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Connection Between Contaminants and Marine Mammals in the Southern Ocean

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Abstract

The Southern Ocean encircles the continent of Antarctica and was once thought to be unaffected by human activities. However, evidence is increasing that this region has many different contaminants that threaten the region’s marine biodiversity, including marine mammals. Many of these contaminants are heavy metals or persistent organic pollutants and enter the Southern Ocean via both natural and anthropogenic processes. The impacts posed by these contaminants vary according to their type and the organism being exposed. All species of cetaceans and pinnipeds in this study were confirmed to have been exposed to one or more the contaminants reviewed. Although research on most contaminants in this study were found to be at concentrations below those required to have biologically significant effects on marine mammals, some of the anthropogenic activities that contribute to them are increasing in the southern hemisphere, and could pose a threat to pinnipeds and cetaceans. Further research into contaminant impacts and continued monitoring of the Southern Ocean is recommended.

Key Words: Southern Ocean, heavy metals, persistent organic pollutants, cetaceans, pinnipeds

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Statement of Purpose

The presence of marine mammal populations is often an indication of high production in marine environments. Understanding the impacts of environmental contaminants on marine mammals of the Southern Ocean is important because of their ecological role. Most species of pinnipeds and cetaceans, especially odontocete whales, are predators of animals that are several trophic levels removed from primary producers (Berta et al. 2015). Also, marine mammals are k-selected, meaning they have adapted to maintain stable population sizes over time that are at or near their environments' carrying capacity (MacArthur & Wilson 1967). Because of this conservative life-history strategy, marine mammal species are likely to be particularly vulnerable to environmental disturbances, such as natural and anthropogenic contaminants.

It's widely accepted that environmental contaminants pose risks to marine mammals globally. Despite their isolation, species living in Antarctica are at risk of exposure because contaminants can be transported over long distances by atmospheric and oceanic currents (Letcher et al. 2010; Trumble et al. 2012). Over time, there have been numerous studies suggesting that pollutants impact marine mammals, especially regarding reproduction and mortality; however, relatively few studies have demonstrated a direct relationship (Rejinders et al. 2009). This is because studying marine mammals is complicated by logistics and ethics (Berta et al. 2015). Because many of them feed at high trophic levels, marine mammals of the Southern Ocean exhibit a top-down influence on populations of organisms at lower trophic positions (Schwarz et al. 2013). Therefore, understanding how they are impacted by contaminants may provide insight into how other organisms of the Southern Ocean are affected as well.

Marine Environments

Southern Ocean

The Southern Ocean encircles the Antarctic continent and lies south of the Antarctic Convergence, or Antarctic Polar Front, at approximately 55° S (Ballance et al. 2006); this area covers approximately 20 million square kilometers (Lavery et al. 2014) (Figure 1). With an average depth of about 4,500 meters (American Museum of Natural History 2014), the Southern Ocean is the only oceanic domain to completely encircle the Earth without obstruction by continents (White & Peterson 1996). Because of this, it does not possess a clearly defined basin

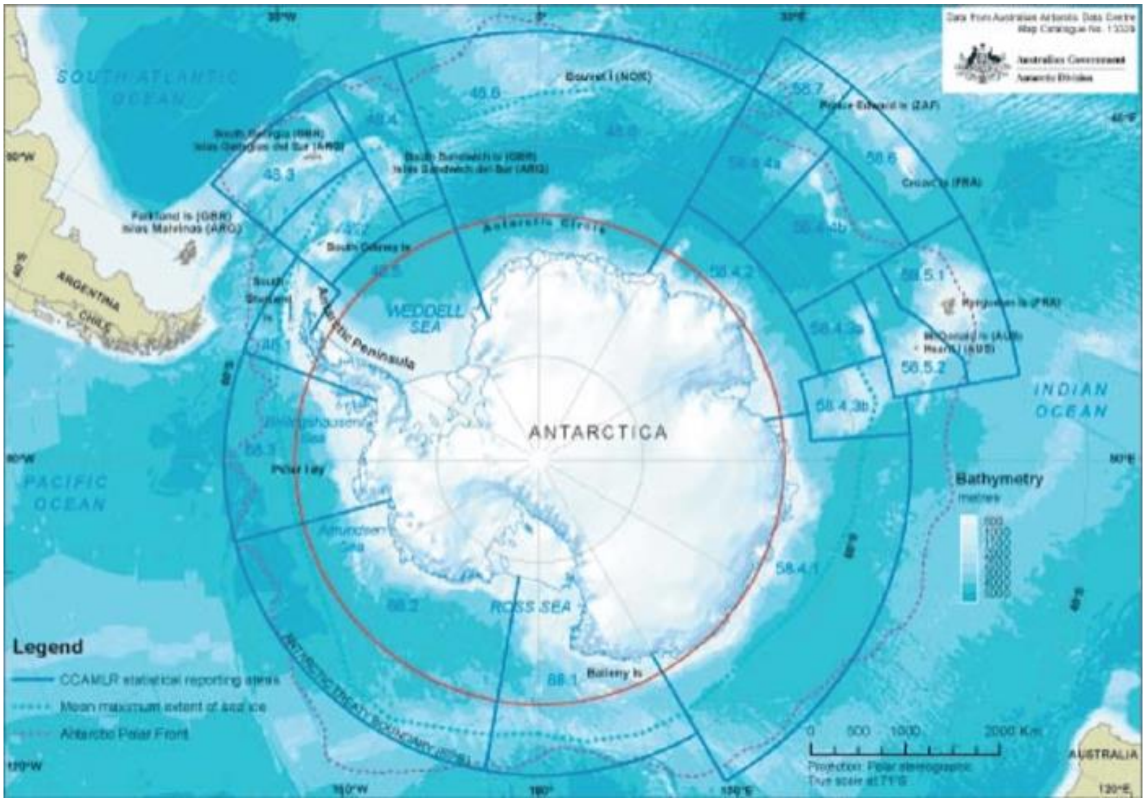

Figure 1. The Southern Ocean and its sectors. (Grant et al. 2006).

bounded by land masses. However, there are a series of deep basins lying between the continental shelf and the ridges located at the edge of the Antarctic Plate (American Museum of Natural History 2014). Given its high latitude, the Southern Ocean experiences extreme seasonal variability with regards to sea ice extent, primary productivity, and distribution and abundance of organisms (Ballance et al. 2006).

The Southern Ocean formed when the continents of the southern hemisphere broke apart, restructuring patterns of ocean circulation and global climate, as well as marine food webs (Berger 2007; Katz et al. 2008; Houben et al. 2013). When the Tethys seaway became restricted between 45 and 40 million years ago, dispersal routes around the southern hemisphere opened, allowing marine life to disperse into the Southern Ocean (Berta et al. 2015). Millions of years later, during the Pliocene, the Panamanian seaway closed, altering oceanic temperatures and circulation patterns, allowing marine life in the northern hemisphere to disperse into the southern hemisphere (Lindberg 1991).

Because the Southern Ocean is located at polar latitudes, the sea surface temperature is always low and the thermocline is weak. Light is the main limiting factor for the growth of phytoplankton because it is less prevalent than in lower latitudes. Light levels are so low that they are only sufficient to sustain high rates of primary production for the few months of the austral summer, which lasts from December to February (Smith et al. 1996). During this time, however, photosynthesis occurs nonstop, allowing phytoplankton populations to grow rapidly (Sakshaug et al. 2009). At the height of the austral summer, the rate of primary production around Antarctica can be over 300 grams of carbon per square meter (Ballerini et al. 2014), making the waters of the Southern Ocean some of the most productive on Earth (Berta et al. 2015). This is possible through a combination of nearly constant light and upwelling of deep, nutrient-rich waters allowing phytoplankton to grow and reproduce rapidly (Berta et al. 2015).

