was significant, we conducted
201 subsequent analyses for each sex separately. All POP concentrations were natural-log
202 transformed prior to analysis to meet the assumptions of general linear models. When sex was
203 not a significant predictor, we removed the term for the predictive equation.
204 In addition, we calculated partitioning coefficients for outer blubber/serum, inner
205 blubber/serum, and outer blubber/inner blubber for each contaminant in female and male
206 elephant seals. Partitioning coefficients were calculated for each individual as the ratio between
207 concentrations in the two tissues. We used mixed effects models to compare partitioning
208 coefficients by sampling period (late molting, early breeding), sex, and a sex × sampling period
209 interaction, with individual as a random effect. If the interaction was not significant, we removed

it and reran the model. We conducted post-hoc pairwise comparisons on least-squares means with a Tukey adjustment on *p*-values. For statistical significance, α was set at $p = 0.05$.

RESULTS

Serum, inner blubber, and outer blubber samples from all elephant seals had detectable concentrations of ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs. The concentrations of POPs used in this study for northern elephant seal serum, inner blubber, and outer blubber have been reported previously (Peterson et al. 2015), although a summary of medians and ranges of POP concentrations can be found in Table 1. The specific equations to predict POP concentrations in one tissue from POPs concentrations in another tissue for all compounds are found in Table 2 and specific statistical results are found in Table 3.

Serum and inner blubber

Late molting seals did not have a significant interaction between sex × serum concentrations of ΣDDTs, ΣPCBs, ΣCHLs, or ΣPBDEs on the concentrations of these POP classes in inner blubber ($F \leq 1.80$, $p \geq 0.18$). Similarly, early breeding seals did not have a significant interaction between serum POP concentrations × sex on the POP concentrations in inner blubber, except for PBDEs ($F_{1,35}=6.45$, $p=0.015$). Therefore, we removed the interaction from all models except for early breeding PBDEs, where we analyzed males and females separately.

Serum POP concentrations were positively related to inner blubber POP concentrations for all major POP classes (ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs) both late in the molting fast

(Fig. 1) and early in the breeding fast (Fig. 2), while accounting for any potential effect of sex. Early in the breeding fast, concentrations of ΣPBDEs in serum were positively related to concentrations of ΣPBDEs in inner blubber for females and males. For ΣDDTs, ΣPCBs, and ΣCHLs at both sampling periods, and ΣPBDEs at late molting, all relationships between serum and inner blubber had R^2 values >0.7, and relationships for all POP classes were stronger at early breeding than at late molting (Table 2). In addition, the highest R^2 values at each life history phase were found for ΣDDTs.

While ΣDDT, ΣPCB, ΣCHL, and ΣPBDE concentrations in serum were related to those in inner blubber, we found varying relationships for the remaining POP compounds (Fig. 3; Fig. 4). During the late molt we did not detect any significant interactions between POP concentrations in serum × sex on POP concentrations in inner blubber for α-HCH, β-HCH, or HCB ($F_{1,34}$≤0.77, p≥0.35). Serum concentrations were positively related to inner blubber concentrations for α-HCH, β-HCH, and HCB. Males were excluded from tests for 6-MeO-BDE 47 due to low detectability of this compound in samples; no significant relationship between serum and inner blubber was found for 6-MeO-BDE 47 in females (Fig. 3).

In early breeding, we did not detect a significant serum × sex interaction for 6-MeO-BDE 47 ($F_{1,34}$=2.20, p=0.15) or β-HCH ($F_{1,34}$=0.11, p=0.75). For α-HCH, we detected a marginally significant interaction ($F_{1,35}$=3.05, p=0.09) and analyzed female and male seals separately. Serum concentrations of 6-MeO-BDE 47 and β-HCH were positively related to inner blubber concentrations, while accounting for any potential effect of sex. For α-HCH we detected a significant relationship between serum and inner blubber concentrations for females, but not males. While the relationships between serum concentrations and inner blubber concentrations of β-HCH at late molting and early breeding were strong (R^2≥0.58), we observed weaker

relationships for α-HCH ($R^2 \leq 0.38$). In addition, there was no significant relationship between serum and inner blubber for HCB, while accounting for sex.

Serum and outer blubber

We detected a significant interaction between POP concentrations in serum × sex on POP concentrations in outer blubber for ΣDDTs, ΣPCBs, and ΣCHLs during late molting ($F_{1,34} \geq 5.27$, $p \leq 0.001$) and early breeding ($F_{1,35} = \geq 7.48$, $p \leq 0.010$). In addition, we detected a serum × sex interaction in early breeding ΣPBDEs ($F_{1,35} = 12.58$, $p < 0.001$), but not late molting ΣPBDEs ($F_{1,34} = 3.57$, $p = 0.067$). Therefore, we removed the interaction from the model for late molting ΣPBDEs, but for all other POP classes we conducted separate statistical analyses on female and male elephant seals.

For combined male and female seals late in the molting fast, concentrations of ΣPBDEs in serum were positively related to concentrations of ΣPBDEs in outer blubber, when accounting for sex. There was not a significant sex effect for ΣPBDEs, indicating that similar ΣPBDE concentrations in serum corresponded to similar ΣPBDE concentrations in outer blubber for males and females (Fig. 1). Early in breeding, serum ΣPBDE concentrations were positively related to outer blubber concentrations for males and females. In addition, serum ΣDDT, ΣPCB, and ΣCHL concentrations were positively related to outer blubber concentrations during both sampling periods for females and males (Fig. 1; Fig. 2). Outer blubber:serum relationships were stronger for males ($0.94 \geq R^2 \geq 0.79$) than females ($0.75 \geq R^2 \geq 0.23$) for ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs at both sampling periods, but the differences between the sexes were more pronounced for ΣPCBs and ΣCHLs at both periods than for ΣDDTs and ΣPBDEs (Fig. 1; Fig. 2). For ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs, the slope of the relationship for males was steeper than

279 females, indicating that at higher serum concentrations individual males had proportionately
280 higher outer blubber contaminant concentrations than females (Table 2).
281 For 6-MeO-BDE 47, α-HCH, β-HCH, and HCB compounds late in the molting fast, we
282 detected a significant interaction between POP concentrations in serum × sex on POP
283 concentrations in outer blubber for α-HCH, β-HCH, and HCB ($F_{1,34} \leq 4.59$, $p \geq 0.039$).
284 Additionally, only 7 males had detectable concentrations of 6-MeO-BDE 47 at late molt, and
285 therefore, were not included in analyses. Although serum concentrations of α-HCH, β-HCH, and
286 HCB were positively related to outer blubber in males (Fig. 3), only β-HCH concentrations were
287 related in females. Concentrations of 6-MeO-BDE 47 in female serum samples were not
288 significantly related to concentrations in outer blubber samples (Fig. 3).
289 In contrast with samples from late in the molting fast, during early breeding we did not
290 detect a serum × sex interaction for 6-MeO-BDE 47, α-HCH, β-HCH, or HCB ($F_{1,35} \leq 1.44$,
291 $p \geq 0.24$). Serum concentrations of 6-MeO-BDE 47, α-HCH, and β-HCH were positively related
292 to outer blubber concentrations (Fig. 4), while accounting for any potential effect of sex. Serum
293 concentrations of HCB were not significantly related to outer blubber concentrations.
294
295 *Inner blubber and outer blubber*
296 We observed a significant interaction between POP concentrations in inner blubber × sex
297 on ΣPCB and ΣCHL concentrations in outer blubber during late molting ($F_{1,34} \geq 18.37$, $p \leq 0.001$)
298 and ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs during early breeding ($F_{1,35} \geq 7.80$, $p \leq 0.008$). In
299 addition, we found no detectable interaction for ΣDDTs and ΣPBDEs during late molting
300 ($F_{1,34} \leq 2.32$, $p \geq 0.14$). Therefore, in the case of late molting, we removed the interaction from the

301 models for ΣDDTs and ΣPBDEs, and for ΣPCBs and ΣCHLs we analyzed females and males
302 separately.
303 Inner blubber POP concentrations were positively related to outer blubber POP
304 concentrations for ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs during both sampling periods, for both
305 females and males (Fig. 2). For late molting seals, concentrations of ΣDDTs and ΣPBDEs in
306 serum were significantly related to concentrations of ΣDDTs and ΣPBDEs in outer blubber,
307 while accounting for sex (Fig. 1). The significant sex effect for ΣPBDEs in outer blubber showed
308 that males and females had the same slope, but males had higher concentrations of ΣPBDEs in
309 outer blubber than females for similar concentrations in inner blubber.
310 Additionally, the relationships between inner and outer blubber were stronger for males
311 than females for ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs at late molting (Fig. 1) and early
312 breeding (Fig. 2). For female concentrations of ΣCHLs in inner blubber and outer blubber, the
313 relationship was stronger in late molting (R^2=0.66) relative to early breeding (R^2=0.19), whereas
314 the relationships between concentrations of ΣPCBs and ΣPBDEs in inner blubber and outer
315 blubber were similar between the two life history stages (Fig. 1; Fig. 2). For ΣDDTs, ΣPCBs, and
316 ΣCHLs from both time periods, and early breeding ΣPBDEs, the slope of the relationship for
317 males was steeper than females, indicating that males with higher inner blubber concentrations
318 had proportionately higher concentrations than females in outer blubber when compared to males
319 and females with lower inner blubber concentrations.
320 Additionally, during the late molt we detected a significant interaction between POP
321 concentrations in inner blubber × sex on POP concentrations in outer blubber for α-HCH, β-HCH
322 and HCB ($F_{1,34}$≥5.51, p≤0.025), but not for 6-MeO-BDE 47 ($F_{1,34}$=0.03, p=0.87). For 6-MeO-
323 BDE 47, inner blubber POP concentrations were positively related to outer blubber

concentrations (Fig. 3). Inner blubber concentrations of α-HCH and β-HCH were positively related to outer blubber POP concentrations at late molting for females and males, separately (Fig. 3). Inner blubber concentrations of HCB were only significantly related for males and not females.

