Anthropogenic flank attack on polar bears: interacting consequences of climate warming and pollutant exposure

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Polar bears (*Ursus maritimus*) are subjected to several anthropogenic threats, climate warming and exposure to pollutants being two of these. For polar bears, one of the main effects of climate warming is limited access to prey, due to loss of their sea ice habitat. This will result in prolonged fasting periods and emaciation and condition related negative effects on survival and reproduction success. Prolonged fasting will result in increases of the tissue concentrations of persistent organic pollutants (POPs) in polar bears, and thus increase the probability for POP levels to exceed threshold levels for effects on health, and thus on reproductive success and survival. There are clear potentials for interactions between impacts of climate warming and impacts of pollutant exposure on polar bears. It is likely that that fasting-induced increases of POPs will add to mortality rates and decrease reproductive success beyond effects caused by loss of habitat alone. However, there is a lack of studies that have addressed this. Thus, there is a need to focus on population effects of POP exposure in polar bears, and to consider such effects in relation to the effects of climate induced habitat loss.

Keywords: arctic, pollution and global change, PCBs, ecology, climate change impacts

POLAR BEARS, CLIMATE WARMING, AND POLLUTION EXPOSURE

Polar bears (*Ursus maritimus*) have received considerable focus as a wildlife species impacted by climate change since projected sea ice loss is argued to restrict their access to seals on the ice, making their survival of global concern (Durner et al., 2009; Edwards et al., 2011; Molnar et al., 2011; Stirling and Derocher, 2012; Derocher et al., 2013). The polar bear is the single species among mammals and birds listed under the U.S. Endangered Species Act that attracts most public attention (Roberge, 2014), and a symbol-species of the potential devastating effects of global climate change on biodiversity and ecosystems. Modeling has shown that the southernmost polar bear populations are those that are most vulnerable, and will struggle to persist there throughout this century (Castro De La Guardia et al., 2013). Models have also predicted losses of polar bear sea ice habitats in the polar basin during this century (Durner et al., 2009) and indicated that two-third of the world's polar bears could disappear if greenhouse gas emissions continue as predicted (Amstrup et al., 2008).

However, climate warming is not the only anthropogenic factor that affects polar bear populations. Exposure to pollutants, hunting and increase in ecotourism and raw material exploration and exploitation are other major anthropogenic threats to this species (IUCN, 2014). Because of their high tropic position and food web biomagnification of persistent organic pollutants

(POPs), and mercury (Hg), polar bears are exposed to high levels of these harmful compounds (Letcher et al., 2010; Sonne, 2010). Due to international regulations on production and use of POPs (www.pops.int) there have been significant decreases in levels of the conventional POPs in polar bears and their prey during the last decades, whereas brominated flame retardants (BFRs) and perfluoroalkyl substances (PFASs) overall have increased over the same period although some have started to decline in recent years (Bytingsvik et al., 2012a,b; Dietz et al., 2013c; Dietz R Rigét et al., 2013b; Riget et al., 2013). However, levels of most POPs such as polychlorinated biphenyls (PCBs), brominated flame retardants (BFRs), organochlorinated pesticides (OCPs) and perfluoroalkyl compounds (PFASs), are still high in polar bears, and often above threshold levels for physiological and toxicological effects reported in the literature for mammals (Letcher et al., 2010; Sonne, 2010). Furthermore, levels of Hg have been shown to increase in polar bears (Dietz et al., 2011) and there are increased concerns about the effects of metabolites produced by endogenous biotransformation of POPs (Letcher et al., 2010).
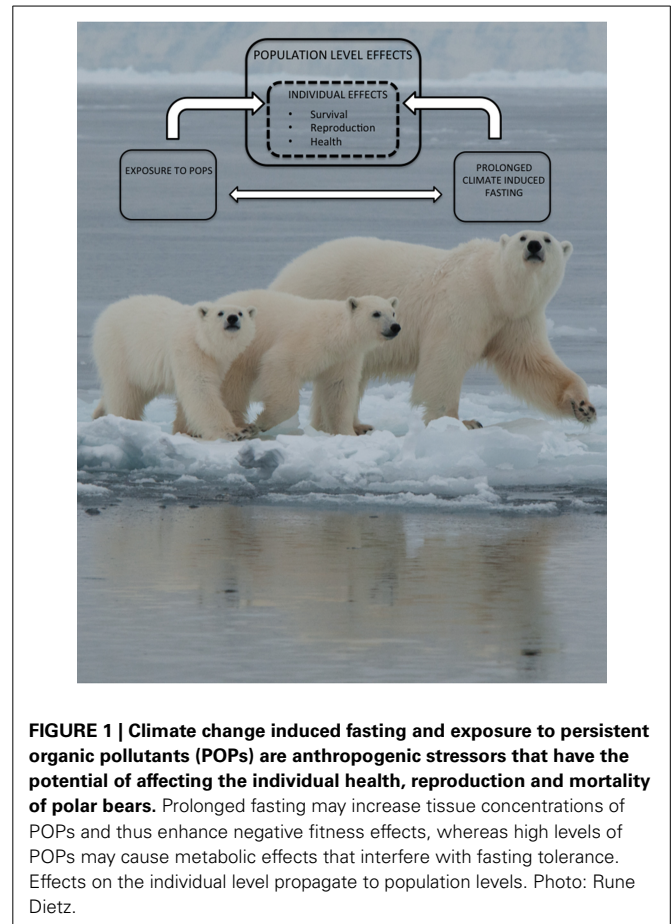
Many POPs and their metabolites, as well as mercury (Hg) have been shown to have endocrine disruptive effects, and are thus classified as endocrine disrupting chemicals (EDCs) (Colborn, 2004). In general, the endocrine system together with the nervous and the immune systems, form the main regulatory mechanisms in the animal body controlling all vital functions