The movement of water and nutrients in the Southern Ocean is made possible by currents. One significant current in the Southern Ocean, perhaps the most heavily studied, is the Antarctic Circumpolar Current (ACC). This current completely encircles the continent of Antarctica, with no landmass blocking its flow (Ballance et al. 2006). It formed during the Oligocene period, between 31.5 and 28 million years ago while the Antarctic continent was undergoing glaciation. This period saw decreased ocean temperatures and increased availability of nutrients, enhancing productivity in the southern hemisphere (Fordyce 1980). The ACC has an eastward flow (White & Peterson 1996) and has been found to be a significant contributor to the turbulent mixing in the Southern Ocean that is believed to strongly influence not only oceanic circulation, but the planetary climatic system (Sheen et al. 2013).

The Antarctic Circumpolar Current forms the boundary of the Southern Ocean, and has been identified as an ecologically important oceanographic region providing whales and other marine organisms a profitable foraging region that is predictable (Loeb 1997). The high biomass of phytoplankton in the ACC is mirrored in the distribution of krill, as well as krill predators such as whales and seals (Tynan 1998). Because krill and other prey species tend to concentrate near their own food sources, they often occupy areas with sharp density differences, such as near the surface, close to the thermocline at the bottom of the photic zone, or close to the seafloor, depending on the prey species. Areas of upwellings, often associated with open-ocean eddies, are also locations for congregating marine life (Berta et al. 2015).

Changes in ocean temperature are also responsible for much of the productivity in the Southern Ocean. As glaciation first took hold in Antarctica, the decrease in temperature led to the formation of bottom-water currents, which increased turnover rates and circulation of nutrient-rich waters. This contributed to increased abundance of small prey species, which in turn benefitted predators like marine mammals (Fordyce 1980).

Productivity and marine mammal diversity in the Southern Ocean have long been linked. In the early Oligocene, there was rapid radiation of both mysticete (baleen whales) and odontocete (toothed whales) species in the Southern Ocean. This diversity has been attributed to changes in zooplankton that arose from the restructuring of the Southern Ocean during this time (Lindberg and Pyenson 2007). In particular, the evolution and diversity of mysticetes have been associated with the ACC and the increased zooplankton productivity its formation made possible (Berta et al. 2015).

Marine mammal diversity in the Southern Ocean is not only made possible by its high productivity; the mammals themselves contribute to it. Recent research has found evidence that sperm whales (*Physeter macrocephalus*) and baleen whales increase the concentration of iron in the Southern Ocean. Sperm whales prey on squid and many baleen whales eat krill, both of which live in deep water and have iron in them. When the whales feed on these prey animals, they bring up extra levels of iron from deeper waters, enriching surface water levels and encouraging the growth of plankton (Roman and McCarthy 2010). Local nitrogen levels are also enhanced by whales. When whales excrete, their droppings contain nitrogenous material that is dispersed into the surrounding water. This action, analogous to upwelling, enhances the nitrogen cycle and has been observed in other regions of the world's oceans as well as the Southern Ocean (Willis 2014).

The Southern Ocean can be divided into five distinct sectors. They are the Ross Sea, the Weddell Sea, Indian Ocean, Pacific Ocean, and Bellinghausen/Amundsen seas (Zwally et al. 1983). These sectors each have their own distinctions but are still interconnected to form the Southern Ocean.

Ross Sea

One water body that has been frequently studied is the Ross Sea, located between latitudes 65º and 78º S, and longitude 160º to 230º E (Wilson et al. 2001). This sea covers approximately 598,000 km^2, about the same size as southern Europe (Ainley 2002), and is home to many species of pinnipeds and cetaceans, as well as penguins and other sea birds, all of which are heavily influenced by sea-ice extent and the flow of water (Ballance et al. 2006).

The Ross Sea is divided into two related biotic systems: the Ross Sea shelf and the associated slope ecosystem (Ainley 2002). Both areas are unusual in that, unlike much of the rest of the Southern Ocean, they have avoided many significant anthropogenic activities (Balance et al. 2006). The region is off limits to mineral extraction and there is no significant pollution (Ainley 2002). Because of this, primary production and plankton levels are so high that the Ross Sea is considered one of the productive bodies of water in the entire Southern Ocean, a claim supported by the large populations of marine mammals and other predators feeding at high trophic levels (Arrigo et al. 1998, 2002).

Like the rest of the Southern Ocean, the Ross Sea's high latitude causes it to experience extreme seasons which affects marine mammals. During the austral summer, the Ross Sea generally experiences no sea-ice (Weatherly et al. 1991). During the austral winter and spring seasons, however, sea-ice coverage is more extensive, but also variable (Wilson et al. 2001). During years where there is extensive ice coverage in winter and spring, Antarctic krill (*Euphasia superba*) experience high recruitment and survival rates which benefits marine mammals and other organisms feeding at higher trophic levels (Ichii 1990). On the other hand, when there is little ice cover during winter and spring, krill recruitment and survival is low which is detrimental to their predators (Wilson et al. 2001).

The Ross Sea experiences an influx of extremely cold abyssal water, below 0° C, that originates in the Weddell Sea and flows eastwards around the Antarctic continent before reaching the Ross Sea. A slightly warmer flow of abyssal water, between 0° and 2º C, flows further north, reaching the western trough of the southern Atlantic Ocean (Stommel & Arons 1959). This abyssal circulation, which influences the whole of the Southern Ocean, is the result of convection events, which occur periodically within the Ross Sea. Westward propagation of water occurs slowly and hinders eastward motion due to advection (Wright & Willmott 1992).

Years of intensive research have shown the Ross Sea to be less negatively influenced by anthropogenic activities than other regions of the Southern Ocean (CITE). Food webs are largely intact, as indicated by populations of high-trophic feeders (CITE). Although the Ross Sea has not seen many anthropogenic disturbances, it is still at risk. Scientists are still unsure of the processes that link trophic levels top down and bottom up, a concern seen by scientists studying many other ecosystems around the world (Ainley 2002). The flow of water and entrained animals into and out of the Ross Sea suggests a continuing possibility of environmental contaminant exposure to resident marine mammal populations.

Weddell Sea

The Weddell Sea stretches latitudinally from 60° W to 20° E (Zwally et al. 1983). Much of the water in the Southern Ocean derives from this water body; it has a temperature below 0^{o}C because of deep thermocline circulation. Within the Weddell Sea, periodic convection events drive abyssal circulation which introduces dense water into the abyssal region (Wright & Willmott 1992). This water, known as Weddell Sea Bottom Water, can have a density as high as 46.15 kg/m^3 (Whitworth III et al. 1991).

Water within the Weddell Sea region of the Southern Ocean can follow many different paths. Surface water in the Weddell Sea flows eastward around the Antarctic Continent until it reaches the Ross Sea (Stommel & Arons 1959). Weddell Sea Deep Water, however, flows toward the equator as a western bottom boundary current. And bottom water in the Weddell Sea is largely confined to the Weddell Basin because of its high density, though some of it enters the Georgia Basin, an ocean basin located to the north of the Weddell Sea at latitude 50° S. Weddell Sea water is not restricted to the Southern Ocean exclusively, as it has been detected in the Argentine Basin, a basin off the southeastern coast of South America located between latitudes 50° S and 35° S (Whitworth III et al. 1991).

