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Deep-ocean foraging northern elephant seals bioaccumulate persistent organic pollutants☆

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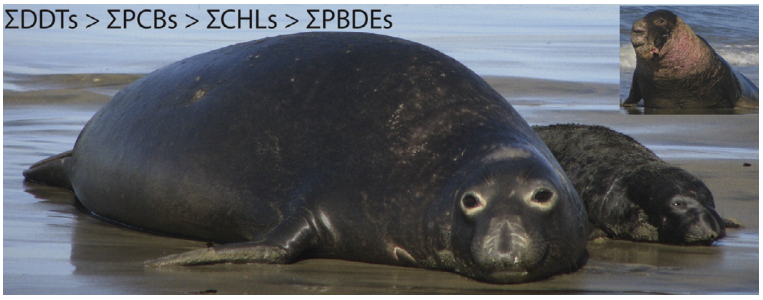
HIGHLIGHTS

- All elephant seals had detectable concentrations of DDTs, PCBs, CHLs, and PBDEs.
- We quantified changes in the blubber burdens of POPs, within individual seals.
- Despite mass dilution while foraging, blubber burdens showed POP ingestion.
- Bioaccumulation of some POP compounds in seals varied across the North Pacific.
- Ratio of ΣDDTs:ΣPCBs corroborated latitudinal variation seen in other species.

GRAPHICAL ABSTRACT



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ABSTRACT

As top predators in the northeast Pacific Ocean, northern elephant seals (*Mirounga angustirostris*) are vulnerable to bioaccumulation of persistent organic pollutants (POPs). Our study examined a suite of POPs in blubber (inner and outer) and blood (serum) of free-ranging northern elephant seals. For adult females (N = 24), we satellite tracked and sampled the same seals before and after their approximately seven month long foraging trip. For males, we sampled different adults and sub-adults before (N = 14) and after (N = 15) the same foraging trip. For females, we calculated blubber burdens for all compounds. The highest POP concentrations in males and females were found for ∑DDTs and ∑PCBs. In blubber and serum, males had significantly greater concentrations than females for almost all compounds. For males and females, ∑DDT and ∑PBDEs were highly correlated in blubber and serum. While ∑PCBs were highly correlated with ∑DDTs and ∑PBDEs in blubber and serum for males, ∑PCBs showed weaker correlations with both compounds in females. As females gained mass while foraging, concentrations of nearly all POPs in inner and outer blubber significantly decreased; however, the absolute burden in blubber significantly increased, indicating ingestion of contaminants while foraging. Additionally, we identified three clusters of seal foraging behavior, based on geography, diving behavior, and stable carbon and nitrogen isotopes, which corresponded with differences in ∑DDTs, ∑PBDEs, MeO-BDE 47, as well as the ratio of ∑DDTs to ∑PCBs, indicating the

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potential for behavior to heighten or mitigate contaminant exposure. The greatest concentrations of ∑DDTs and ∑PBDEs were observed in the cluster that foraged closer to the coast and had blood samples more enriched in ^{13}C. Bioaccumulation of POPs by elephant seals supports mesopelagic food webs as a sink for POPs and highlights elephant seals as a potential sentinel of contamination in deep ocean food webs.

1. Introduction

Persistent organic pollutants (POPs) are a continued threat to wildlife because they are widely dispersed, bioaccumulate in top predators, and can disrupt physiological pathways, thus leading to adverse health effects (Tartu et al., 2015; Jenssen, 2006). Despite international regulation (2009 Stockholm Convention) and bans of some POPs by individual countries, the presence of polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT) and its metabolites, polybrominated diphenyl ethers (PBDEs), chlordanes (CHLs), and other POPs in marine and terrestrial ecosystems remains pervasive (Braune et al., 2005; Farrington and Takada, 2014). While POPs have multiple sources and mechanisms of transport, the deep ocean can serve as a sink (Farrington and Takada, 2014), where POPs can enter marine food webs and can magnify with trophic level (Weijs et al., 2009). POPs are resistant to biological degradation and associate mainly with lipids in biological organisms (Muir et al., 1999). The legacy of POPs is important for marine mammals because persistent exposure to even low levels of POPs can influence mammalian endocrine systems (Tanabe, 2002), neural function (Haijima et al., 2010; Winneke, 2011) and immune systems (Ross et al., 1996; Schwacke et al., 2012). Bioaccumulation of POPs in marine mammals may have population-level consequences through the combination of weakened immune function and infectious disease (Hall et al., 2006). In addition, POPs in adult female marine mammals are concerning because POPs can transfer from mother to offspring via placental transfer and lactation (Greig et al., 2007; Vanden Berghe et al., 2012; Wolkers et al., 2004), meaning that young animals are exposed to a suite of contaminants during critical periods of development.