Early in the breeding fast, we did not detect significant interactions between inner blubber × sex on outer blubber concentrations of 6-MeO-BDE 47, α-HCH, β-HCH, or HCB ($F_{1,35}$≤1.43, p≥0.24). Inner blubber concentrations for all four compounds were significantly related to outer blubber concentrations, when accounting for any potential effect of sex (Fig 4).

Partitioning coefficients

Inner blubber/serum partitioning coefficients for ΣDDTs, ΣCHLs, and ΣPBDEs were significantly lower at late molt than early breeding ($F_{1,45.9}$=15.64, p<0.001), but did not differ by sex ($F_{1,60.0}$=*0.61,* p=0.44; Table 4). For ΣPCBs, we detected a significant sex × time period interaction ($F_{1,59.6}$=10.25, p=0.002). Females and males did not differ in ΣPCB inner blubber/serum partitioning coefficients at late molting (t=1.15, p=0.99), but females had higher inner blubber/serum partitioning coefficients than males at early breeding (t=4.73, p<0.001), indicating that females had proportionally higher outer blubber concentrations relative to serum than males at early breeding. Female partitioning coefficients for ΣPCBs were lower at late molt relative to early breeding (t=5.75, p<0.001), while male coefficients for ΣPCBs did not differ (t=0.413, p=0.98).

For outer blubber/serum partitioning coefficients, we detected a significant interaction between sex and time period for ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs (F≥6.57, p≤0.01; Table 4). Females and males did not differ at late molting for ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs

($t \leq 1.85$, $p \geq 0.26$), but partitioning coefficients for females were significantly higher than males for each contaminant compound at early breeding ($t \geq 3.27$, $p \leq 0.01$). For males, partitioning coefficients were lower at late molting than early breeding for ΣDDTs and ΣCHLs ($t \geq 3.75$, $p \leq 0.002$), but not for ΣPCBs and ΣPBDEs ($t \leq 1.94$, $p \geq 0.22$; Table 4). For females, partitioning coefficients were lower during late molting than early breeding for ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs ($t \geq 7.39$, $p \leq 0.001$; Table 4).

For outer blubber/inner blubber partitioning coefficients, we detected a significant sex × time period interaction for ΣPCBs ($F_{1,59.6}=15.10$, $p=0.003$), ΣCHLs ($F_{1,59.6}=5.80$, $p=0.02$), and ΣPBDEs ($F_{1,61.1}=6.63$, $p=0.01$), but not ΣDDTs ($F_{1,59.6}=2.45$, $p=0.12$). At late molting, outer blubber/inner blubber coefficients were lower for females relative to males for ΣPCBs ($t=3.05$, $p=0.02$; Table 4), but ΣCHLs and ΣPBDEs did not differ between males and females at this time period ($t \leq 1.13$, $p \geq 0.67$). Early in breeding, females and males did not differ for ΣPCBs, ΣCHLs, or ΣPBDEs (Table 4). For males, outer blubber/inner blubber partitioning coefficients were lower at late molting than early breeding for ΣCHLs ($t=2.86$, $p=0.028$), but the time periods did not differ for ΣPCBs or ΣPBDEs ($t \leq 1.48$, $p \geq 0.45$). Female outer blubber/inner blubber partitioning coefficients were lower at late molting than early breeding for ΣPCBs, ΣCHLs, and ΣPBDEs ($t \geq 5.05$, $p \leq 0.0001$). For ΣDDTs, outer blubber/inner blubber partitioning coefficients were significantly lower at late molt than early breeding ($F_{1,45.9}=42.37$, $p<0.001$), but did not differ by sex ($F_{1,60.0}=2.96$, $p<0.09$).

DISCUSSION

Body condition fluctuations

Free-ranging northern elephant seals demonstrated strong, predictive relationships among serum, inner blubber, and outer blubber POP concentrations, even after the influence of lengthy periods of foraging at sea or weeks of fasting on land. The ability to predict POP concentrations between components of blood and blubber is important because POP concentrations can fluctuate asynchronously among serum, inner blubber, and outer blubber in response to recent fasting or foraging activities (Debier et al. 2012, Peterson et al. 2014, Louis et al. 2016). For example, when northern elephant seals were sampled late in the molting fast after fasting for several weeks, POP concentrations in serum and inner blubber likely reflected recent mobilization of POPs from inner blubber to serum (Louis et al. 2014) and redistribution of POPs among other internal tissues. Early in the breeding fast, elephant seals had recently returned from an extensive, months-long foraging trip; therefore, serum and inner blubber POP concentrations likely represented a combination of POPs acquired from food, as well as ongoing redistribution of POPs from other internal tissues. Outer blubber, on the other hand, is less metabolically active than inner blubber (Strandberg et al. 2008, Debier et al. 2012, Ellisor et al. 2013), and may reflect a different, longer-term signal of POP bioaccumulation relative to inner blubber or serum.

Mobilization of fatty acids and POPs from blubber is complex, and is influenced by the relative lipophilicity of individual fatty acids (Hall et al. 2008, Louis et al. 2016) and POPs (Louis et al. 2016), as well as the vertical composition of the blubber itself (Koopman et al. 1996). Therefore, the relationship between POP concentrations in different tissues could change as a consequence of preferential mobilization of some POP compounds over others. Of the POPs investigated in this study, HCHs and HCB have the lowest lipophilicity and therefore likely redistribute differently than the other POPs, which may explain why HCHs and HCBs demonstrated poorer correlations among certain tissues.

392 Partitioning coefficients from the extremes of body condition corroborate the concept that
393 POP concentrations of different tissues do not fluctuate in parallel. For female seals, lower inner
394 blubber/serum, outer blubber/serum, and outer blubber/inner blubber partitioning coefficients for
395 ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs from late molting (pre-foraging), compared with early
396 breeding (post-foraging), showed that although both serum and blubber layers decreased in POP
397 concentrations during foraging (Peterson et al. 2015), the greatest decrease in magnitude
398 occurred in serum POP concentrations, followed by inner blubber and outer blubber,
399 respectively. Differences in partitioning coefficients between time periods were less consistent
400 for males, which may be a result of the lack of paired samples for males or may signal
401 differences in POP mobilization between males and females. However, in most cases males had
402 lower partitioning coefficients at late molt relative to early breeding.
403
404 *Predictive equations*
405 Serum generally performed well as a predictor of inner blubber POP concentrations for
406 female and male elephant seals at two extremes in body condition. For example, we found
407 relatively strong predictive relationships between serum and inner blubber for ΣDDTs, ΣPCBs,
408 ΣCHLs, and ΣPBDEs at both body condition extremes. Among tissue comparisons, serum and
409 inner blubber were notable because both female and male seals could be included in the same
410 equation for nearly all POP compounds during both time periods. Serum and inner blubber have
411 higher turnover rates compared with outer blubber, which may be more important in these tissues
412 than the differences in offloading mechanisms between males and females. The lack of
413 detectable interactions between serum POP concentrations × sex, or an effect of sex, except for
414 ΣPBDEs during early breeding, indicates that serum and inner blubber relate similarly in males

and females despite concurrent gestation of a pup by females and the highly probable corresponding placental transfer of POPs, as well as transfer of POPs from mother to pup during the first 5 days of lactation.

Unlike inner blubber:serum relationships, for outer blubber:serum and outer blubber:inner blubber we detected a significant interaction between predictor tissue POP concentration and sex for all major POP compounds, except ΣPBDEs. When there was a significant interaction, and thus a difference in the slope of the relationships, male elephant seals were always characterized by a steeper slope compared with females, resulting in greater differences between male and female outer blubber concentrations at higher concentrations of serum or inner blubber than at lower concentrations. Although this may be attributed to differences in the impact of concurrent lactation on specific POP compounds during the breeding fast (Debier et al. 2012, Vanden Berghe et al. 2012), the fact that significant interactions also existed in late molting, when lactation and gestation should not be having immediate effects, suggest that a lifetime of offloading opportunities for females may cause persistent differences in bioaccumulation among tissue compartments.

Furthermore, while predictive equations for males performed well among all tissues and nearly all POP compounds at both sampling periods, the strength of female tissue relationships was inconsistent across POP compounds. Female serum and inner blubber were strong predictors of outer blubber for ΣDDTs and ΣPBDEs, but weaker predictors for ΣPCBs and ΣCHLs. Female lactation physiology results in disproportionate mobilization and transfer to milk of some POP compounds over others (Debier et al. 2012, Vanden Berghe et al. 2013), which may explain the weaker performance of predictive equations for ΣPCBs and ΣCHLs. For example, ΣPCBs represents the sum of a suite of congeners, each with compound-specific log K_{ow} (octanol-water

438 partitioning coefficient; Hawker and Connell 1988). When females lactate during the breeding
439 fast, lower lipophilic congeners are more readily mobilized from inner blubber to serum and
440 from serum to milk during lactation (Debier et al. 2003, 2012a, Vanden Berghe et al. 2012),
441 which may make serum POP concentrations an unreliable predictor of inner or outer blubber
442 POP concentrations for some compounds in certain scenarios. In the current study, differences in
443 lipophilicity of specific congeners may distort the ability to predict outer blubber concentrations
444 from serum or inner blubber for ΣPCBs in both seasons ($R^2 \leq 0.44$) and for ΣCHLs in early
445 breeding ($R^2 \leq 0.25$).
446
447 *Interspecies comparisons*
448 Significant positive relationships between blood and fat compartments have been
449 observed and quantified for POPs in the tissues of polar bears (Bernhoft et al. 1997), turtles
450 (Keller et al. 2004), dolphins (Yordy et al. 2010c), and Hawaiian monk seals (Lopez et al. 2012).
451 Hawaiian monk seals and northern elephant seals are both pinnipeds, the taxonomic group that
452 includes seals, sea lions, and walrus. Similar to the elephant seal inner blubber:serum
453 relationships in the present study, Hawaiian monk seals of various ages and both sexes had
454 strong relationships between blubber and serum for ΣDDTs, ΣPCBs, and ΣCHLs (Lopez et al.
455 2012), while ΣPBDE relationships were not reported.
456 Our study of a pinniped species is similar in approach to a study on an odontocete, the
457 taxonomic group that includes toothed cetaceans, which determined predictive equations for
458 ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs in bottlenose dolphin (*Tursiops truncatus*) from Sarasota
459 Bay, Florida, USA (Yordy et al. 2010c). Bottlenose dolphin predictive equations were
460 established for male and female dolphins using plasma and full-thickness blubber; the blubber of

bottlenose dolphins varies with vertical profile (Ellisor et al. 2013). Partitioning coefficients (blubber/plasma) were calculated for males, juveniles, and females (Yordy et al. 2010c). Northern elephant seals differ from bottlenose dolphins in several aspects, namely that they come ashore and undergo extreme fasting periods that mobilize POPs from blubber to serum (Debier et al. 2006). Additionally, the inter-offspring interval for dolphins is longer than for elephant seals, which provides less frequent opportunities for contaminant elimination. Finally, dolphins have a lipid-rich internal melon tissue that can accumulate POPs (Yordy et al. 2010a), while elephant seals do not. Although different in certain life history aspects, both northern elephant seals and bottlenose dolphins are relatively long-lived, top marine predators with relatively large fat compartments (blubber) that can bioaccumulate POPs from marine prey.