The Weddell Sea is the location of one of the longest demographic studies of pinnipeds, with research on Weddell seals conducted since the 1960s. Initially, these seals were hunted as food for dogs, but this practice was ended in the early 1980s with the enactment of the Antarctic Treaty (CITE). Prior to the ban, in the early 1970s, these Weddell Seals showed fluctuations in the number of pups born and estimated number of adults. Following the ban, however, the population has remained relatively stable (Ainley 2002).

The Weddell Sea is a "natural laboratory" in the sense that it is a neritic marine ecosystem that has not been significantly altered by human activities. It also remains isolated from direct anthropogenic inputs by wind and water currents. Many other marine environments have been impacted by anthropogenic forces spanning decades, if not centuries. But while the

Weddell Sea is protected from direct human harm, such as commercial fishing (Ainley 2002), it is still exposed to contaminants. Studies in the 1990s found levels of iron in the Weddell Sea to be twenty-five times higher than concentrations of iron in the central Pacific surface (CITE). Concentrations of other metals, including cadmium, nickel, and zinc, were all found to be at least twice as high as levels measured in the surface waters of other open ocean sites (CITE). Organic contaminants are also present in the Weddell Sea, and can spread to other bodies of water in the Southern Ocean. The Weddell Sea Deep Water that enters the Georgia Basin shows relatively high concentrations of chlorofluorocarbons (CFCs), possibly the result of exposure to the atmosphere (Whitworth III et al. 1991). The presence of contaminants such as these are concerning because the Weddell Sea is one of the two main areas of deep and intermediate water formation in the global ocean (Sañudo-Wilhelmy et al. 2002). Understanding the threats posed by these contaminants and how water in the Weddell Sea interacts with other bodies of water is crucial to determining how marine mammals in this sector of the Southern Ocean are impacted.

Bellinghausen-Amundsen seas

The sector of the Southern Ocean encompassing the Bellinghausen and Amundsen seas stretches from 130 ^{o} W to 60 ^{o} W and, like the Weddell and Ross seas, is adjacent to the Antarctic continent. Unlike in the Ross, Indian, and Pacific regions, sea ice in the Bellinghausen-Amundsen seas does not retreat to the coast during the austral summer. This is possible because strong stratification in the upper layer of ocean water allows sea ice to be retained (Zwally et al. 1983).

This region is also heavily influenced by an isotherm that stretches from the Weddell Sea to the Bellinghausen Sea. During the austral winter, this isotherm, with a temperature of -1.95 ^{o}C, does not shift more than 150 kilometers. Climatological research from 1973 to 1976 suggests that any ice melt during the winter is the result of oceanic heating and solar radiation or deviations from the average atmospheric temperature. Cold air flowing from the Antarctic continent also affects this sector. Other regions are more strongly affected by advection of warm air from lower latitudes, allowing for repeated opening and closing of polynyas along coastlines, an action not seen in the Bellinghausen-Amundsen seas (Zwally et al. 1983).

Like the rest of the Southern Ocean, the Bellinghausen-Amundsen seas sector is impacted by anthropogenic contaminants, including lead and zinc (Dick 1991). In addition, research comparing mercury concentrations to essential elements such as calcium and potassium in Antarctic seals showed that for those living in the Weddell Sea, the livers of these animals had the highest mercury concentrations, followed by the kidneys and then muscle mass (CITE). The Bellinghausen-Amundsen seas sector is near the Weddell Sea, located on the opposite side of the Antarctic Peninsula (Szefer et al. 1993). As shown in the relationship between the Ross Sea and Pacific Ocean regions, populations Antarctic seals can occur in more than one region of the Southern Ocean (Ainley 2002). Given how close the Weddell and Bellinghausen-Amundsen Seas are, if movement of animals between the two sectors occurred here as well, contaminants could move between them as well.

Antarctica was once thought to be unpolluted because of its distance from human activities (Dick 1991). However, research has shown this to be inaccurate. In fact, the Antarctic region has seen the largest human-induced perturbations of the marine ecosystem in the entire world (Mori & Butterworth 2004). Some contaminants are composed of organic molecules while others contain metals. Regardless of their compositions, many of these contaminants are byproducts of anthropogenic activities at the local and global levels and can be transported to the Southern Ocean, even over distances of thousands of kilometers (Bargagli 2008). Garbage incineration, paint production, and burning fuels are just a few of the main sources of some of these contaminants. Marine mammals in the Southern Ocean are particularly vulnerable to contaminants that are biomagnified because they feed at higher trophic levels than other organisms (Majer et al. 2014).

Indian Ocean

The Indian Ocean sector of the Southern Ocean lies between 20^{o} E and 90^{o} E. Like the rest of the Southern Ocean, this area is influenced by the seasonal change of sea ice. During the month of September, when sea ice reaches its maximum extent, about 80% of the Indian Ocean region is covered by ice, an area of about 3,200,000 square kilometers (Zwally et al. 1983). Like the other sectors of the Southern Ocean, the Indian Ocean region is influenced by external sources. Past studies have identified detritus in the far south of this sector as being Himalayan in origin (Pattan et al. 2008).

Like the rest of the Southern Ocean regions, the Indian Ocean sector was once seen as pristine (CITE). However, studies of heavy metals showed high concentrations of copper to be present in krill (Kureishy et al. 1993). This is concerning because the krill fishing industry is present in the Indian Ocean sector (Ichii 1990). Humans are not the only species at risk from high contamination. Since the 1950s, population sizes of nine different species of seabirds and pinnipeds have been studied. Many of these species are krill predators who have experienced population changes related to krill abundance. Some of these krill predators have already begun to show population changes related to long-term warming trends. If the krill they prey upon are contaminated with heavy metals such as copper, the survival of these predators is further complicated (Ballance et al. 2006).

Pacific Ocean

The Pacific Ocean sector stretches from 90° E to 160° E. Of the five regions of the Southern Ocean, this one shows the least amount of ice growth. While 80% of the Weddell, Ross, and Indian Ocean regions are covered by ice during the peak around September, the ice concentration in the Pacific region is only about 75% (Zwally et al. 1983). This ice impacts the distribution of krill in this sector. Data from krill trawlers indicate that krill occur most frequently near continental and insular shelf breaks that are free of ice, not within the vicinity of the sea ice (CITE). This in turn affects the distribution of krill predators, such as minke whales (Ichii 1990).

The Pacific region of the Southern Ocean is located directly north of the Ross Sea. As a result, there is exchange of biota between the two bodies of water; this is especially true of Southern Ocean pinnipeds. Within the Ross Sea are 45% of all Pacific sector of Weddell seals (*Leptonychotes weddellii*), 11% of leopard seals (*Hydrurga leptonyx*), and 12% of crabeater seals (*Lobodon carcinophaga*) (Ainley 2002). The Pacific region is also closely linked to the Weddell Sea. Surface water in the Weddell Sea flows north towards the Antarctic Convergence, where it sinks and mixes with upwelled deep water to form Antarctic Intermediate Water before spreading out into the Pacific Ocean (Sañudo-Wilhelmy et al. 2002).

Such interconnectedness raises the possibility that contaminants in the Pacific sector could impact other areas of the Southern Ocean. The ratio of silver to copper concentrations in the Weddell Sea were found to be almost the same as concentrations detected in the Pacific (CITE). This same study also found concentrations of dissolved aluminum to be similar between the two sectors. When mercury concentrations in fish were examined, pelagic fish species in the

Pacific region showed higher levels than in other regions of the Southern Ocean (Eisler 1984). Biomagnification of mercury has been documented in marine organisms (Yin et al. 2008), leaving pinnipeds and other marine mammals of the Pacific sector vulnerable to contaminants.

