Monograph

Endocrine-Disrupting Chemicals and Climate Change: A Worst-Case Combination for Arctic Marine Mammals and Seabirds?

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The effects of global change on biodiversity and ecosystem functioning encompass multiple complex dynamic processes. Climate change and exposure to endocrine-disrupting chemicals (EDCs) are currently regarded as two of the most serious anthropogenic threats to biodiversity and ecosystems. We should, therefore, be especially concerned about the possible effects of EDCs on the ability of Arctic marine mammals and seabirds to adapt to environmental alterations caused by climate change. Relationships between various organochlorine compounds, necessary such as polychlorinated biphenyls, dichlorophenyldichloroethylene, hexachlorobenzene, and oxychlordane, and hormones in Arctic mammals and seabirds imply that these chemicals pose a threat to endocrine systems of these animals. The most pronounced relationships have been reported with the thyroid hormone system, but effects are also seen in sex steroid hormones and cortisol. Even though behavioral and morphological effects of persistent organic pollutants are consistent with endocrine disruption, no direct evidence exists for such relationships. Because different endocrine systems are important for enabling animals to respond adequately to environmental stress, EDCs may interfere with adaptations to increased stress situations. Such interacting effects are likely related to adaptive responses regulated by the thyroid, sex steroid, and glucocorticosteroid systems. *Key words:* glaucous gull, *Haliocherus, Larus hyperboreus,* PBDEs, PCB, polar bears, POPs, seal, *Ursus maritimus. Environ Health Perspect* 114(suppl 1):76–80 (2006). doi:10.1289/ehp.8057 available via *http://dx.doi.org/* [Online 21 October 2005]

Before the 17th century the anthropogenic impact on Arctic ecosystems was restricted to a sustainable level by a very limited number of indigenous inhabitants, and most of the Arctic was untouched by humans. As a consequence of the search for the Northeastern and Northwestern passages by scientific and mercantile expeditions, the vast natural resources in the Arctic ecosystem were discovered. The exploitation of these resources has resulted in the depletion and/or extinction of many marine mammal species and populations such as the Steller's sea cow (*Hydrodamalis gigas*), the bowhead whale (*Balaena mysticetus*), and the walrus (*Odobenus rosmarus*). Within a century, the characteristics and function of the Arctic ecosystem were dramatically changed, and they have never recovered. Even today there is considerable concern within the scientific community, government regulators, and the public about the impact of direct human activities such as hunting, fishing, and habitat change and/or destruction on Arctic biodiversity and ecosystem functioning.

During the last four decades of the 20th century, the Arctic became threatened by long-range atmospheric transport of manmade chemicals. Anthropogenic and persistent organic pollutants (POPs) were detected in endemic Arctic species, such as polar bears (*Ursus maritimus*) (Norheim et al. 1992), glaucous gulls (*Larus hyperboreus*) (Bourne and Bogan 1972), walrus (Born et al. 1981), Arctic phocids (Bang et al. 2001), and beluga whales (*Delphinapterus leucas*) (Andersen et al. 2001). POPs are chemicals that are resistant to physical, chemical, and biochemical degradation and, therefore, remain available for uptake and bioaccumulation for a long period of time. Thus, they have a potential for long-range environmental transport, and they have adverse effects (Stockholm Convention 2005). Examples of POPs found in Arctic marine mammals and seabirds are industrial organochlorines (OCs) such as polychlorinated biphenyls (PCBs), hexachlorobenzene (HCB), polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), and polychlorinated naphthalenes (PCNs), as well as OC pesticides such as dichlorophenyl-trichloroethane (DDT) and its metabolites, chlordane, heptachlor, dieldrin, endrin, and mirex (Arctic Monitoring and Assessment Programme 2004). Recently, several so-called novel POPs such as polybrominated diphenyl ethers (PBDEs) and perfluorooctane sulfonate (PFOS) have also been reported in Arctic marine mammals and seabirds (Giesy and Kannan 2001; Herzke et al. 2003; Ikonomou et al. 2002; Wolkers et al. 2004). The concentrations of some of these compounds such as PBDEs show an increasing trend in Arctic marine mammals (Ikonomou et al. 2002). Thus, even though there is evidence that levels of classic POPs such as PCBs are decreasing or have leveled off [for example, as reported in polar bears from the Svalbard and Barents Sea region (Henriksen et al. 2001)], it is likely that the total exposure of Arctic biota to POPs will increase during the next decade.