Both studies found positive relationships among POP concentrations in male blood and blubber. Predictive equations for bottlenose dolphins showed strong relationships for all POP classes ($R^2 \geq 0.91$), but Yordy et al. (2010) did not quantify predictive relationships for females. Bottlenose dolphin predictive equations for males and juvenile had slopes from 0.91-1.08, similar to male elephant seals at early breeding (0.78-0.99), when they had recently completed their foraging trip and thus were most directly comparable to continuously foraging bottlenose dolphins. Male elephant seal equations showed a greater range of slopes (0.91-1.42) for POP compounds late in the molting fast.

Additionally, blubber/plasma partitioning coefficients reported in Yordy et al. (2010) for male bottlenose dolphins were higher for ΣDDTs (mean=1.95, 95% CI=1.73-2.17) and ΣCHLs (2.52, 2.23-2.81), but lower for ΣPCBs (1.42, 1.24-1.60) and ΣPBDEs (1.24, 1.04-1.44), than either inner blubber/serum or outer blubber/serum partitioning coefficients for male elephant seals (Table 4). Further, female bottlenose dolphins (Yordy et al. 2010c) had lower partitioning

coefficients for ΣDDTs (1.93, 1.66-2.20), ΣPCBs (1.77, 1.42-2.10), and ΣCHLs (2.35, 1.14-3.55) than female elephant seals early in the breeding fast, but higher partitioning coefficients than female elephant seals late in the molting fast. Early in breeding, female elephant seals have just returned from a long foraging trip, and have very recently given birth to a pup and begun lactation. Although recent lactation could eliminate some POPs from serum, higher partitioning coefficients in elephant seals early in the breeding fast are likely representative of greater dilution of POPs in serum compared with blubber, in response to recent foraging.

The differences in partitioning coefficients between elephant seals and bottlenose dolphins in this case may also be attributed to different compound-specific exposures related to foraging location and prey. Elephant seal females during both time periods had higher partitioning coefficients for ΣPBDEs than bottlenose dolphins, which may reflect lower exposure during foraging, and consequently lower serum ΣPBDEs concentrations, than Sarasota Bay bottlenose dolphins, which have higher concentrations for all POP compounds than northern elephant seals (Yordy et al. 2010c).

Implications for biomonitoring

Measurements of POP concentrations in marine mammals are common in oceans around the globe, but selection of tissues for sampling varies among studies. Therefore, the ability to estimate POP blubber concentrations from serum, or vice versa, has the potential to enhance toxicological assessment in marine mammals by providing a tool for expanding studies where only one tissue is collected. In cases where blubber samples are more attainable than blood (Elfes et al. 2010), the ability to estimate blood concentrations increases the capacity for toxicological risk assessment, because blood interacts with vital organs. In other cases, blood samples are

507 more attainable or are banked from past collections and could be used to estimate blubber
508 concentrations, which may enable comparisons across space or time.
509 Further, the distinction between inner and outer blubber is important. The use of biopsy
510 darting to sample marine mammal blubber is increasingly used in the study of wild, free-ranging
511 marine mammals, yet the relationship of that sample to inner blubber or serum is unclear. For
512 example, outer blubber samples are commonly collected from large free-ranging mysticetes for
513 studies of hormones and contaminants because outer blubber is often the only sample that can be
514 obtained (*e.g.*, Hunt et al. 2015); therefore, the potential to link outer blubber to other tissues is
515 particularly important. Because blubber is the largest reservoir for POPs, the relationship
516 between blubber reserves and serum may enable estimations of peak serum concentrations
517 relative to life history phases and variability in body condition. The seals in the current study
518 were seemingly healthy animals that naturally fluctuate in body condition, but may represent the
519 processes that may occur in other mammals undergoing rapid changes in body condition.
520 Therefore, the relationship between contaminant concentrations in blood and blubber at such
521 extremes may be an important factor to assessments of animal health and relative vulnerability to
522 contaminant accumulation.
523 The detection of strong, positive relationships between concentrations of POP
524 compounds in blood and blubber of two marine mammals, in the current study and in Yordy et
525 al. (2010c), with clear behavior and life history differences raises the question: are predictive
526 equations species-specific or can we determine generalities among species? If future research
527 that involves direct handling of animals can produce additional blood-blubber relationships, then
528 it may be possible to construct more generalized equations for groups of similar mammals.
529 Generalized relationships, even for a few POPs, would enhance monitoring of contaminants in

wildlife, particularly in situations where free-ranging animals are difficult to sample. Furthermore, comparisons among many species, including pinnipeds and odontocetes, could identify differences in contaminant metabolism among species, and thereby further inform models of potential health effects or risk assessment.

ACKNOWLEDGEMENTS

The Institutional Animal Care and Use Committee at the University of California, Santa Cruz approved all procedures and we captured animals under National Marine Fisheries Service permit 14636. We thank the many volunteers, technicians, and graduate students who were instrumental in the success of this project, especially P. Robinson, C. Goetsch, M. Tift, L. Hückstädt, L. McHuron, J. Sharick, D. Somo, D. Ensminger, and C. Louis. We thank the rangers and docents at Año Nuevo State Reserve, as well as P. Morris, and B. Hatfield for assistance in resighting seals, and R. Condit for development of the demographic database. Research and logistic support was provided by funds to S.H.P. from the Friends of Long Marine Lab, the Earl and Ethel Myers Oceanographic Trust, the University of California NRS Mildred Mathias Graduate Student Research Grant Program, the Rebecca and Steve Sooy Graduate Fellowship in Marine Mammals, the ARCS Foundation, and grants N00014-13-1-0134 and N00014-10-1-0356 to D.P.C. from the Office of Naval Research (ONR). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of this manuscript.

LITERATURE CITED

Baron, E., J. Gimenez, P. Verborgh, P. Gauffier, R. De Stephanis, E. Eljarrat, and D. Barcello. 2015. Bioaccumulation and biomagnification of classical flame retardants, related halogenated natural compounds and alternative flame retardants in three delphinids from

554 Southern European waters. Environmental Pollution 203:107–115.

555 Bernhoft, A., O. Wiig, & Janneche, and U. Skaare. 1997. Organochlorines in Polar Bears (*Ursus*
556 *Maritimus*) at Svalbard. Environmental Pollution 95:159–175.

557 Costa, D. P., B. J. Le Boeuf, A. C. Huntley, and C. L. Ortiz. 1986. The energetics of lactation in
558 the northern elephant seal, *Mirounga angustirostris*. Journal of Zoology 209:21–33.

559 Crocker, D. E., R. M. Ortiz, D. S. Houser, P. M. Webb, and D. P. Costa. 2012. Hormone and
560 metabolite changes associated with extended breeding fasts in male northern elephant seals
561 (*Mirounga angustirostris*). Comparative Biochemistry and Physiology - Part A: Molecular
562 & Integrative Physiology 161:388–94.

563 Crocker, D. E., J. D. Williams, D. P. Costa, and L. B. B. J. 2001. Maternal traits and
564 reproductive effort in northern elephant seals. Ecology 82.

565 Debier, C., C. Chalon, B. J. Le Boeuf, T. de Tillesse, Y. Larondelle, and J.-P. Thomé. 2006.
566 Mobilization of PCBs from blubber to blood in northern elephant seals (*Mirounga*
567 *angustirostris*) during the post-weaning fast. Aquatic Toxicology 80:149–157.

568 Debier, C., D. E. Crocker, D. S. Houser, M. Vanden Berghe, M. Fowler, E. Mignolet, T. de
569 Tillesse, J.-F. Rees, J.-P. Thomé, and Y. Larondelle. 2012. Differential changes of fat-
570 soluble vitamins and pollutants during lactation in northern elephant seal mother–pup pairs.
571 Comparative Biochemistry and Physiology - Part A: Molecular & Integrative Physiology
572 162:323–330.

573 Debier, C., P. P. Pomeroy, C. Dupont, C. Joiris, V. Comblin, E. Le Boulengé, Y. Larondelle, and
574 J. Thomé. 2003. Quantitative dynamics of PCB transfer from mother to pup during lactation
575 in UK grey seals *Halichoerus grypus*. Marine Ecology Progress Series 247:237–248.

576 Debier, C., G. M. Ylitalo, M. Weise, F. Gulland, D. P. Costa, B. J. Le Boeuf, T. de Tillesse, and
577 Y. Larondelle. 2005. PCBs and DDT in the serum of juvenile California sea lions:
578 Associations with vitamins A and E and thyroid hormones. Environmental Pollution
579 134:323–332.