(Lintelmann et al., 2003). Many POPs also interfere with immune function, lipid storage and metabolism and reproduction, and may perturb important processes during early growth and development (Letcher et al., 2010). There are concerns that effects on organisms caused by climate change and contaminant exposure interact, thus causing combined effects that may have large-scale ecological impacts (Jenssen, 2006; Schiedek et al., 2007; Wingfield, 2008; Noyes et al., 2009; Unep/Amap, 2011; Moe et al., 2013). The combined effects of these two anthropogenic factors on populations and ecosystems may be additive, or even synergistic. Herein, we focus on how POPs may interact with, and possibly enhance the effects of climate warming in polar bears. Insight into such combined effects caused by these two major anthropogenic stressors provides perspectives that are of importance for research and for conservation management of the species.

COMBINED EFFECTS ON ENERGETIC PROCESSES

In some regions periods of open-water force polar bears onshore during summer and autumn, and thus limit access to their most common high-energy containing prey, that mainly are ringed seals (*Pusa hispida*) (Stirling and Derocher, 2012; Derocher et al., 2013). During these periods they fast and rely on body lipid reserves for energy (Cherry et al., 2009). Climate warming causes earlier break-up of sea-ice and thus prolongs this fasting period in polar bears, resulting in increased mortality rates due to emaciation and starvation (Gagnon and Gough, 2005; Molnar et al., 2010, 2014; Stirling and Derocher, 2012). Because many lipid-soluble POPs are not excreted, fasting and especially emaciation will cause large increases of the concentrations of these compounds in blood and target tissues (Polischuk et al., 2002; Christensen et al., 2007; Helgason et al., 2013). Thus, prolonged fasting due to climate induced ice-loss and resultant lowered prey availability increases the likelihood for POPs levels to exceed threshold levels for effects. Many POPs have health effects that directly affect survival rates, such as their negative effects on the immune system (Vos et al., 2000). Thus, it is likely that fasting-induced increases of these compounds will increase the mortality rates beyond those predicted to be caused by the climate-induced prolonged fasting period alone (Molnar et al., 2010, 2014). It is also likely that fasting-induced increases of burdens of POPs that are reproductive EDCs will add to the predicted negative reproductive effects that lower body condition alone has on reproductive success of polar bears (Regehr et al., 2010); **Figure 1**.