Southern Ocean Marine Mammals

The Southern Ocean is home to many species of marine mammals and include cetaceans (whales and dolphins) and pinnipeds (seals, fur seals, and sea lions). All marine mammals in the Southern Ocean depend on euphausiid crustaceans for food, especially the Antarctic krill. Some marine mammals feed on these crustaceans directly, such as baleen whales, while others feed on krill predators (Ballance et al. 2006). Regardless of their position within the food web, all marine mammals in the Southern Ocean tend to feed at high trophic levels, which leaves them particularly vulnerable to contaminants (Aguilar et al. 2002). Many contaminants found in the Southern Ocean have been discovered to be serious threats to these animals. For effective conservation, however, it’s important to understand the biology and ecology of these organisms.

This capstone reviews nine different species of marine mammals. For cetaceans, it profiles the blue whale, Antarctic minke whale, humpback whale, and killer whale (Figure 2). For pinnipeds, it reviews the Weddell seal, southern elephant seal, leopard seal, crabeater seal, and Antarctic fur seal. The order Cetacea is divided into two groups; the odontocetes, who possess teeth, and the mysticetes, which lack teeth and instead have baleen (Berta et al. 2015). Both are represented in this study, with the blue, Antarctic minke, and humpback whales as mysticetes, and odontocetes represented by the killer whale. Pinnipeds are aquatic members of the taxonomic order of mammals Carnivora and consist of three monophyletic families. Two of these families are represented in the fauna of the Southern Ocean. These include the family Phocidae, including the Weddell, southern elephant, leopard, and crabeater seals. The family Otariidae is represented by the Antarctic fur seal (Berta & Churchill 2012).

These species represent a broad range of taxonomy, trophic levels, and ecological interactions. Some of these marine mammals are migratory, while others are more sedentary. Some feed at higher trophic levels than others, and some species represented in this study have specialized niches in the Southern Ocean environment while others are more generalized in relation to their lifestyles.

Cetaceans

Blue Whale

The blue whale (*Balaenoptera musculus*) (Figure 2) is the largest animal on Earth, growing up to 30 meters in length (Branch et al. 2007). Current population structure of this animal is not well known (Lavery et al. 2014). There are currently three recognized species of blue whales, with two of them, the Antarctic blue whale (*B.m. intermedia*) and the pygmy blue whale (*B.m. brevicauda*), occurring in the Southern Ocean (Williams & Donovan 2007). Geographic variations in blue whale size and proportions have been acquired using past whaling records as well as aerial photo surveys (Gilpatrick & Perryman 2008). Whether located in the southern or northern hemisphere, feeding habits of blue whales are similar wherever they occur (Corkeron et al. 1999). Like other baleen whales, blue whales of the southern hemisphere tend to migrate from low latitudes in the winter to the Southern Ocean where they feed on seasonally abundant prey in the austral summer (Ballance et al. 2006). They often congregate in the waters around Antarctica during the austral summer to feed on Antarctic krill and usually avoid oligotrophic central gyres while seeking areas of upwelling, frontal meandering, and other dynamic processes (Branch et al. 2007).

The anatomy of the blue whale is adapted to feeding on krill at depth (Berta et al. 2015). As a species in the Family Balaenopteridae, they have elongated, streamlined bodies with a small dorsal fin, and their flukes and flippers exhibit high aspect ratios (length greater than width) (Woodward et al. 2006). Like other balaenopterids, they have proportionally large heads, which some have suggested evolved because of the overall increase in the body size of the whale, which in turn facilitated fat deposits necessary for fasting and long-distance migration (Goldbogen et al. 2010).

Blue whale foraging dives typically exhibit a gliding descent followed by several lunges at depth and concluding with a steady ascent propelled by the flukes (Goldbogen et al. 2011; Doniol-Valcroze et al. 2011). Most dives are within 100 meters of the surface, but blue whales have been known to dive as deep as 200 meters and hold their breath up to 50 minutes (Lagerquist et al. 2000). During feeding, the blue whale’s grooved mouth opens and the ventral groove blubber, known as pleats, extend, increasing the volume of water the mouth can hold, up to 70% the whale’s mass (Pivorunas 1979). The blue whale, like all cetaceans, has a stomach

Figure 2. Blue whale (*Balaenoptera musculus*). (Modified from "The Blue Whale *Balaenoptera musculus*").

divided into four separate chambers, with the forestomach and main stomach holding up to 1000 kilograms of krill prey (Slijper 1979).

Blue whales are traditionally thought to migrate to temperate latitudes to mate and give birth before returning to the Antarctic the following summer. However, recent evidence shows that not all blue whale populations follow this pattern, as some Antarctic blue whales remain in Antarctic waters year-round, and pygmy blue whales generally do not migrate to Antarctica in the austral summer (Branch et al. 2007).

Legal harvesting of blue whales began in 1904 and lasted nearly 60 years (Yablokov et al. 1998). Prior to whaling, blue whales are estimated to have had a population of approximately 239,000 individuals (Branch et al. 2004). However, it is estimated that over the course of nearly sixty years, over 360,000 blue whales were commercially harvested (Clapham & Baker 2002). By 1996, blue whale numbers were less than 1% the levels they were before harvesting (Branch et al. 2004). Blue whale populations have been steadily increasing at a rate of about 7.3% annually, and by 2012 the number of blue whales in the Southern Ocean alone was estimated to be close to 5,000 animals (Branch et al. 2004). This population increase could prove beneficial to fishing industries in the Southern Ocean, as blue whales have been found to produce feces with iron levels over seven orders of magnitude higher than surrounding seawater, enriching the photic zone (Nicol et al. 2010). They've even been found to stimulate more growth in commercially valuable species, such as krill, than they render unavailable to fisheries. They are currently estimated to increase primary production available to fisheries by about 2.4 x 10^8 kg of carbon annually (Lavery et al. 2014).

Antarctic Minke Whale

The Antarctic minke whale (*Balaenoptera bonaerensis*) (Figure 3) is a pagophilic cetacean found in the Southern Ocean (Murphy 1995). They are distinguished from other minke whales by their comparatively narrower skulls and rostrums. The rostrums of Antarctic minkes are also more convex when viewed dorsally (Omura 1975). At birth, they weigh approximately 230 kilograms (Pomeroy 2011) and take four to five years to reach sexual maturity (Ainley 2002). An adult male has a mass approximately 7000 kg, and females can be as much as 8250 kg (Ainley 2002). As with other mysticetes of the Southern Ocean, Antarctic minke whales are known to undergo annual migrations to low latitudes during the austral winter (Berta et al. 2015). However, adult minke whales tend to feed year-round, even during migrations, a trait not seen in larger mysticetes (Sekiguchi and Best 1992).

Antarctic minke whales have different diets depending on where they occur. Those in the Ross Sea shelf ecosystem feed on crystal krill (*Euphausia crystallorophias*) and Antarctic silverfish (*Pleuragramma antarcticum*), while those in the Ross Sea slope ecosystem mostly prey on Antarctic krill (*E. superba*) (Ichii et al. 1998). Female minke whales are larger than males, and adults consume about 4% of their body mass daily, which means females eat about 330 kg daily, and males 280 kg (Ichii & Kato 1991). Minke whales have been found to have volatile fatty acids and anaerobic bacteria in their colon, indicating bacterial fermentation is a crucial part of digestion (Herwig and Staley 1986). Minke whales have a similar diet to Antarctic pinnipeds, but because they have relatively shorter intestines, their multichambered stomach, a trait shared by all cetaceans, is vital for minke whales to optimize utilization of krill prey (Olsen et al. 1994).