580 Desforges, J.-P. W., C. Sonne, M. Levin, U. Siebert, S. De Guise, and R. Dietz. 2016.
581 Immunotoxic effects of environmental pollutants in marine mammals. Environment
582 International 86:126–139.

583 De Swart, R. L., P. S. Ross, J. G. Vos, and A. D. M. E. Osterhaus. 1996. Impaired immunity in
584 harbour seals (*Phoca vitulina*) exposed to bioaccumulated environmental contaminants:
585 Review of a long-term feeding study. Environmental Health Perspectives 104:823–828.

586 Deutsch, C. J., M. P. Haley, and B. J. Le Boeuf. 1990. Reproductive effort of male northern
587 elephant seals: Estimates from mass loss. Canadian Journal of Zoology 68:2580–2593.

588 Elfes, C. T., G. R. VanBlaricom, D. Boyd, J. Calambokidis, P. J. Clapham, R. W. Pearce, J.
589 Robbins, J. C. Salinas, J. M. Straley, P. R. Wade, and M. M. Krahn. 2010. Geographic
590 variation of persistent organic pollutant levels in humpback whale (*Megaptera*
591 *novaeangliae*) feeding areas of the North Pacific and North Atlantic. Environmental
592 Toxicology and Chemistry 29:824–834.

593 Ellisor, D., W. McLellan, H. Koopman, L. Schwacke, W. McFee, and J. Kucklick. 2013. The
594 distribution and stratification of persistent organic pollutants and fatty acids in bottlenose
595 dolphin (*Tursiops truncatus*) blubber. Science of the Total Environment 463-464:581–588.

596 Fowler, M. A., C. Debier, E. Mignolet, C. Linard, D. E. Crocker, and D. P. Costa. 2014. Fatty
597 acid mobilization and comparison to milk fatty acid content in northern elephant seals.
598 Journal of Comparative Physiology B 184:125–135.

599 Frouin, H., M. Lebeuf, M. Hammill, B. Sjare, and M. Fournier. 2011. PBDEs in serum and
600 blubber of harbor, grey and harp seal pups from Eastern Canada. Chemosphere 82:663–669.

601 Hall, A. J., F. M. D. Gulland, G. M. Ylitalo, D. J. Greig, and L. Lowenstine. 2008. Changes in
602 blubber contaminant concentrations in California sea lions (*Zalophus californianus*)
603 associated with weight loss and gain during rehabilitation. Environmental Science &
604 Technology 42:4181–4187.

605 Hawker, D. W., and D. W. Connell. 1988. Octanol-water partition coefficients of polychlorinated
606 biphenyl congeners. Environmental Science & Technology 22:382–387.

607 Hunt, K. E., R. M. Rolland, and S. D. Kraus. 2015. Conservation physiology of an uncatchable
608 animal: The North Atlantic right whale (*Eubalaena glacialis*). Integrative and Comparative
609 Biology 55:577–586.

610 Keller, J. M., J. R. Kucklick, C. A. Harms, McClellan-Green, and P. D. 2004. Organochlorine
611 contaminants in sea turtles: Correlations between whole blood and fat. Environmental
612 Toxicology and Chemistry 23:726–738.

613 Koopman, H. N., S. J. Iverson, and D. E. Gaskin. 1996. Stratification and age-related differences
614 in blubber fatty acids of the male harbour porpoise (*Phocoena phocoena*). Journal of
615 Comparative Physiology B 165:628–639.

616 Le Boeuf, B. J., D. E. Crocker, D. P. Costa, S. B. Blackwell, P. M. Webb, and D. S. Houser.
617 2000. Foraging ecology of northern elephant seals. Ecological Monographs 70:353–382.

618 Lopez, J., D. Boyd, G. M. Ylitalo, C. Littnan, and R. Pearce. 2012. Persistent organic pollutants
619 in the endangered Hawaiian monk seal (*Monachus schauinslandi*) from the main Hawaiian
620 Islands. Marine Pollution Bulletin 64:2588–2598.

621 Louis, C., A. Covaci, D. E. Crocker, and C. Debier. 2016. Lipophilicity of PCBs and fatty acids
622 determines their mobilisation from blubber of weaned northern elephant seal pups. Science
623 of the Total Environment 541:599–602.

624 Louis, C., A. C. Dirtu, M. Stas, Y. Guiot, G. Malarvannan, K. Das, D. P. Costa, D. E. Crocker,
625 A. Covaci, and C. Debier. 2014. Mobilisation of lipophilic pollutants from blubber in
626 northern elephant seal pups (*Mirounga angustirostris*) during the post-weaning fast.
627 Environmental Research 132:438–48.

628 Lyderson, C., H. Wolkers, T. Severinsen, L. Kleivane, E. S. Nordøy, and J. U. Skaare. 2002.
629 Blood is a poor substrate for monitoring pollution burdens in phocid seals. Science of the
630 Total Environment 292: 193-203.

631 Peterson, S. H., J. L. Hassrick, A. Lafontaine, J.-P. Thomé, D. E. Crocker, C. Debier, and D. P.
632 Costa. 2014. Effects of age, adipose percent, and reproduction on PCB concentrations and
633 profiles in an extreme fasting North Pacific marine mammal. PLoS ONE 9:e96191.

634 Peterson, S. H., M. G. Peterson, C. Debier, A. Covaci, A. C. Dirtu, G. Malarvannan, D. E.
635 Crocker, L. K. Schwarz, and D. P. Costa. 2015. Deep-ocean foraging northern elephant
636 seals bioaccumulate persistent organic pollutants. Science of the Total Environment
637 533:144–155.

638 R Development Core Team. 2012. R: A language and environment for statistical computing. R
639 Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL
640 http://www.R-project.org.

641 Randhawa, N., F. Gulland, G. M. Ylitalo, R. DeLong, and J. A. K. Mazet. 2015. Sentinel
642 California sea lions provide insight into legacy organochlorine exposure trends and their
643 association with cancer and infectious disease. One Health 1:37–43.

644 Robinson, P. W., D. P. Costa, D. E. Crocker, J. P. Gallo-Reynoso, C. D. Champagne, M. A.
645 Fowler, C. Goetsch, K. T. Goetz, J. L. Hassrick, L. A. Hückstädt, C. E. Kuhn, J. L. Maresh,
646 S. M. Maxwell, B. I. McDonald, S. H. Peterson, S. E. Simmons, N. M. Teutschel, S.
647 Villegas-Amtmann, and K. Yoda. 2012. Foraging behavior and success of a mesopelagic
648 predator in the northeast Pacific Ocean: Insights from a data rich species, the northern
649 elephant seal. PLoS ONE 7:e36728.

650 Schwarz, L. K., S. Villegas-Amtmann, R. S. Beltran, D. P. Costa, C. Goetsch, L. Hückstädt, J. L.
651 Maresh, and S. H. Peterson. 2015. Comparisons and uncertainty in fat and adipose tissue
652 estimation techniques: The northern elephant seal as a case study. PLoS ONE 10:e0131877.

653 Strandberg, U., A. Käkelä, C. Lydersen, K. M. Kovacs, O. Grahl-Nielsen, H. Hyvärinen, and R.
654 Käkelä. 2008. Stratification, composition, and function of marine mammal blubber: The
655 ecology of fatty acids in marine mammals. Physiological and Biochemical Zoology 81:473–
656 485.

657 Tanabe, S. 2002. Contamination and toxic effects of persistent endocrine disrupters in marine
658 mammals and birds. Marine Pollution Bulletin 45:69–77.

659 Vanden Berghe, M., L. Weijs, S. Habran, K. Das, C. Bugli, S. Pillet, J. F. Rees, P. Pomeroy, A.
660 Covaci, and C. Debier. 2013. Effects of polychlorobiphenyls, polybromodiphenylethers,
661 organochlorine pesticides and their metabolites on vitamin A status in lactating grey seals.
662 Environmental Research 120:18–26.

663 Vanden Berghe, M., L. Weijs, S. Habran, K. Das, C. Bugli, J.-F. Rees, P. Pomeroy, A. Covaci,
664 and C. Debier. 2012. Selective transfer of persistent organic pollutants and their metabolites
665 in grey seals during lactation. Environment International 46:6–15.

666 Weijs, L., K. Das, H. Neels, R. Blust, and A. Covaci. 2010. Occurrence of anthropogenic and
667 naturally-produced organohalogenated compounds in tissues of Black Sea harbour
668 porpoises. Marine Pollution Bulletin 60:725–731.

669 Worthy, G. A. J., P. A. Morris, D. P. Costa, and B. J. Le Boeuf. 1992. Moult energetics of the
670 northern elephant seal (*Mirounga angustirostris*). Journal of Zoology 227:257–265.

671 Yordy, J. E., D. A. Pabst, W. A. McLellan, R. S. Wells, T. K. Rowles, and J. R. Kucklick. 2010a.
672 Tissue-specific distribution and whole-body burden estimates of persistent organic
673 pollutants in the bottlenose dolphin (*Tursiops truncatus*). Environmental Toxicology
674 29:1263–1273.

675 Yordy, J. E., R. S. Wells, B. C. Balmer, L. H. Schwacke, T. K. Rowles, and J. R. Kucklick.
676 2010b. Life history as a source of variation for persistent organic pollutant (POP) patterns in
677 a community of common bottlenose dolphins (*Tursiops truncatus*) resident to Sarasota Bay,
678 FL. Science of the Total Environment 408:2163–2172.

679 Yordy, J. E., R. S. Wells, B. C. Balmer, L. H. Schwacke, T. K. Rowles, and J. R. Kucklick.

2010c. Partitioning of persistent organic pollutants between blubber and blood of wild bottlenose dolphins: Implications for biomonitoring and health. Environmental Science & Technology 44:4789–95.