Because of structural similarities with endogenous hormones, abilities to interact with hormone transport proteins, or abilities to disrupt hormone metabolism, many POPs can mimic or in some cases block the effects of the endogenous hormones. In either case, these chemicals disrupt the normal actions of endogenous hormones and, thus, have become known as endocrine-disrupting chemicals (EDCs) (Colborn et al. 1993). Examples of environmental pollutants with endocrine-disrupting properties are some OC pesticides, phthalates, alkylphenolic compounds, PCBs, PCDDs and PCDFs, bisphenol A, PBDEs, tetrabromobisphenol A (TBBPA), and heavy metals, including lead, mercury, and cadmium (Crisp et al. 1998; Meerts et al. 2001). It should also be noted that Arctic marine mammals and seabirds have the ability to metabolize many POPs to more polar forms that contain hydroxy groups via the hepatic cytochrome P450 enzyme system. Paradoxically, many of the metabolites formed during phase I or II metabolism have endocrine-disrupting properties (van den Berg et al. 2003). Thus, a well-developed detoxification system is not a guarantee against endocrine-disrupting effects of POPs.

Recently, climate change has been recognized as another significant threat to Arctic biodiversity and ecosystem functioning. Although debate is ongoing as to the causative factors with respect to the climate change issue, there is clear evidence of the ecological impact of recent climate change, from polar terrestrial to tropical marine environments (Crowley 2000; Jones et al. 2001; Moritz et al. 2002; Overpeck et al. 1997; Rind 2002). The responses of both flora and fauna span an array of ecosystems and organizational hierarchies, from the species to the community levels (Stenseth et al. 2002; Walther et al. 2002). Several reports emphasize that high-latitude regions are particularly susceptible to climate change (Moritz et al. 2002; Overpeck et al. 1997). Case studies, especially in the marine environment, have indicated that climate change can reinforce the detrimental

effects of human impact and push species and ecosystem tolerances over their limits (Planque and Frédou 1999). Biomagnification of many POPs is particularly high for marine endothermic animals (Hop et al. 2002); these animals are also among the most vulnerable to climate changes.

The effects of global change on biodiversity and ecosystem functioning encompass multiple complex dynamic processes. Climate change and exposure to EDCs are currently regarded as two of the most serious anthropogenic threats to biodiversity and ecosystems. We should, therefore, be especially concerned about the possible effects of EDCs on the ability of Arctic marine mammals and seabirds to adapt to environmental alterations caused by climate change. My aim in the present article is to give a short review of the effects of EDCs on Arctic mammals and seabirds, and to assess the possible interactions between climate change and endocrine disruptors.

Endocrine Disruption in Arctic Marine Mammals and Seabirds

Chemical pollutants can disrupt endocrine function in animal groups ranging from invertebrates, amphibians, and reptiles to birds and large carnivorous mammals (Guillette and Gunderson 2001; Scanes and McNabb 2003; Verslycke et al. 2004; Vos et al. 2000). Although most of the endocrine-disrupting properties of chemicals have been documented through experimental exposure of animals, there is an increasing number of studies in which disruptions or alterations in reproductive activity, morphology, or physiology have been reported in wildlife populations (Guillette and Gunderson 2001; Vos et al. 2000). The modes of action by which the chemicals exert their endocrine-disruptive effects have been described in many of the studies and reviews listed above, and will not be elucidated here. In several recent studies and reviews, the links between endocrine disruption, particularly of the thyroid system, and neurodevelopment and cognitive effects have received attention (Colborn 2002; Colborn 2004; Schantz and Widholm 2001; Zoeller et al. 2002).

The glaucous gull is a top predator in the Arctic food web, and high levels of POPs have been reported in this species (Bourne and Bogan 1972; Gabrielsen et al. 1995). Verreault et al. (2004) reported significant negative relationships between plasma levels of HCB and oxychlordane and plasma concentrations of free thyroxin (FT_4) and total thyroxin (TT_4) in adult breeding glaucous gull males from Bear Island (Bjørnøya) in the Barents Sea. Furthermore, negative correlations were found between several other OCs and the FT_4:free triiodothyronine (FT_3) and TT_4:total triiodothyronine (TT_3) ratios in males. No effects were found in females.