As a member of the *Balaenopteridae* family, Antarctic minke whales use the engulfment feeding technique, whereby they capture prey by taking water into their mouths as they swim horizontally through the water column (Berta et al. 2015). This style of feeding is reflected in the shape of their flippers. All cetaceans use their flippers as control surfaces for swimming, maneuvering, and stabilizing the body (Weber et al. 2013; Cooper et al. 2008). The

Figure 3. Antarctic minke whale (*Balaenoptera bonaerensis*). (Modified from "The Minke Whale *Balaenoptera bonaerensis*").

short, narrow flippers of Antarctic minke whales are particularly ideal for maintaining trim while feeding (Cooper 2008).

The demographics and ecology of Antarctic minke whales influence others in their environment. Their diets put them in direct trophic competition with Adelie penguins (Ainley et al. 2010). Minke whales are themselves preyed upon by orcas, of which there is an ecotype that appears to specialize in hunting them (Ballance et al. 2006). Because of these interactions, a change in minke whale demographics can also impact penguins and orcas. During the 1970s and 1980s, 20,164 minke whales were harvested by commercial whaling around Victoria Land, Antarctica (CITE). Although this represents only 20% of the minke whales in the region, their removal had a significant impact on penguins allowing them to increase their own numbers following the decrease of minke whales, their competitors for krill (Ainley et al. 2010).

Despite this population decline, populations of Antarctic minke whales appear have increased in the Southern Ocean, as during the first half of the 20th century, populations of other species of mysticetes were reduced by whaling (Kato & Sakuramoto 1991). This led to a hypothesized increase in the abundance of krill, known as a krill surplus, that some scientists believe has allowed minke whales and other smaller krill predators to be freed from trophic competition (Mori & Butterworth 2006). The decline in large baleen whales may have allowed minke whales to increase their populations to the point where they, and other smaller krill predators such as crabeater seals, are potentially restricting the recovery of populations of larger baleen whales (Wade 2009).

Today, populations of minke whales appear stable but average body conditions may be declining (Ainley et al. 2010). Recent evidence found that Antarctic minke whales in the Ross

Sea have lower body masses than would be expected, especially among pregnant females. Scientists reasoned the minke whales were using the sea ice in the Ross Sea as a means of deterring attacks by orcas, their main predator. Since the 1980s, Antarctic minke whales are harvested from the Ross Sea at a rate of about 80 individuals annually, over half of them pregnant females (Ichii et al. 1998).

Humpback Whale

The humpback whale (*Megaptera novaeangliae*) (Figure 4) is one of thirteen species of baleen whales (Ballance et al. 2006). They undergo seasonal migrations, traveling between coastal waters in low latitudes to give birth and mate, and higher latitude foraging grounds, such as the Southern Ocean (Fossette et al. 2014). Studies in the late 20th and early 21st centuries have recorded three main lineages of humpbacks, with one each in the North Atlantic, North Pacific, and Southern Ocean, as shown in their mitochondrial DNA (Baker et al. 1990, 1993, 1994; Baker & Medrano-Gonzalez 2002). For some humpbacks in the southern hemisphere, the Bight of Benin, in the northern Gulf of Guinea, is a nursery ground (Segniagbeto et al. 2014). Humpbacks are considered one of the chief predators of Antarctic krill, and in East Antarctica, the ranges of predator and prey overlap (Nicol et al. 2000).

Like other balaenopterids, humpback whales exhibit a gliding descent, multiple lunges while at depth, and then a powered ascent while foraging (Goldbogen et al. 2011; Doniol-Valcoze et al. 2011). They've been recorded diving as deep as 148 meters and holding their breath up to 21 minutes (Schreer and Kovacs 1997; Ponganis 2011). However, humpbacks do not use this feeding strategy exclusively; they demonstrate various engulfment-feeding techniques (Ware et al. 2013). Humpbacks have also been known to use lunging at the surface, and body rolling while lunging has been documented (Stimpert et al. 2007). Humpbacks are known to hunt cooperatively when feeding on herring and other schooling fish. One whale exhales underwater and produces an ascending ring of bubbles about 10 meters in diameter (Wiley et al. 1992). These bubble clouds appear to confuse schools of prey, causing them to mass together in tight clumps, allowing the humpbacks to capture them more efficiently (Weinrich et al. 1992).

Figure 4. Humpback whale (*Megaptera novaeangliae*). (Modified from "The Humpback Whale *Megaptera novaeangliae*").

The humpback was one of many species of whales persecuted by commercial whaling during the nineteenth and twentieth centuries (Ballance et al. 2006). Over 208,000 humpback whales were commercially harvested from the southern hemisphere (Clapham & Baker 2002). Legal harvesting of humpbacks ended in 1967, but some illegal hunting after this occurred (Yablokov et al. 1998). Soviet whalers were found to have harvested 43,000 more humpbacks from the southern hemisphere than they reported in official whaling records (Ballance et al. 2006). False records such as these, combined with illegal harvesting, has made it difficult to determine the extent to which populations of humpbacks and other whale species were reduced (Ballance et al. 2006).

Since legal whale hunting ended, humpback populations in the southern hemisphere have been increasing. In western Australia, their population grows by 11% annually (Mori & Butterworth 2004). Those near the Antarctic Peninsula have an annual growth rate of 5%. And around Adelie Land, humpbacks whales are increasing at a rate of 12 to 13% a year (Ainley et al. 2010).

Killer whale

The killer whale (*Orcinus orca*) (Figure 5) is a predatory cetacean feeding at high trophic levels and has a global oceanic range (Riesch et al. 2012). Growing up to 9.5 meters long, they are the largest species in the family Delphinidae (Geisler et al. 2011). In addition to size, killer whales are further distinguished by their spotted and striped black and white pattern with contrasting colored areas on the head, flanks, ventral area, and flukes (Caro et al. 2011), along with rounded, paddle-shaped flippers (Weber 2009).

Figure 5. Killer whale (*Orcinus orca*). (Modified from "The Killer Whale *Orcinus orca*").

Killer whales have been recorded diving as deep as 260 meters and holding their breath up to fifteen minutes (Schreer and Kovacs 1997; Ponganis 2011). However, they are considered shallow divers, and usually don't dive deeper than twelve meters (Stewart 2009). When swimming, their dorsal fins, which are supported by fibrous tissue similar to that found in their flukes, aid in maneuvering and maintaining balance. Dorsal fins also help with thermoregulation and are believed to serve as a means of individual or conspecific recognition and can be up to two meters tall in mature males (Fish 2002).

Killer whales have different types of social groups based on where they occur and on what they prey. Regardless, pods typically consist of an older female, her offspring, and the offspring of the mature females of the next generation after the lead female. Mature males remain with the pods they were born into throughout their lives, and there are no records indicating movement or exchange of individual killer whales between different pods (Bigg et al. 1990). Killer whales appear to avoid mating with closely related individuals within their groups, but genetic analysis shows no evidence of females mating with males of different social groups (Ford et al. 2011). As odontocetes, they communicate with echolocation (Au 2004). Pods are documented to have an average of about ten discrete calls each that are shared by all pod members and remain unchanged for decades. These repetitious calls are referred to as dialects and may serve as a means of pod affiliation and communication within the pod (Ford 1991).