It is suggested that decreases of polar bear sea ice habitats will result in increased movement and migration rates and distances to remain on ice (Derocher et al., 2004; Durner et al., 2009), thus causing increased energetic requirements and feeding rates. In female polar bears it has been suggested that high movement rates and distances associated with occupying large home range sizes may result in high blood concentrations of PCBs (Olsen et al., 2003). This is because the high activity level associated with occupying large home range sizes requires high food intake, which causes high dietary intake of these persistent compounds (Olsen et al., 2003). It is therefore possible that long-range annual migrations mitigated by sea ice habitat

FIGURE 1 | Climate change induced fasting and exposure to persistent organic pollutants (POPs) are anthropogenic stressors that have the potential of affecting the individual health, reproduction and mortality of polar bears. Prolonged fasting may increase tissue concentrations of POPs and thus enhance negative fitness effects, whereas high levels of POPs may cause metabolic effects that interfere with fasting tolerance. Effects on the individual level propagate to population levels. Photo: Rune Dietz.

loss will result in increased uptake and accumulation of POPs due to the increased feeding demands needed for longer migrations. In some regions, decline of sea ice extension has resulted in changes in the presence of seal species that polar bears depredate, and this has been shown to cause increased bioaccumulation of certain POPs (Thiemann et al., 2008; McKinney et al., 2009, 2013). Dietary shift toward feeding on plants, berries and caribou (*Rangifer tarandus*) and seabird eggs, respectively (Ramsay and Hobson, 1991; Gormezano and Rockwell, 2013a,b; Iles et al., 2013; Iverson et al., 2014), will most likely decrease and increase, respectively, the dietary uptake of POPs. Furthermore, climate warming induced immigrating warm-adapted fish species (Valdimarsson et al., 2012; Mackenzie et al., 2014) may act as biovectors that increases contaminant levels in marine arctic ecosystems (Macdonald et al., 2005; Carrie et al., 2010), ultimately causing increased bioaccumulation of these compounds in polar bears.

In polar bears, the thyroid hormone system is sensitive to the effects of several POPs (Skaare et al., 2001; Braathen et al., 2004; Gutleb et al., 2010; Knott et al., 2011; Villanger et al., 2011; Bytingsvik et al., 2013; Simon et al., 2013; Gabrielsen et al., 2015). The effects of EDCs on thyroid hormones appear to be particularly pronounced in female and subadult polar bears, whereas adult males appear to be much more resistant (Braathen et al., 2004; Villanger et al., 2011). In polar bears there are also

indications that concentrations of T4 in muscle tissue and deio-dinase activities in muscle, kidney and liver are influenced by circulating concentrations of POPs (Gabrielsen et al., 2015). Since thyroid hormones are involved in nearly all metabolic pathways (McNabb, 1995), EDC induced thyroid disruption may seriously interfere with energy expenditure during fasting. Thyroid dys-function has also been linked to reduced fertility, increased rates of spontaneous abortion, premature delivery and low birth weight (Krassas et al., 2010). Because climate driven fasting and emaci-ation will increase contaminant loads in target tissues, the thyroid related effects might become "self-reinforcing" and thus escalate the negative effects on survival and reproduction.

The glucocorticoid endocrine system also plays an important role in metabolism and energetic processes (Hiller-Sturmhöfel and Bartke, 1998). In polar bears, the main glucocorticoid hor-mone in mammals, cortisol, has been reported to be influenced by plasma concentrations of pesticides and PCBs (Oskam et al., 2004; Bechshøft et al., 2012). Cortisol in polar bears is also influ-enced by climate conditions, indicating that the bears are under higher levels of physiological stress during years with less ice cover and thus less easy access to seals (Bechshøft et al., 2013). Pollutant exposure may thus add to the physiological stress encountered by polar bears during years with low ice coverage, enhancing the effects of climate warming.

Polar bears have an enrichment of genes associated with adipose tissue development that may be important in the adaptation to their lipid-rich diet and high blood concentra-tions of cholesterol and low-density lipoproteins (Liu et al., 2014). Recently, there has been an increased focus on the role of POPs on development of obesity in humans (Hotchkiss et al., 2008; Dirinck et al., 2013; De Cock and Van De Bor, 2014; Donat-Vargas et al., 2014). One mechanism for this effect may be that POPs causes "leptin-resistance" in adipose tissue, a typical metabolic alteration related to obesity (Ferrante et al., 2014). Furthermore, dietary exposure to PCBs may result in increased metabolic rates (Voltura and French, 2000). Since lipid storage and metabolism are important environmental adaptations in polar bears, disrup-tion of these processes by POPs may seriously inflict on the ability of polar bears to tolerate prolonged fasting periods that are pre-dicted to be associated with climate warming. If POPs increases metabolic rates, high body burdens of POPs are likely to induce higher rates of body mass loss, and thus increase mortality rates beyond those predicted to be caused by prolonged fasting alone (Molnar et al., 2010, 2014); **Figure 1**.