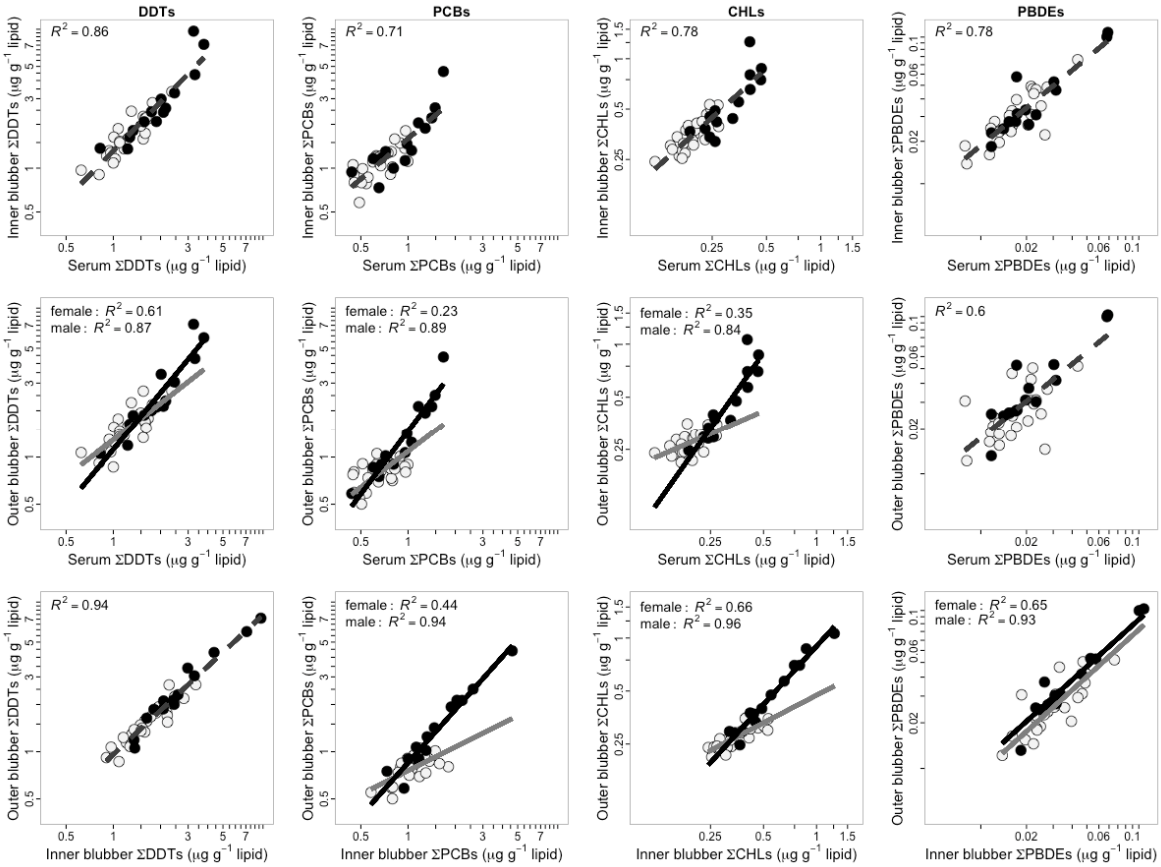

Figure 1. Relationships between concentrations of ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs in inner blubber and serum (upper panels), outer blubber and serum (middle panels), and outer blubber and inner blubber (lower panels) of adult female and male northern elephant seals late in the molting fast (pre-foraging). Regression lines indicate significant relationships (p<0.05) between the two tissues; if there was a significant difference in the slope or y-intercept between females and males, the relationship and R^2 value for both sexes are shown. Males are shown using solid circles and black lines, whereas females are open symbols and solid gray lines. Dashed lines represent the relationship for both males and females when they were not significantly different.

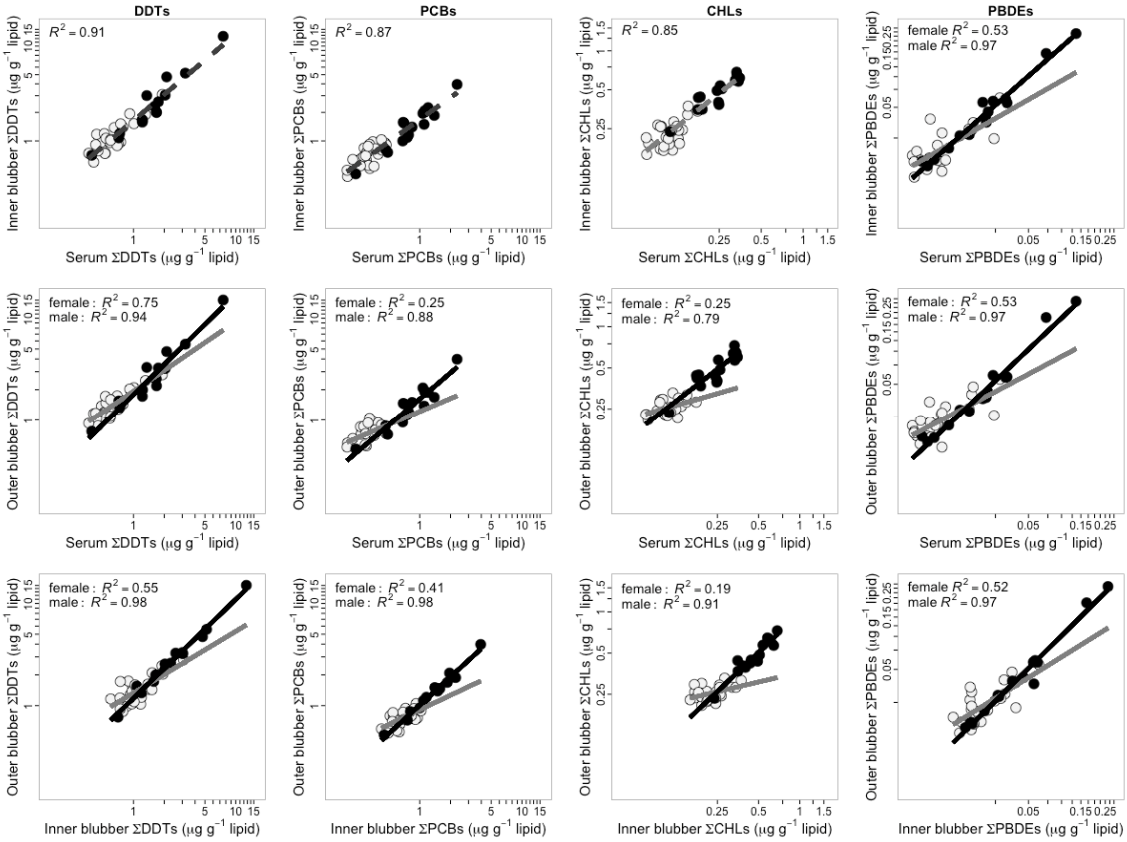

Figure 2. Relationships between concentrations of ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs in inner blubber and serum (upper panels), outer blubber and serum (middle panels), and outer blubber and inner blubber (lower panels) of adult female and male northern elephant seals early in the breeding fast (post-foraging). Regression lines indicate significant relationships (p<0.05) between the two tissues; if there was a significant difference in the slope or y-intercept between females and males, the relationship and R^2 value for both sexes are shown. Males are shown using solid circles and black lines, whereas females are open symbols and solid gray lines. Dashed lines represent the relationship for both males and females when they were not significantly different.

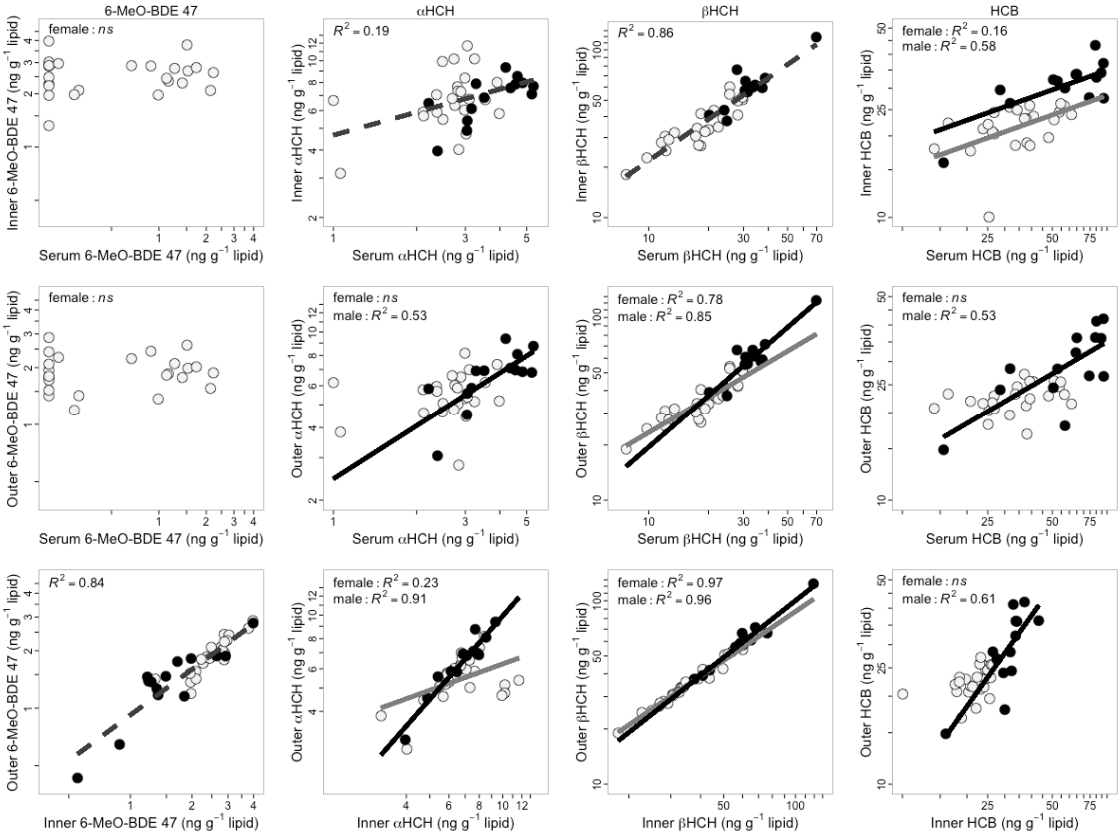

Figure 3. Relationships between concentrations of 6-MeO-BDE 47, α-HCH, β-HCH, and HCB in inner blubber and serum (upper panels), outer blubber and serum (middle panels), and outer blubber and inner blubber (lower panels) of adult female and male northern elephant seals late in the molting fast (pre-foraging). Regression lines indicate significant relationships (p<0.05) between the two tissues; if there was a significant difference in the slope or y-intercept between females and males, the relationship and R^2 value for both sexes are shown. Males are shown using solid circles and black lines, whereas females are open symbols and solid gray lines. Dashed lines represent the relationship for both males and females when they were not significantly different.