In a series of articles Bustnes and co-workers have focused on ecological effects of OCs in glaucous gulls from Bear Island. The proportion of time that adult glaucous gulls were absent from the nest when not incubating and the total number of absences were both significantly related to blood concentrations of PCB (Bustnes et al. 2001). The authors suggested that the effect could be apparent because individuals with high blood concentrations of OCs need more time to gather food as a result of either endocrine disruption or neurological disorders. Furthermore, females with high blood levels of OCs, including HCB, oxychlordane, dichlorophenyldichloroethylene (DDE), and PCBs, were more likely to have nonviable eggs than females with low blood levels of OC (Bustnes et al. 2003). Adult yearly survival rate was also reported to have a significant negative relationship to blood concentrations of DDE, persistent PCBs, and HCB, and especially to oxychlordane (Bustnes et al. 2003). Bustnes and co-workers also reported a significant positive relationship between wing feather asymmetry (difference between the length of right and left wing feathers) and blood concentrations of two PCB congeners (PCB-99 and PCB-118), oxychlordane, DDE, and especially HCB (Bustnes et al. 2002).

Thyroid hormones (THs) are central in regulating the molting and replacement of feathers (Kuenzel 2003; Leeson and Walsh 2004). As noted above, significant negative relationships between plasma concentrations of HCB and oxychlordane and THs have been reported in glaucous gulls (Verreault et al. 2004). Thus, a link may exist between the TH-disruptive effects of HCB and oxychlordane and the growth and development of the primary wing feathers following molting.

There is a high aerodynamic cost of asymmetry (Thomas 1993), and Bustnes et al. (2001) suggested that increased flight costs may be an important factor in explaining why birds with high blood concentrations of POPs spend more time on feeding trips than birds with low levels (Bustnes et al. 2001). Exposure to PCBs has been associated with cognitive and behavioral changes (Jacobson et al. 1990; Schantz 1996; Sher et al. 1998), and it has been suggested that the effects of PCBs on brain development may be attributable, at least in part, to their ability to affect the thyroid system (Zoeller 2001; Zoeller et al. 2002). It is, therefore, tempting to speculate that TH disruption caused by POPs may be the ultimate cause of this altered parental behavior. However, more research into linking endocrine disruption to behavioral and ecological alterations in free-living animals is needed before conclusions regarding this feeding behavior can be drawn.

Endocrine effects of POPs have been studied in several species of phocid seals from temperate waters. Because many of these species also inhabit Arctic waters, I have chosen to include some of the main findings from these studies here. In ribbon seals (*Phoca fasicata*) from Japanese waters, TT_3 levels decreased significantly with increased blubber concentrations of PCB-170 and PCB-180, whereas no such relationship was found between blubber PCBs and FT_3 (Chiba et al. 2001). In Larga seals (*Phoca largha*), also from Japanese waters, plasma TT_3 and FT_3 correlated negatively with blubber PCB concentrations, whereas no such relationships were found between blubber PCB concentrations and TT_4 and FT_4 in either Larga or ribbon seals (Chiba et al. 2001).

For gray seal (*Halichoerus grypus*) pups from the United Kingdom, there was generally no relationship between PCB exposure through mother's milk or between PCB concentrations in blubber and plasma levels of TT_4, FT_4, TT_3, or FT_3 (Hall et al. 1998). In captive harbor seals (*Phoca vitulina*) de Swart et al. (1995) showed that plasma TT_3 measured after fasting was lower in seals fed herring from the Baltic Sea than in the control seals fed cleaner herring from the open waters of the Atlantic Ocean. In a similar feeding experiment, captive harbor seals given a diet of OC-contaminated fish had significantly lower plasma levels of TT_4, FT_4, and TT_3 compared with seals fed with less contaminated fish (Brouwer et al. 1989). Sormo et al. (2005) found that gray seal pups from the Baltic Sea have lower plasma concentrations of TT_3 and FT_3 compared with pups from the Norwegian Sea, whereas there was no difference in plasma concentrations of TT_4 and FT_4 between the two groups. Because concentrations of OCs in blubber were significantly higher in the Baltic group than in the Norwegian group, the results can be interpreted as a strong indication that plasma TT_3 and FT_3 concentrations may be affected by the exposure of young phocids to OCs. Furthermore, stranded immature northern elephant seals (*Mirounga angustirostris*) with a skin disease had elevated serum levels of PCBs and DDT and depressed levels of TT_3 and TT_4 compared with those in unaffected controls (Beckmen et al. 1997). In northern fur seal (*Callorhinus ursinus*) neonates, TT_4 was reported to correlate negatively with several PCB congeners (Beckmen et al. 1999).