COMBINED EFFECTS ON REPRODUCTION AND IMMUNITY

Several POPs have been documented to have harmful effects on reproductive organs and hormones, and to adversely affect fer-tility and fecundity in mammals (Vos et al., 2000). In polar bears, POPs have been reported to affect reproductive hormones (Haave et al., 2003; Oskam et al., 2003) and to influence the morphology of male and female reproductive organs such as testicles, penis, uteri and ovary (Sonne et al., 2006). This may reduce their repro-ductive success (Sonne et al., 2006; Letcher et al., 2010). These morphological changes are probably a result of both pre- and post-natal effects and the pathways being via the hypothalamic-pituitary-axis likely with a thyroid cross-talk (Sonne, 2010).

Although poor recruitment in the Svalbard polar bear popula-tion has been linked to their high burdens of reproductive EDCs (Derocher et al., 2003), it not possible to fully estimate the impact from these reproductive related disruptions and pathological con-ditions. It is likely that fasting-induced increases in reproductive EDCs will enhance the reported negative effects on reproductive success in polar bears caused by increasing duration of the ice-free period (Regehr et al., 2010)

Climate warming increases risks of disease spreading (Harvell et al., 2002), and may induce a shift in the micro-pathogen composition toward higher virulence (Shope, 1992; Burek et al., 2008). Polar bears may therefore become exposed to health chal-lenges that they have not previously encountered (Sonne, 2010). Many POPs are immune toxic (Vos et al., 2000) and in polar bears inverse relationships between POP concentrations and immune globulins and cellular immune responses have been reported (Bernhoft et al., 2000; Lie et al., 2004, 2005). The combina-tion of spreading of new diseases and micro-pathogens to the Arctic caused by global warming (Harvell et al., 2002) and a weakened immune system in polar bears caused by pollutant exposure will cause combined effects that can increase mortal-ity rates. Polar bears also have low genetic diversity in their immune system, which is consistent with a long-term exposure to low levels of pathogens and parasites (Weber et al., 2013). Thus, contaminant exposure could depress their response toward micro pathogens and diseases even further, and thereby increase mortality rates. In addition, pathogens and diseases may affect reproductive rates (Sonne, 2010). It is likely that fasting will enhance immune related effects, both due to fasting-induced increases in POPs, and due to that fasting generally is associated with immunosuppression and poorer general health conditions (Sonne, 2010).

COMBINED EFFECTS ON NEUROLOGICAL PROCESSES, BEHAVIOR AND DEVELOPMENT

POPs can cause neurobehavioral effects, such as sexual and other reproductive behaviors, activity, motivation, communica-tion, aggression, dominance and other social behaviors, as well as learning and other cognitive abilities (Zala and Penn, 2004). Field studies of behavioral effects of POPs in polar bears are, of natural causes, difficult to conduct. However, several POPs and methylmercury reported in brain tissue of polar bears, (Greaves et al., 2012, 2013; Krey et al., 2012; Dietz et al., 2013a) are known or suspected developmental neurotoxicants in humans and exper-imental animals (Grandjean and Landrigan, 2006, 2014; Fonnum and Mariussen, 2009; Mariussen, 2012).

POPs might affect brain function or development through many mechanisms, such as interacting with brain neurotrans-mitter systems (Fonnum and Mariussen, 2009). Also, the ability of some POPs to induce epigenetic changes could present a mechanistic pathway of neurodevelopmental perturbations (Mill and Petronis, 2008; Bollati and Baccarelli, 2010; Crews, 2011). Associations between neurochemical and epigenetic biomarkers and mercury levels in brain tissue have been reported for polar bears (Basu et al., 2009; Pilsner et al., 2010; Dietz et al., 2013a). Another proposed mechanism of developmental neurotoxicity is through thyroid hormone disruption, as these hormones

are essential during fetal and early neonatal neurodevelopment (Crofton and Zoeller, 2005; Ahmed et al., 2008). Thus, the high levels of POPs reported in 4-month old polar bear cubs (Bytingsvik et al., 2012a,b) and their associated thyroid disrupting properties in cubs (Bytingsvik et al., 2013; Simon et al., 2013) raises concern for neurodevelopmental effects in polar bears.