Killer whales have wide dietary ranges, including fish, other cetaceans, pinnipeds, birds, cephalopods, sea turtles, sea otters, and even sharks (Hoyt 1984; Estes et al. 1998; Pyle et al. 1999; Ford et al. 2011). Although killer whales are traditionally seen as generalists, some researchers have suggested that they are specialists, with different populations able to respond to variations in type and abundance of their preferred prey (Felleman et al. 1991). Killer whales hunting herring-sized schooling fish are known to use their flukes to slap and stun prey (Domenici 2001). They are also known to emit loud impulse sounds, possibly as a means of debilitating prey through sensory system overload (Norris & Mohl 1983). Killer whales have been documented using bubble clouds to capture prey, a technique similar to that used by humpback whales (Similä & Ugarte 1993). They are even known to hunt cooperatively to capture prey items larger than themselves, a foraging strategy not observed in any other marine mammal (Frost et al. 1992; Berta et al. 2015)

Understanding the ecology of killer whales is difficult because there is little information on them from pre-whaling times. This is further complicated by the fact that orcas were historically regarded as a single species but are now believed to be multiple species with variation in color, prey selection, habitat, and genetics (Riesch et al. 2012). Within the Southern Ocean, there are three orca ecotypes distinguished by variations in their body coloration, shape and orientation of eyepatches, body size, and diet. Type A orcas mainly prey on cetaceans, mainly minke whales, while Type B orcas specialize in pinnipeds, and Type C orcas eat fish, including the Antarctic toothfish (*Dissostichus mawsoni*) (Ballance et al. 2006).

Killer whales in the Southern Ocean are among the few odontocetes to take part in migrations (Berta et al. 2015). Type B orcas have been documented leaving Antarctica between February and April and traveling as far as the subtropical waters off the coasts of Uruguay and Brazil. Analysis of these movements suggest the orcas are not motivated by feeding or breeding purposes, but rather as a means of physiological maintenance of their skin. This is supported by thick accumulations of diatoms on the skin of Antarctica killer whales that are not seen in other populations (Durban and Pitman 2011).

Changes in demographics of organisms at lower trophic levels could have cascading effects on orcas. The population decline of minke whales in the late 1970s lead to the hypothesis that some orcas switched prey species, resulting in increased mortality of adult male emperor penguins (*Aptenodytes forsteri*) at Pointe Geologie, Adelie Land (Ainley et al. 2010). Southern

Ocean orcas that prey on pinnipeds and fish are also at risk to changes in prey demographics. Type C orca prey on the Antarctic toothfish (species name), a fishery for which has developed. This would put these orcas in competition with humans for prey, as the closely related Patagonian toothfish (species name) has been overharvested by industrial fishing (Ainley 2002). Type B orcas are also at risk of demographic changes because their main prey, pinnipeds, are K-strategists, meaning they are slow to reproduce (Croxall et al. 1999). If the main prey species of any of the orcas were to decline, this may lead to either orcas decreasing their own populations, or switching prey, which could lead to competition with other species (Ainley 2002).

Pinnipeds

Weddell Seal

The Weddell seal (*Leptonychotes weddellii*) (Figure 6) is a coastal species of seal that occupies a high trophic level (Laws 1977). They are a pagophilic species with a light-colored fur coat covered in dark spots (Caro et al. 2012). Like other ice-dwelling seals, this species exhibits reverse sexual dimorphism, where males, growing up to 360 kg (Bininda-Emonds 2000), are smaller than females, which some believe allows males to be more agile swimmers and thus more attractive to potential mates (Le Boeuf 1991). Weddell seals are not migratory and remain in the Southern Ocean year-round (Yamamoto et al. 1987). However, they are believed to change their locations seasonally due in part to prey availability, a behavior seen in other phocids (Berta et al. 2015). During the Antarctic winter, they maintain a breathing hole that determines prey availability (Casaux et al. 2011).

Compared to other ice-dwelling seals of Antarctica such as Antarctic fur seals and leopard seals, the diet of Weddell seals is more ichthyophagous (Casaux et al. 2011). They prey mainly on fish, especially species of the taxonomic families Nototheniidae and Channichthyidae, but they also known to feed on cephalopods and crustaceans (Casaux et al. 2011). Their prey is mainly pelagic, vertically migrating species occurring at depths of over 1000 meters (Berta et al. 2015).

Weddell seals exhibit four styles of diving that vary in depth and duration in accordance with their current activity (Davis et al. 2013). Type 1 dives are the deepest (average maximum depth between 324 and 378 meters) and longest in duration (15 to 27 minutes), and correspond

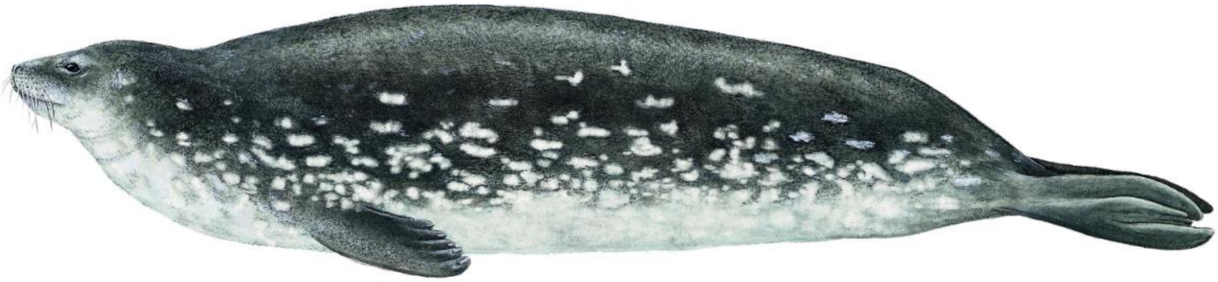

Figure 6. Weddell seal (*Leptonychotes weddellii*). (Illustration by Pieter Folkens © 1989).

with hunting prey, primarily the Antarctic silverfish (*Pleuragramma antarctica*). Type 2 dives, only some of which involve foraging, form a continuum from dives lasting between 3.6 and 7.7 minutes and were much shallower and near the ice hole. Type 3 dives are similar to Type 2 in duration but differ in that no foraging activity has been documented, suggesting the seals are transitioning between breathing holes or exploring new areas (Kooyman et al. 1981). Type 4 dives are exploratory dives that last longer than Type 3 and occur only under unnatural conditions associated with studies of isolated breathing holes (Berta et al. 2015). Although Weddell seals can hold their breath under water over an hour, most dives are under 20 minutes long, as this is their aerobic dive limit, the longest dive that does not lead to increased blood-lactate concentrations during the dive (Kooyman et al. 1981).

Weddell Seals prey species include the Antarctic toothfish (*Dissostichus mawsoni*), but as their numbers are reduced, the seals switch to hunting smaller fish at lower trophic levels, such as the Antarctic Silverfish. This prey depletion suggests that areas where Weddell seals occur, such as the Ross Sea Shelf Ecosystem, are sensitive to top-down trophic interactions. Weddell seals are not the only marine mammals they prey on Antarctic toothfish; orcas (Orcinus orca) also eat them. If the abundance of toothfish were to decline, both Weddell seal and orca populations would either decrease or prey on other species (Ainley 2002).

Weddell seals living in the Ross Sea have been studied since the 1960s, one of the longest studies of pinniped demographics in the world (Ainley 2002). In the early 1970s, Weddell seals showed fluctuations in the number of pups born and the estimated number of adults (Cameron 2001). However, since the mid-1980s, their population has shown less variability. The reason for this is not yet determined but has been attributed to climatic or food web factors (Ainley 2002).