Ikonomou et al. (2002) reported increasing levels of brominated flame retardants such as PBDEs in Arctic ring seals (*Phoca hispida*); in gray seals, Hall et al. (2003) found that TH levels may be affected by PBDEs. Thus, it is important to include novel POPs when assessing the effects on endocrine disruption.

The polar bear is the ultimate apex predator in the Arctic food chain. Even though the polar bear has a relatively well-developed capacity for metabolizing and excreting POPs (Bernhoft et al. 1997), this animal accumulates

relatively large amounts of POPs because it feeds almost exclusively on large amounts of seal blubber (Derocher et al. 2002). During the last decade, Skaare and co-workers have conducted a series of studies on the accumulation and effects of POPs in polar bears from the Svalbard and the Barents Sea region. They found significant relationships between POPs and THs and vitamin A (Skaare et al. 2001). In a recent study (Braathen et al. (2004) these relationships were studied in more detail, and it was found that PCBs affected five TH variables in females (TT_4, FT_4, FT_3, TT_3:FT_3, TT_4:TT_3) but only two variables in males (FT_3, FT_4:FT_3). These results indicate that female polar bears could be more susceptible than males to TH-related effects of POPs. The actions of THs are mediated by nuclear TH receptors that have their highest affinity for FT_3 (McNabb 1995). It is therefore worth noting that in polar bears, PCB was reported to have a greater effect on T_3 than on T4 (Braathen et al. 2004). Furthermore, in female polar bears, plasma progesterone levels were positively correlated with plasma concentrations of PCBs (Haave et al. 2003). Increased levels of progesterone may disturb the normal reproductive cycle of the females, thereby hindering successful mating. In male polar bears, plasma concentrations of both OC pesticides and PCBs contributed negatively to the plasma testosterone levels (Oskam et al. 2003); thus, it is possible that male reproductive performance is affected by POPs. Recently, relationships between blood levels of OCs and cortisol levels have also been documented in polar bears from Svalbard and the Barents Sea (Oskam et al. 2004). The OC pesticides contributed negatively, whereas PCBs contributed positively to the variation in plasma cortisol. The authors do, however, report that the overall contribution of the POPs to the cortisol levels was negative. It is possible that the altered plasma cortisol levels inhibit physiological processes involved in homeostasis and thereby render the polar bears less able to deal with other environmental stressors.

Climate Change

The Earth's climate has warmed by approximately 0.6°C over the past 100 years. Since 1976, the rate of warming has been greater than at any other time during the last 1,000 years [Intergovernmental Panel on Climate Change (IPCC) 2001]. There appear to be regional variations in climate change. For example, in mid- and high-latitude regions there has been a 10% decrease in snow cover and ice extent since the late 1960s as a consequence of decreased diurnal temperature ranges (IPCC 2001). General circulation models predict that climate changes will be greatest at high latitudes (Phoenix and Lee 2004). Although we are only at an early stage

in the projected trends of global warming, ecological responses to recent climate change are already clearly visible (Stenseth et al. 2002; Walther et al. 2002).