The relative high concentrations of several POPs reported in polar bear brains may cause adverse effects, with a possible heightened susceptibility during the more sensitive fetal and neonatal stages of brain development (Rodier, 1995; Grandjean and Landrigan, 2006). Similarly to humans, this could alter behavioral traits and reduce cognitive abilities related to memory and learning in offspring. For polar bears, this could functionally reduce, e.g., hunting skills or alter mating behavior, and thus ultimately affect reproduction and survival.

COMBINED EFFECTS ON POPULATIONS, GENETICS, AND EVOLUTION

Several studies have documented that climate induced loss of sea ice has negatively affected the long-term survival and abundance of polar bears in some subpopulations (Regehr et al., 2010; Stirling and Derocher, 2012; Bromaghin et al., 2015). In contrast, there appear to be no documentation that POPs have caused decreases in polar bear populations. However, there are numerous reports that POPs affect fitness-related variables in polar bears at the individual level (Letcher et al., 2010; Sonne, 2010). Modeling of effects of POPs at the population level is thus warranted. The effects of both POPs and climate warming will affect density-dependent processes at the population level. Thus, mortality due to POP exposure and habitat loss caused by climate warming can separately and/or combined, reduce competition for food and thus reduce starvation in surviving animals.

The divergence of polar bears from brown bears (*Ursus arctos*) has taken 480-340 thousand years (Edwards et al., 2011; Liu et al., 2014). It is also indicated that polar bears were adapted to arctic marine diet and life 130-110 thousand years ago (Lindqvist et al., 2010), indicating an unprecedented time for rapid evolution of less than 20,500 generations (Liu et al., 2014). Furthermore, dispersal events driven by climate fluctuations has caused opportunistic mating between these two species, suggesting that interspecific hybridization may be a mechanism by which polar bears deals with marginal habitats during previous non-anthropogenic periods of environmental deterioration (Edwards et al., 2011). The history of the large-scale environmental changes caused by anthropogenic pollution is short in relation to their evolutionary history. Whereas polar bears most likely have experienced rapid and dramatic climatic fluctuations during the past hundreds of thousand years, exposure to anthropogenic POPs have occurred for less than 100 years. Although Atlantic tomcod (*Microgadus tomcod*) inhabiting waters highly polluted with PCBs and dioxins, genetically evolved AhR resistance over the time-span of three decades (Wirgin et al., 2011), it is very unlikely that a similar rapid evolution will occur in a polar bears.

Morphometric differences in the size and shape of individual polar bear skulls collected in 1892–1932, which is prior to the major anthropogenic environmental changes, as compared to in skulls from 1961 to 2002 were suggested to be a combined consequence of exposure to POPs and climate induced changes in the availability of food resources (Pertoldi et al., 2009). These combined effects may also have affected the polar bears' genetic composition and effective population size (Pertoldi et al., 2009). An epigenetic study documented Hg-associated DNA hypomethylation in brain stems of male polar bears (Pilsner et al., 2010). Epigenetic responses do not represent a permanent redirection of phenotype in the same way as mutation and natural selection (Burggren and Crews, 2014), and are "turned off" in downstream generations when the environmental stressor that created them diminishes or disappears (Burggren, 2014). However, multi-generation *in utero* exposure to a stressor (such as Hg and POPs) may cause long-lasting transgenerational effects (Burggren and Crews, 2014). It should also be noted that although in mammals, epigenetic markers are erased before being reestablished, a process referred to as "reprogramming," recent studies show that some epigenetic marks escape epigenetic reprogramming (Mendizabal et al., 2014).

CONCLUDING REMARKS

According to the points discussed above, there are clear potentials for interactions between impacts of climate warming and impacts of pollutant exposure on polar bears. However, there is a lack of studies that can confirm or discard the presence of such interactions. Of particular concern are the interacting effects of the climate induced prolonged fasting periods and the resultant increased POP levels in polar bears. We hypothesize that fasting-induced increases of POPs will add to mortality rates and decrease reproductive success beyond effects caused by loss of habitat alone. When considering the numerous fitness-related traits reported to be influenced by POPs, there is a need to focus on population effects of POP exposure in polar bears, and to consider such effects in relation to the effects of habitat loss.

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