The main source of POPs to marine mammals is through food (Muir et al., 1999), therefore specific foraging behaviors, including location or diet, may exacerbate or mitigate POP exposure. For example, proximity to industrialization and point sources of contaminant entry into the environment can result in higher POP bioaccumulation in some marine mammals than others (Frouin et al., 2011; Lopez et al., 2014; Ross et al., 2004; Schwacke et al., 2012). Differences in diet, within and among species, can also influence bioaccumulation of POPs (Bentzen et al., 2008; Ross et al., 2000). Concentrations of POPs are often higher in males than females because females can transfer contaminants to offspring while males are unable to offload any of their accumulated contaminant burden (Barron et al., 2003; Storelli et al., 2012; Wang et al., 2007). Marine mammals are vulnerable to bioaccumulation of POPs because they often have relatively long life spans over which to accumulate POPs, and many species are more susceptible to biomagnification due to their high trophic position.

Studies of contaminant bioaccumulation in mammals are challenging because factors such as animal age and body condition can confound analyses. Contaminants are primarily reported in concentrations, either by wet weight or lipid weight; however, concentrations of POPs are significantly influenced by body condition and physiological state in both stranded and free-ranging animals (Debier et al., 2012; Hall et al., 2008; Myers and Atkinson, 2012; Peterson et al., 2014). Varying contaminant concentrations have been observed for a significant number of marine mammal species, although many studies have focused on quantification of contaminants in stranded animals and less so in free-ranging animals. Contaminant concentrations in stranded and deceased animals may not represent healthy animals due to the complications of disease, dehydration, or starvation; therefore, sampling free-ranging animals provides a more complete quantification of the range of bioaccumulation experienced by a population as a whole. Additionally, quantification of the blubber burden of contaminants (mg contaminant) and the subsequent change in burden over time makes it possible to track changes in contaminants contained within the blubber layer, regardless of physiological changes. Indeed, variations of blubber POP concentrations, which are directly related to physiological state and blubber mass, do not necessarily reflect variations of POP burden. For example, increased POP concentrations in blubber of northern elephant seals at the end of the lactation-associated fast, compared with the beginning of the fast, may actually correspond to a decreased body burden as a result of POP excretion through milk (Debier et al., 2012). In contrast, lower POP concentrations in elephant seal blubber after a foraging trip (Peterson et al., 2014) may correspond to a greater body burden as a result of foraging. Furthermore, the inner and outer portions of blubber differ in their metabolic activity during fasting and foraging periods (Fowler et al., 2014; Strandberg et al., 2008), which may differentially influence contaminant concentrations across the blubber layer. The challenges associated with repeatedly sampling the same free-ranging animals have limited the number of studies that directly link individual foraging behavior with contaminant bioaccumulation (inner and outer blubber) or changes in contaminant burden.

As relatively long-lived, high trophic level predators foraging in the mesopelagic (200–1000 m) northeast Pacific Ocean, northern elephant seals (*Mirounga angustirostris*) can serve as biomonitors of remote ocean habitats that are difficult to sample. Elephant seals undergo biannual foraging trips, ranging upwards of 5000 or 10000 km depending on the season, within several open-ocean and near-coastal hydrographic ecoregions, including the Subarctic Gyre, the North Pacific Polar Front, and the California Current (Le Boeuf et al., 2000; Robinson et al., 2012; Springer et al., 1999). The northern elephant seal is the only pinniped species in the North Pacific that forages almost entirely on fish and squid in the mesopelagic zone (Antonelis et al., 1987; Le Boeuf et al., 2000; Naito et al., 2013). Biannual foraging trips (Fig. 1) are interspersed with extensive fasting periods on land, at which time individuals lose up to 40% of their body mass (Costa et al., 1986; Worthy et al., 1992).

Our study is one of few to repeatedly sample individuals at the start and end of a long foraging trip and to calculate variations in the contaminant mass in blubber. For this study, our objectives were to use free-ranging northern elephant seals to: 1) Measure a suite of POP compounds and compare the concentrations between adult females and males before and after the foraging trip, 2) Determine how well correlated different POP compounds are in females and males upon arrival to the colony at the end of the foraging trip, 3) Quantify changes in concentrations (females — paired seals, males — unpaired seals) and blubber burdens (females) from the start to the end of the foraging trip, and 4) Determine if contaminant concentrations and blubber burdens in females vary with clusters of foraging behavior.

2. Methods

2.1. Animal sampling

We collected paired blubber and blood samples from adult northern elephant seals at the Año Nuevo State Reserve (37.11° N, 122.33° W) in 2012 and 2013. 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) the approximately seven month foraging trip (Fig. 1). Blubber cores and blood samples were also 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 at the start of the early breeding fast (Fig. 1). Due to the challenges associated with repeatedly sampling males, we were unable to