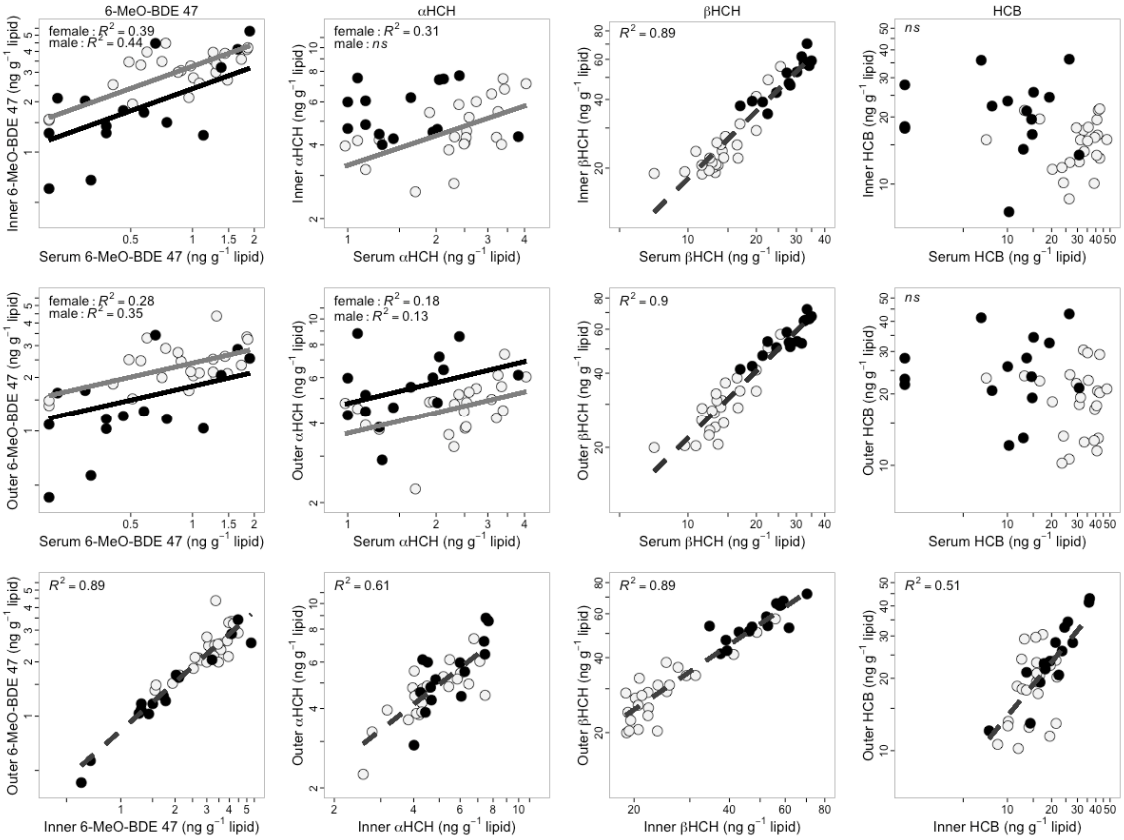

Figure 4. Relationships between concentrations of 6-MeO-BDE 47, α-HCH, β-HCH, and HCB in inner blubber and serum (upper panels), outer blubber and serum (middle panels), and outer blubber and inner blubber (lower panels) of adult female and male northern elephant seals early in the breeding fast (post-foraging). Regression lines indicate significant relationships (p<0.05) between the two tissues; if there was a significant difference in the slope or y-intercept between females and males, the relationship and R^2 value for both sexes are shown. Males are shown using solid circles and black lines, whereas females are open symbols and solid gray lines. Dashed lines represent the relationship for both males and females when they were not significantly different.

Table 1. Lipid-normalized POP concentrations (ng g^{-1}) are reported as median (min-max) POP concentration for each compound in serum, inner blubber, and outer blubber of male and female northern elephant seals. The same females (N = 24) were sampled late in the molting fast and early in the breeding fast, before and after an extensive foraging migration. Unpaired males were sampled late in the molting fast (N=14) and early in the breeding fast (N=15). The full summary of these data are presented in Peterson et al. (2015).

		Late molting fast			Early breeding fast		
Compound	Sex	Serum	Inner	Outer	Serum	Inner	Outer
ΣDDTs	Female	1136 (623-2360)	1589 (902-3354)	1513 (865-2677)	593 (365-1912)	994 (598-3086)	1408 (875-2803)
	Male	1950 (823-3778)	2512 (1054-7107)	2222 (1355-8730)	1604 (390-7532)	2030 (705-12689)	2556 (770-15061)
ΣPCBs	Female	651 (445-997)	1097 (580-1806)	821 (501-1053)	311 (194-470)	713 (422-1029)	787 (539-1046)
	Male	971 (437-1679)	1346 (584-4396)	1333 (733-4610)	778 (236-2317)	1495 (448-3942)	1456 (517-3975)
ΣCHLs	Female	196 (120-271)	345 (242-532)	278 (211-352)	109 (74-175)	229 (158-373)	507 (207-327)
	Male	335 (187-468)	486 (247-1061)	436 (320-1262)	249 (111-350)	492 (237-684)	445 (233-729)
ΣPBDEs	Female	16 (7-43)	27 (14-76)	24 (12-52)	7 (4-27)	16 (10-61)	21 (13-55)
	Male	19 (11-68)	32 (13-112)	31 (18-118)	21 (5-135)	38 (13-264)	38 (14-284)

721 Table 2. Predictive equations, including only significant terms, for concentrations of ΣDDTs, ΣPCBs, ΣCHLs,
722 ΣPBDEs, 6-MeO-BDE 47 (MeOBDE), α-HCH, β-HCH, and HCB in inner blubber:serum, outer blubber:serum, and
723 outer:inner blubber for two times of year (late molting and early breeding). The R^2 refers to goodness of fit of the
724 data to the predictive equation. Subscripts indicate the tissue type: In (inner), Out (outer), and Ser (serum). The 95%
725 confidence interval (CI) is provided for the slope and intercept of each equation. Equations are developed using the
726 natural log of tissue concentrations.

Sex	Equation: ln(tissue Y) = slope× ln(tissue X) + intercept	R^2	95% CI for slope	95% CI for intercept
Late molting (N=14 males, 24 females)				
Inner blubber:serum				
F+M	$\Sigma DDT_{In} = 1.107 \times \Sigma DDT_{Ser} - 0.467$	*0.86*	(0.957, 1.258)	(-1.561, 0.627)
F+M	$\Sigma PCB_{In} = 0.921 \times \Sigma PCB_{Ser} + 1.014$	*0.71*	(0.721, 1.121)	(-0.312, 2.341)
F+M	$\Sigma CHL_{In} = 0.971 \times \Sigma CHL_{Ser} + 0.739$	*0.78*	(0.795, 1.147)	(-0.221, 1.699)
F+M	$\Sigma PBDE_{In} = 0.888 \times \Sigma PBDE_{Ser} + 0.883$	*0.78*	(0.730, 1.045)	(0.416, 1.349)
F	MeOBDE: *Not significant*	--	--	--
M	MeOBDE: *Low detectability*	--	--	--
F+M	$\alpha\text{-HCH}_{In} = 0.340 \times \alpha\text{-HCH}_{Ser} + 1.539$	0.19	(0.105, 0.574)	(1.271, 1.807)
F+M	$\beta\text{-HCH}_{In} = 0.820 \times \beta\text{-HCH}_{Ser} + 1.197$	0.86	(0.707, 0.932)	(0.845, 1.549)
F	$HCB_{In} = 0.282 \times HCB_{Ser} + 2.071$	0.16	(0.145, 0.419)	(1.586, 2.557)
M	$HCB_{In} = 0.282 \times HCB_{Ser} + 2.28$	0.58	(0.145, 0.419)	(1.727, 2.841)
Outer blubber:serum				
F	$\Sigma DDT_{Out} = 0.782 \times \Sigma DDT_{Ser} + 1.761$	*0.61*	(0.504, 1.061)	(-0.219, 3.742)
M	$\Sigma DDT_{Out} = 1.212 \times \Sigma DDT_{Ser} - 1.349$	*0.87*	(0.924, 1.501)	(-3.531, 0.833)
F	$\Sigma PCB_{Out} = 0.370 \times \Sigma PCB_{Ser} + 4.269$	*0.23*	(0.075, 0.665)	(2.353, 6.184)
M	$\Sigma PCB_{Out} = 1.342 \times \Sigma PCB_{Ser} - 1.973$	*0.89*	(1.046, 1.637)	(-3.995, 0.050)
F	$\Sigma CHL_{Out} = 0.436 \times \Sigma CHL_{Ser} + 3.321$	*0.35*	(0.172, 0.701)	(1.929, 4.713)
M	$\Sigma CHL_{Out} = 1.423 \times \Sigma CHL_{Ser} - 2.055$	*0.84*	(1.031, 1.816)	(-4.308, 0.197)
F+M	$\Sigma PBDE_{Out} = 0.814 \times \Sigma PBDE_{Ser} + 0.980$	*0.60*	(0.587, 1.040)	(0.310, 1.650)
F	MeOBDE: *Not significant*	--	--	--
M	MeOBDE: *Low detectability*	--	--	--
F	α-HCH: *Not significant*	--	--	--
M	$\alpha\text{-HCH}_{Out} = 0.732 \times \alpha\text{-HCH}_{Ser} + 0.897$	0.53	(0.302, 1.163)	(0.321, 1.473)
F	$\beta\text{-HCH}_{Out} = 0.640 \times \beta\text{-HCH}_{Ser} + 1.682$	0.78	(0.490, 0.789)	(1.245, 2.119)
M	$\beta\text{-HCH}_{Out} = 0.939 \times \beta\text{-HCH}_{Ser} + 0.810$	0.85	(0.687, 1.190)	(-0.067, 1.687)
F	HCB: *Not significant*	--	--	--
M	$HCB_{Out} = 0.431 \times HCB_{Ser} + 1.618$	0.53	(0.178, 0.684)	(0.594, 2.642)
Outer blubber:inner blubber				
F+M	$\Sigma DDT_{Out} = 0.932 \times \Sigma DDT_{In} + 0.430$	*0.94*	(0.853, 1.011)	(-0.174, 1.034)
F	$\Sigma PCB_{Out} = 0.499 \times \Sigma PCB_{In} + 3.184$	*0.44*	(0.251, 0.747)	(1.450, 4.918)
M	$\Sigma PCB_{Out} = 1.124 \times \Sigma PCB_{In} - 1.019$	*0.94*	(0.942, 1.306)	(-2.351, 0.312)
F	$\Sigma CHL_{Out} = 0.521 \times \Sigma CHL_{In} + 2.563$	*0.66*	(0.355, 0.687)	(1.589, 3.537)
M	$\Sigma CHL_{Out} = 1.098 \times \Sigma CHL_{In} - 0.782$	*0.96*	(0.957, 1.238)	(-1.665, 0.101)
F	$\Sigma PBDE_{Out} = 0.906 \times \Sigma PBDE_{In} + 0.150$	*0.65*	(0.753, 1.060)	(-0.377, 0.677)