The Weddell seal is a useful indicator species for understanding bioaccumulation process of heavy metals in the Antarctic ecosystem. One study found that concentrations of heavy metals, especially mercury, were higher in the liver and kidneys of Weddell seals than in the brain, blubber, and skin. Concentrations of mercury in the liver, for example were 3.10 μg g^{-1} (wet weight) for adult females and 8.50 for adult males, while in the kidneys, mercury concentrations in females were 0.38 μg g^{-1} (wet weight) and 0.09 for males. Inputs of heavy metals are largely anthropogenic in origin, and compared to studies of seals in the northern hemisphere, these concentrations are considered negligible (Yamamoto et al. 1987).

Organic contaminants pose a growing threat to Weddell seals. One study of eight compounds of technical toxaphene (CTTs) found that concentrations of these organic contaminants are an order of magnitude higher than those seen in Icelandic Grey seals in the Northern Hemisphere (Vetter et al. 2001). In addition, concentrations of other organic contaminants, such as DDT, are increasing in other marine mammals in the Southern Ocean (Aono et al. 1997). As an indicator species, Weddell seals could be useful by providing scientists with a means of understanding how these contaminants impact the Southern Ocean environment.

Leopard Seal

The leopard seal (*Hydrurga leptonyx*) (Figure 7) has a circumpolar distribution around Antarctica between 50° S and 80° S (Rogers et al. 2005). They are a pagophilic species that exhibits contrasting patterns of light and dark color, with dark spots on a lighter-colored body (Caro et al. 2012). As with other ice-breeding seals, males are smaller than females (Berta et al. 2015). At birth, leopard seal pups weigh approximately 35 kilograms (Schulz and Bowen 2005). As they reach adulthood, however, males weigh up to 324 kilograms, while females are larger (Bininda-Emonds 2000).

As a pagophilic species, sea ice is important to leopard seals for many purposes. The ice serves as a location for giving birth during the austral late spring and early summer, molting in summer, and as a resting platform year-round. Most leopard seals spend most or all the year located within range of the pack ice. Unlike other ice-dwelling seals, leopard seals are known to

Figure 7. Leopard seal (*Hydrurga leptonyx*). (Illustration by Pieter Folkens © 1989).

disperse beyond the edge of the sea ice as its extent expands, and then return closer to the Antarctic continent as the sea ice contracts (Meade et al. 2015).

Leopard seals have a broad diet and eat prey at various trophic levels (Meade et al. 2015). Antarctic krill make up the largest portion of their diet, followed by penguins, and occasionally fish (Casaux et al. 2011). They are even known to prey on other pinnipeds, including Antarctic fur seal (*Arctocephalus gazella*) pups (Hiruki et al. 1999). Prey composition changes with age. Juvenile leopard seals eat mostly krill while adults prey on penguins and even other seals more often (Hiruki et al. 1999). The diet of leopard seals is also known to change seasonally (Hofman et al. 1977). During the austral summer, they prey on penguins, but only hunt fur seal pups between late December and mid-February (Hiruki et al. 1999). Leopard seals are among the most famous pinnipeds known to feed on other warm-blooded prey (Berta et al. 2015). This is reflected in the length of their intestines, which are relatively shorter than the intestines of pinnipeds that regularly feed on squid, which are harder to digest than warm-blooded prey or fish (Bryden 1972). Throughout their lives, however, krill remains a significant component of their diet (Laws 1984).

To cope with such a varied diet, leopard seals utilize a variety of foraging strategies. For krill, they are believed to suck prey into their open mouths by retracting their tongues before forcing excess water out through their cheek teeth, which act as sieves (Bonner 1982). For larger prey, such as sea birds and pups of other pinnipeds, leopard seals use enlarged canine teeth to seize prey (Hocking et al. 2012).

For fur seal pups, particularly those near the South Shetland Islands, leopard seals are known to use three distinct hunting methods. The first is stalking, where the leopard seal swims into a cove where the fur sea pup rookery is located, with only their nostrils exposed, and moves slowly along the beach before lunging at any pups that approach. The second technique is the rapid approach, where the leopard seal rides a swell toward the beach to lunge at pups on the shore. The third method for hunting fur seal pups is known as open hunting, where the leopard seal enters a shallow intertidal pool during high tide while making no effort to conceal itself. The open water hunting method has also been observed to be used when hunting penguins (Hiruki et al. 1999). Regardless of prey, leopard seals are considered shallow-water divers, as evidenced by the fact that their aortic bulb is not as enlarged as that seen in deep-diving pinnipeds such as the Weddell seal (Drabek 1975; 1977).

Leopard seals are mostly solitary and avoid contact with each other outside of breeding. Because of this, they do not engage in territorial defense calls or engage in interanimal disputes through aggressive grunts, barks, or groans the way more social pinnipeds do, but rather use softer, more lyrical calls when vocalizing (Rogers et al. 1995; Thomas and Golladay 1995). Recent research, however, has documented social interactions between that are not easily categorized. At Bird Island, leopard seals were seen swimming in pairs with one being larger and the smaller seal following. This behavior is believed to be related to leopard seals hunting Antarctic fur seal pups during the austral summer, though the exact relationships between these pairs of leopard seals are not fully understood (Hiruki et al. 1999).

One study comparing concentrations of ten different metals in leopard, crabeater, and Weddell seals found that leopard seals had the highest concentrations of zinc in the liver, at 179 micrograms per gram wet weight. This same study also found levels of copper in muscles to be highest in leopard seals (Szefer et al. 1994). Biomagnification is known to occur in some contaminants, including organic compounds (Bargagli 2008). Longer trophic chains enhance biomagnification of some contaminants (Bargagli et al. 1998). As predators that feed at high trophic levels and have low population densities, leopard seals may be vulnerable to contaminants in the Southern Ocean.

Crabeater Seal

The crabeater seal (*Lobodon carcinoph*aga) (Figure 8), like the Weddell and leopard seals, is a pagophilic pinniped that exhibits contrasting patterns of light and dark colors (Caro et al. 2012) Like all ice-breeding pinnipeds, they mate in the water (Berta et al. 2015). The breeding season for crabeater seals occurs during the austral spring from September to October (Siniff et al. 1979). During this time, they have been observed occurring in trios on the ice. This is believed by some scientists to be a form of serial monogamy known as mate guarding, but has not been fully studied (Bengston and Siniff 1981). Pups are also born between September and October (Siniff et al. 1979) and weigh approximately 30.7 kilograms at birth (Schulz and Bowen 2005). Lactation for this species can be as short as four weeks, and pups are weaned as early as November (Siniff et al. 1979).

Most species of pinnipeds are adapted to prey on animals that are several trophic levels removed from primary producers. Crabeater seals, however, are specialized to feed on organisms at lower trophic levels (Berta et al. 2015). Despite its common name, the diet of the crabeater seal does not prey on crabs. About 94% of its diet is actually krill, with fish constituting an additional 3%, and cephalopods 2% (Mori & Butterworth 2004). As they prey primarily on krill, which are typically about one centimeter in length (Gaskin 1982) crabeater seals possess anatomical specializations that enable them to exploit this food source (Berta et al. 2015). They have an elongated symphysis, located on the lower jaw, as well as a long tooth row believed to filter krill from sea water (Jones et al. 2013). Their cheek teeth are also modified to trap and strain krill, possessing complex, elongated cusps (King 1983). Crabeater seals, like leopard seals, are believed to use suction to draw krill into their open mouths by retracting their tongues and then forcing excess water out through their cheek teeth (Bonner 1982). When swimming, crabeater seals usually dive to depths of about 100 meters and remain underwater for less than 10 minutes (Bengtson and Stewart 1992), but they have been documented diving as deep as 528 meters and holding their breath up to 10.8 minutes (Schreer and Kovacs 1997; Ponganis 2011).