Changes in species abundances and distribution in migratory species are among the best-documented effects of climate change (Crick and Sparks 1999; Easterling et al. 2000). Climate change has affected the reproductive grounds of krill (*Euphausia superba*) and, consequently, its recruitment, by reducing the area of sea ice formed near the Antarctic Peninsula (Cushing 1995; Loeb et al. 1997). Karnovsky et al. (2003) reported that little auks (*Alle alle*) at Svalbard feed mainly on the large copepod (*Calanus glacialis*), restrict their foraging activity to Arctic water that contains this copepod, and avoid Atlantic water that contains a smaller copepod (*Calanus finmarchicus*). They argued that these little auks may be affected by climate change because during years when the flow of Atlantic water increases, they may be forced to forage in areas with suboptimal conditions. In addition Brown et al. (1999) reported that climatic warming may make birds breed earlier. Negative relationships between sea temperature and hatching date have been reported for several seabird species (Bertram et al. 2001; Durant et al. 2004; Gjerdrum et al. 2003). Thus, when sea temperature increases because of climate warming, it is likely that the breeding and hatching starts earlier. Extensive studies of large mammals indicate that climatic extremes influence juvenile survival, primarily during winter, although not independently of population density (Milner et al. 1999; Post and Stenseth 1999). The ice-edge is a particularly productive area, and for Arctic seals it is apparent that the loss of ice will reduce the availability of areas for efficient feeding, haulout possibilities, and breeding. For the polar bear, reduced ice-coverage in the Arctic will reduce their possibilities for hunting seals. Also, lowered seal populations would most likely affect hunting success and survival and in turn populations of polar bears.

Possible Combined Effects of EDCs and Climate Change

In Artic marine mammals and seabirds, THs, sex steroid hormones, and glucocorticosteroids seem to be the most vulnerable endocrine variables influenced by POPs. Important functions of THs are the regulation of metabolic processes and the growth and differentiation of tissues, including the regulation of neuronal proliferation, cell migration, and differentiation of the developing animal (Zoeller et al. 2002). Sex steroid hormones are essential for reproduction, but they also are important in sexual behavior. Glucocorticosteroids are involved in a range

of physiological processes including reproduction, behavior, and adaptation to stress (Wingfield and Sapolsky 2003). These hormones are also important in the regulation of immune function.

In polar bears, learning and cognitive abilities are probably important factors for successful hunting. There is concern that disruption of the TH balance by EDCs may affect neurodevelopment, and that this outcome in turn may affect behavior and cognitive abilities of wildlife (Jenssen 2003). It is therefore possible that EDCs affect behavior and cognitive abilities in polar bears such that they are less able to cope with changes in ice-coverage caused by climate change. Bustnes et al. (2001) reported a correlation between levels of OCs and behavior in glaucous gulls. In a temporal and/or spatial change in the distribution of food caused by climate change, an altered behavior caused by EDCs could hamper the breeding success or even the survival rates of adult glaucous gulls. It is possible that the behavioral changes in glaucous gulls are linked to an increase in energy expenditure caused by increased rates of asymmetry in highly polluted gulls (Bustnes et al. 2002). Because THs are important in feather growth after molting, it is possible that disruption of TH homeostasis by OCs is involved in the reported wing asymmetry in glaucous gulls (Verreault et al. 2004). In combination with a climate-induced spatial change in the availability of food resources in relation to breeding areas, additional effects of EDCs on morphological features may result in even higher energy demands for feeding. This effect may cause a further decrease in the breeding success of polluted glaucous gulls. Conversely, if climate change results in an allocation of food closer to the breeding areas, the functional effects of wing asymmetry could lessen, and even highly polluted birds might be able to breed successfully.

In the Arctic the summer season is short, and proper timing of breeding, molting, and migration is important for seabirds. Exposure to EDCs could disrupt the endocrine systems and mechanisms that regulate these events, thereby leading to suboptimal timing in relation to the season. However, because the most pronounced effect of the current climate change is climate warming, it is possible that an expanded summer season would modulate and reduce these functional effects of EDCs on Arctic mammals and seabirds.

Many Arctic marine mammals undergo periods of fasting as an adaptation to natural seasonal reductions in food availability, and THs seem to play an important role in regulating these cycles. EDCs may disrupt the hormonal regulation and thus lead to suboptimal timing of the fasting period. This scenario may again result in reduced survival and reproduction of the animals.

Conclusions

Climate change is likely to pose additional stress to individuals, and, because different endocrine systems are important for enabling animals to respond adequately to environmental stress, EDCs may interefere with adaptation to increased stress situations. Thus, when taking into consideration the long-range transport of novel EDCs into the Arctic ecosystem, the combination of EDCs and climate change may be a worst-case scenario for Arctic mammals and seabirds. However, knowledge of the responses of animals to multiple natural and anthropogenic stressors is at the present time not sufficient for investigators to forecast the combined effects of these two stressors. Clearly there is a need for more focus on the interacting effects of multiple stressors (natural or anthropogenic) on wildlife.

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