M	$\Sigma PBDE_{Out} = 0.906 \times \Sigma PBDE_{In} + 0.303$	*0.93*	(0.753, 1.060)	(-0.266, 0.872)
F+M	$MeOBDE_{Out} = 0.793 \times MeOBDE_{In} - 0.083$	*0.84*	(0.675,0.912)	(-0.183, 0.018)
F	$\alpha\text{-}HCH_{Out} = 0.362 \times \alpha\text{-}HCH_{In} + 1.005$	*0.23*	(0.070, 0.653)	(0.444, 1.566)
M	$\alpha\text{-}HCH_{Out} = 1.144 \times \alpha\text{-}HCH_{In} - 0.340$	*0.91*	(0.912, 1.376)	(-0.788, 0.108)
F	$\beta\text{-}HCH_{Out} = 0.885 \times \beta\text{-}HCH_{In} + 0.393$	*0.97*	(0.821, 0.950)	(0.163, 0.624)
M	$\beta\text{-}HCH_{Out} = 1.028 \times \beta\text{-}HCH_{In} - 0.127$	*0.96*	(0.900, 1.156)	(-0.651, 0.396)
F	HCB: *Not significant*	--	--	--
M	$HCB_{Out} = 1.034 \times \Sigma HCB_{In} - 0.181$	*0.61*	(0.516, 1.552)	(-1.955, 1.593)

Early breeding (N=15 males, 24 females)

Inner blubber:serum

F+M	$\Sigma DDT_{In} = 0.911 \times \Sigma DDT_{Ser} + 1.110$	*0.91*	(0.814, 1.008)	(0.448, 1.772)
F+M	$\Sigma PCB_{In} = 0.774 \times \Sigma PCB_{Ser} + 2.082$	*0.87*	(0.674, 0.873)	(1.471, 2.692)
F+M	$\Sigma CHL_{In} = 0.851 \times \Sigma CHL_{Ser} + 1.451$	*0.85*	(0.732, 0.970)	(0.854, 2.048)
F	$\Sigma PBDE_{In} = 0.615 \times \Sigma PBDE_{Ser} + 1.684$	*0.53*	(0.357, 0.872)	(1.138, 2.229)
M	$\Sigma PBDE_{In} = 0.947 \times \Sigma PBDE_{Ser} + 0.913$	*0.97*	(0.848, 1.047)	(0.608, 1.218)
F	$MeOBDE_{In} = 0.440 \times MeOBDE_{Ser} + 1.181$	0.39	(0.269, 0.611)	(1.035, 1.327)
M	$MeOBDE_{In} = 0.440 \times MeOBDE_{Ser} + 0.873$	0.44	(0.269, 0.611)	(0.661, 1.084)
F	$\alpha\text{-}HCH_{In} = 0.403 \times \alpha\text{-}HCH_{Ser} + 1.195$	0.32	(0.141, 0.664)	(0.958, 1.432)
M	α-HCH: *Not significant*	--	--	--
F+M	$\beta\text{-}HCH_{In} = 0.984 \times \beta\text{-}HCH_{Ser} + 0.623$	0.89	(0.868, 1.100)	(0.285, 0.962)
F+M	HCB: *Not significant*			

Outer blubber:serum

F	$\Sigma DDT_{Out} = 0.683 \times \Sigma DDT_{Ser} + 2.847$	*0.75*	(0.509, 0.857)	(1.725, 3.969)
M	$\Sigma DDT_{Out} = 0.986 \times \Sigma DDT_{Ser} + 0.677$	*0.94*	(0.831, 1.141)	(-0.460, 1.814)
F	$\Sigma PCB_{Out} = 0.389 \times \Sigma PCB_{Ser} + 4.410$	*0.25*	(0.093, 0.685)	(2.709, 6.111)
M	$\Sigma PCB_{Out} = 0.857 \times \Sigma PCB_{Ser} + 1.467$	*0.88*	(0.669, 1.045)	(0.205, 2.730)
F	$\Sigma CHL_{Out} = 0.287 \times \Sigma CHL_{Ser} + 4.194$	*0.25*	(0.066, 0.509)	(3.151, 5.237)
M	$\Sigma CHL_{Out} = 0.777 \times \Sigma CHL_{Ser} + 1.904$	*0.79*	(0.540, 1.014)	(0.600, 3.207)
F	$\Sigma PBDE_{Out} = 0.532 \times \Sigma PBDE_{Ser} + 2.044$	*0.53*	(0.310, 0.754)	(1.574, 2.513)
M	$\Sigma PBDE_{Out} = 0.946 \times \Sigma PBDE_{Ser} + 0.941$	*0.97*	(0.840, 1.053)	(0.615, 1.268)
F	$MeOBDE_{Out} = 0.350 \times MeOBDE_{Ser} + 0.891$	0.28	(0.183, 0.518)	(0.748, 1.034)
M	$MeOBDE_{Out} = 0.350 \times MeOBDE_{Ser} + 0.518$	0.35	(0.183, 0.518)	(0.311, 0.724)
F	$\alpha\text{-}HCH_{Out} = 0.270 \times \alpha\text{-}HCH_{Ser} + 1.295$	0.18	(0.059, 0.480)	(1.094, 1.496)
M	$\alpha\text{-}HCH_{Out} = 0.270 \times \alpha\text{-}HCH_{Ser} + 1.569$	0.13	(0.059, 0.480)	(1.410, 1.728)
F+M	$\beta\text{-}HCH_{Out} = 0.905 \times \beta\text{-}HCH_{Ser} + 0.998$	0.90	(0.803, 1.008)	(0.699, 1.298)
F+M	HCB: *Not significant*	--	--	--

Outer blubber:inner blubber

F	$\Sigma DDT_{Out} = 0.603 \times \Sigma DDT_{In} + 3.027$	*0.55*	(0.360, 0.847)	(1.320, 4.735)
M	$\Sigma DDT_{Out} = 0.967 \times \Sigma DDT_{In} + 0.393$	*0.98*	(0.893, 1.042)	(-0.184, 0.970)
F	$\Sigma PCB_{Out} = 0.475 \times \Sigma PCB_{In} + 3.535$	*0.41*	(0.222, 0.727)	(1.877, 5.193)

M	$\Sigma PCB_{Out} = 0.920 \times \Sigma PCB_{In} + 0.565$	*0.98*	(0.835, 1.004)	(-0.047, 1.178)
F	$\Sigma CHL_{Out} = 0.235 \times \Sigma CHL_{In} + 4.265$	*0.19*	(0.017, 0.453)	(3.081, 5.450)
M	$\Sigma CHL_{Out} = 0.951 \times \Sigma CHL_{In} + 0.317$	*0.91*	(0.767, 1.135)	(-0.815, 1.449)
F	$\Sigma PBDE_{Out} = 0.624 \times \Sigma PBDE_{In} + 1.299$	*0.52*	(0.360, 0.888)	(0.512, 2.085)
M	$\Sigma PBDE_{Out} = 0.988 \times \Sigma PBDE_{In} + 0.070$	*0.97*	(0.892, 1.085)	(-0.296, 0.435)
F+M	$MeOBDE_{Out} = 0.889 \times MeOBDE_{In} - 0.183$	*0.89*	(0.787, 0.991)	(-0.289, -0.077)
F+M	$\alpha\text{-}HCH_{Out} = 0.782 \times \alpha\text{-}HCH_{In} + 0.340$	*0.61*	(0.575, 0.988)	(0.006, 0.673)
F+M	$\beta\text{-}HCH_{Out} = 0.865 \times \beta\text{-}HCH_{In} + 0.618$	*0.89*	(0.264, 0.972)	(0.264, 0.972)
F+M	$HCB_{Out} = 0.746 \times HCB_{In} + 0.916$	*0.51*	(0.500, 0.992)	(0.217, 1.615)

729 Table 3. Results from linear models examining the relationships between POP concentrations in pairs of tissues (inner blubber:serum, outer blubber:serum, and
730 outer blubber:inner blubber) and the influence of sex for northern elephant seals late in the molting fast (pre-foraging trip) and early in the breeding fast (post-
731 foraging trip).

Predicted tissue contaminant	Late molting model (predictor tissue and sex[a])	Early breeding model (predictor tissue and sex[a])
Inner blubber	Serum	Serum
ΣDDTs	ΣDDTs: $F_{1,35}$=156.92, p<0.001 Sex: $F_{1,35}$<0.01, p=0.95	ΣDDTs: $F_{1,36}$=227.55, p<0.001 Sex: $F_{1,36}$=0.75, p=0.39
ΣPCBs	ΣPCBs: $F_{1,35}$=63.83, p<0.001 Sex: $F_{1,35}$<0.01, p=0.96	ΣPCBs: $F_{1,36}$=133.32 Sex: $F_{1,36}$=3.35, p=0.08
ΣCHLs	ΣCHLs: $F_{1,35}$=76.84, p<0.001 Sex: $F_{1,35}$=1.27, p=0.27	ΣCHLs: $F_{1,36}$=49.38, p<0.001 Sex: $F_{1,36}$=2.13, p=0.15
ΣPBDEs	ΣPBDEs: $F_{1,35}$=116.72, p<0.001 Sex: $F_{1,35}$=0.01, p=0.91	ΣPBDEs (female): $F_{1,22}$=24.55, p<0.001 ΣPBDEs (male): $F_{1,13}$=422.54, p<0.001
αHCH	αHCH: $F_{1,35}$=10.96, p=0.002 Sex: $F_{1,35}$=2.09, p=0.16	αHCH (female): $F_{1,22}$=10.2, p=0.004 αHCH (male): $F_{1,13}$=0.04, p=0.84
βHCH	βHCH: $F_{1,35}$=111.79, p<0.001 Sex: $F_{1,35}$=2.81, p=0.10	βHCH: $F_{2,36}$=153.3, p<0.001 Sex: $F_{1,36}$=6.54, p=0.015
HCB	HCB: $F_{1,35}$=17.57, p<0.001 Sex: $F_{1,35}$=9.76, p=0.003	HCB: $F_{1,36}$=0.02, p=0.89 Sex: $F_{1,36}$=4.2, p=0.048
6-MeO-BDE 47	6-MeO-BDE 47: $F_{1,22}$=0.347, p=0.56 (females only)	6-MeO-BDE 47: $F_{2,36}$=23.65, p<0.001 Sex: $F_{1,35}$=1.95, p=0.17
Outer blubber	Serum	Serum
ΣDDTs	ΣDDTs (female): $F_{1,22}$=33.95, p<0.001 ΣDDTs (male): $F_{1,12}$=83.77, p<0.001	ΣDDTs (female): $F_{1,22}$=66.43, p<0.001 ΣDDTs (male): $F_{1,13}$=188.90, p<0.001
ΣPCBs	ΣPCBs (Female): $F_{1,22}$=6.77, p=0.016 ΣPCBs (male): $F_{1,12}$=97.86, p<0.001	ΣPCBs (female): $F_{1,22}$=7.44, p=0.012 ΣPCBs (male): $F_{1,13}$=97.18, p<0.001
ΣCHLs	ΣCHLs (female): $F_{1,22}$=11.71, p=0.002 ΣCHLs (male): $F_{1,12}$=62.53, p<0.001	ΣCHLs (female): $F_{1,22}$=7.22, p=0.013 ΣCHLs (male): $F_{1,13}$=50.00, p<0.001
ΣPBDEs	ΣPBDEs: $F_{1,35}$=45.13, p<0.001 Sex: $F_{1,35}$=2.37, p=0.13	ΣPBDEs (female): $F_{1,22}$=24.80, p<0.001 ΣPBDEs (male): $F_{1,13}$=368.10, p<0.001
αHCH	αHCH (female): $F_{1,22}$=1.13, p=0.30 αHCH (male): $F_{1,12}$=13.74, p=0.003	αHCH: $F_{1,36}$=5.78, p=0.007 Sex: $F_{1,36}$=9.49, p=0.004
βHCH	βHCH (female): $F_{1,22}$=78.55, p<0.001 βHCH (male): $F_{1,12}$=65.98, p<0.001	βHCH: $F_{1,36}$=166.13, $p\leq$0.001 Sex: $F_{1,36}$=2.09, p=0.16
HCB	HCB (female): $F_{1,22}$=3.34, p=0.08 HCB (male): $F_{1,12}$=13.79, p=0.003	HCB: $F_{1,34}$=3.05, p=0.06 Sex: $F_{1,36}$=3.34, p=0.08
6-MeO-BDE 47	6-MeO-BDE 47: $F_{1,22}$=0.11, p=0.74 (females only)	6-MeO-BDE 47: $F_{1,36}$=20.61, $p\leq$0.001 Sex: $F_{1,36}$=10.04, p=0.003

Outer blubber	Inner blubber	Inner blubber
ΣDDTs	ΣDDTs: $F_{1,35}$=409.70, p<0.001	ΣDDTs (female): $F_{1,22}$=26.36, p<0.001
	Sex: $F_{1,35}$=0.64, p=0.43	ΣDDTs (male): $F_{1,13}$=791.90, p<0.001
ΣPCBs	ΣPCBs (female): $F_{1,22}$=17.40, p<0.001	ΣPCBs (female): $F_{1,22}$=15.15, p<0.001
	ΣPCBs (male): $F_{1,12}$=181.40, p<0.001	ΣPCBs (male): $F_{1,13}$=552.00, p<0.001
ΣCHLs	ΣCHLs (female): $F_{1,22}$=42.37, p<0.001	ΣCHLs (female): $F_{1,22}$=5.02, p=0.036
	ΣCHLs (male): $F_{1,12}$=290.40, p<0.001	ΣCHLs (male): $F_{1,13}$=124.82, p<0.001
ΣPBDEs	ΣPBDEs: $F_{1,35}$=143.80, p<0.001	ΣPBDEs (female): $F_{1,22}$=24.05, p<0.001
	Sex: $F_{1,35}$=4.26, p<0.047	ΣPBDEs (male): $F_{1,13}$=489.40, p<0.001
αHCH	αHCH (female): $F_{1,22}$= 6.63, p=0.017	αHCH: $F_{1,36}$=49.34, p<0.001
	αHCH (male): $F_{1,12}$=115.6, p<0.001	Sex: $F_{1,36}$=0.60, p=0.45
βHCH	βHCH (female): $F_{1,22}$=807.2, p<0.001	βHCH: $F_{1,36}$=92.61, p<0.001
	βHCH (male): $F_{1,12}$=307.0, p<0.001	Sex: $F_{1,36}$=2.10, p=0.16
HCB	HCB (female): $F_{1,22}$=4.16, p=0.054	HCB: $F_{1,36}$=27.18, p<0.001
	HCB (male): $F_{1,12}$=18.90, p<0.001	Sex: $F_{1,36}$=0.52, p=0.47
6-MeO-BDE 47	6-MeO-BDE 47: $F_{1,34}$=140.92, p<0.001	6-MeO-BDE 47: $F_{1,36}$=224.36, p<0.001
	Sex: $F_{1,34}$=1.04, p=0.31	Sex: $F_{1,36}$=3.30, p=0.08

[a]Model results are shown for sex unless males and females were run separately because of a significant predictor tissue × sex interaction. Results are shown by sex if males and females were analyzed separately.

734 Table 4. Partitioning coefficient least-squares means (95% confidence interval)
735 for ΣDDTs, ΣPCBs, ΣCHLs, and ΣPBDEs in female and male elephant seals
736 late in the molting fast and early in the breeding fast.

Type	Sex	Late molting	Early breeding
Inner blubber/serum			
ΣDDTs	Female	1.36 (1.23-1.49)	1.77 (1.64-1.90)
	Male	1.45 (1.28-1.62)	1.57 (1.40-1.74)
ΣPCBs	Female	1.68 (1.53-1.82)	2.28 (2.13-2.42)
	Male	1.66 (1.46-1.85)	1.71 (1.53-1.90)
ΣCHLs	Female	1.84 (1.70-1.99)	2.13 (1.98-2.27)
	Male	1.76 (1.57-1.95)	1.96 (1.77-2.14
ΣPBDEs	Female	1.80 (1.53-2.06)	2.59 (2.32-2.85)
	Male	1.76 (1.42-2.11)	2.16 (1.82-2.49)
Outer blubber/serum			
ΣDDTs	Female	1.26 (1.12-1.40)	2.27 (2.13-2.41)
	Male	1.31 (1.13-1.50)	1.80 (1.62-1.98)
ΣPCBs	Female	1.23 (1.08-1.39)	2.50 (2.34-2.66)
	Male	1.48 (1.27-1.68)	1.69 (1.49-1.89)
ΣCHLs	Female	1.44 (1.30-1.59)	2.37 (2.23-2.52)
	Male	1.49 (1.30-1.68)	2.00 (1.81-2.18)
ΣPBDEs	Female	1.59 (1.30-1.88)	3.10 (2.81-3.39)
	Male	1.70 (1.32-2.08)	2.22 (1.85-2.59)
Outer blubber/inner blubber			
ΣDDTs	Female	0.93 (0.84-1.02)	1.33 (1.23-1.42)
	Male	0.92 (0.80-1.04)	1.15 (1.04-1.27)
ΣPCBs	Female	0.74 (0.68-0.81)	1.11 (1.05-1.18)
	Male	0.90 (0.82-0.99)	0.99 (0.91-1.07)
ΣCHLs	Female	0.79 (0.72-0.85)	1.14 (1.08-1.21)
	Male	0.85 (0.76-0.93)	1.02 (0.94-1.10)
ΣPBDEs	Female	0.87 (0.76-0.99)	1.27 (1.15-1.38)
	Male	0.97 (0.83-1.12)	1.03 (0.89-1.18)

737