The hazardous and remote environments of crabeater seals and other pagophilic species make long-term studies difficult and expensive. Even so, there are some long-term studies of crabeater seals (Ballance et al. 2006). One study of them in the Antarctic Peninsula region has been compiled with 44 years of cohort studies. Variation from one year to the next was observed,

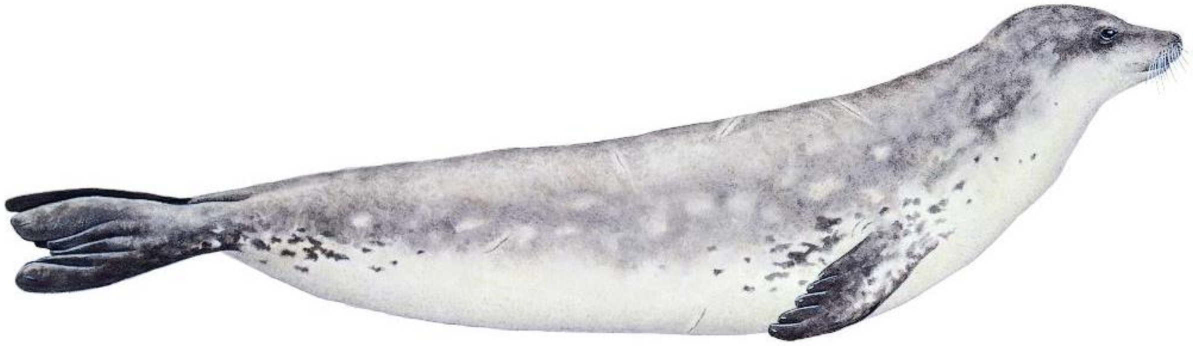

Figure 8. Crabeater seal (*Lobodon carcinophagus*). (Illustration by Pieter Folkens © 1989).

but there appeared to be no long-term population trends (Boveng and Bengtson 1997). Across their entire range, crabeater seals are among the most numerous of all marine mammal species, with a population estimated to be between 5 million and 10 million individuals (Bengtson 2009). This large population has been attributed to competitive release. Some scientists have suggested that the reduced populations of large whales in the Southern Ocean through the whaling industry contributed to an abundance of krill known as a "krill surplus" that allowed crabeater seals and other smaller krill predators to increase in abundance (Ballance et al. 2006).

Other studies of crabeater seals have examined concentrations of heavy metals in their tissues. One study compared the concentrations of ten different heavy metals in the livers, kidneys, and muscles of crabeater, leopard, and Weddell seals. The result showed crabeater seals to have higher concentrations of cadmium in their muscles than the other two species. They were also found to have the highest concentrations of lead and manganese in the liver, and their kidneys contained higher levels of cobalt than the kidneys of leopard and Weddell seals. In this same study, crabeater seals were also found to have hepatic concentrations of iron to be as high as 30 mg per gram dry weight. This is because crabeater seals have proteins in their liver that store iron (Szefer et al. 1994). Cadmium also poses a potential threat to crabeater seals through diet. Crustaceans in the Antarctic are believed to accumulate high concentrations of cadmium (Bargagli 2008). As krill forms most of their diet, crabeater seals may accumulate high levels of cadmium themselves during feeding.

Heavy metals are not the only contaminants posing a threat to crabeater seals. In a study of the distribution and levels of eight toxaphene congeners, the octachlorobornate B8-1413 was found at higher concentrations than in the Northern Hemisphere. As anthropogenic release of particulate trace materials continues, crabeater seals may be exposed to even higher concentrations of these contaminants (Majer et al. 2014).

Southern Elephant Seal

The Southern elephant seal (*Mirounga leonina*) (Figure 9) is the largest species of seal in the world and exhibits pronounced sexual dimorphism, with adult females weighing up to 900 kg and males as much as 5000 kg (Tao et al. 2006). This is because females reach reproductive age faster than males but invest a lot of energy into caring for their young. Males do not provide parental care, so they can allocate more energy to growth and developing secondary sexual characteristics such as their elongated proboscis, enlarged canines for fighting, and thick, cornified skin around their necks (Berta et al. 2015).

The Southern elephant has a circumpolar distribution with major concentrations for reproduction on islands of the Antarctic Convergence. They come ashore in remote areas of the Southern Ocean to reproduce, sometimes traveling thousands of kilometers before coming ashore. Southern elephant seals have two separate annual terrestrial periods, reproducing in the austral spring from September to October and molting in the austral summer December to February. During these two seasons, the elephant seals stay on land and do not feed. The rest of the year, they are feeding at sea (Miranda-Filho et al. 2007). While on land during the breeding season, males establish hierarchies within aggregations of females. Because they do not feed during this time, males rely on lipid stores to withstand extended fasting (Crocker et al. 2012). The females also fast during the breeding season, and lipids in their body tissues are converted into high-fat milk for nursing pups (Boness and Bowen 1996). Southern elephant seal pups are approximately 42.6 kg at birth (Schulz and Bowen 2005), about 40% of which is body fat (Boness and Bowen 1996). Mother seals have a lactation period lasting only four to five weeks, during which time they do not enter the water (Arnbom 1994; Costa et al. 1986).

Southern elephant seals have two feeding migrations annually, one occurring after the breeding season and the other after molting. During these migrations, they are at sea for months at a time (Berta et al. 2015). During these regular movements, male and female elephant seals exhibit differences in behavior and location. Males are known to migrate from sub-Antarctic islands to the Antarctic continent further south (Biuw et al. 2010). Females, on the

Figure 9. Southern elephant seal (*Mirounga leonina*) smallest to largest: pup, adult female, adult male. (Illustration by Pieter Folkens © 1989).

other hand, spend more time in the waters of the Antarctic Circumpolar Current (ACC). For both males and females, eddies, gyres, and areas of frontal upwelling are important for foraging when elephant seals are feeding in pelagic waters. Some elephant seals are attracted to seamounts, where they dive to feed benthically (Maxwell et al. 2012).

For elephant seals, the duration of a dive varies with the time of day and the seasons. Morning dives are typically longer in duration than those later in the day, and dives during winter can last twice as long as summer dives (Bennett et al. 2001). Elephant seals are capable of making regular dives of over 1000 meters lasting between 15 and 45 minutes (Matthews 1966). The maximum depth for a male southern elephant seal was recorded to be 1256 meters, and for females, the record is 1430 meters, with both holding their breath 120 minutes (Slip et al. 1994). They have many adaptations to cope with making these dives, including an enlarged spleen accounting for 2 to 4% of the animal’s body mass to serve as a reserve storage for red blood cells (Cabanac et al. 1997). When diving, they use a stroke-and-glide motion during both descent and ascent to reduce the cost of transport and increase the duration of the dive (Williams et al. 2000; Davis et al. 2001).

Southern elephant seals make such deep dives because they mainly feed on pelagic, vertically migrating fish and squid (Berta et al. 2015). Because squid are more difficult to digest than warm-blooded prey or fish, elephant seals have relatively long intestines compared to other pinnipeds (Bryden 1972). The small intestine in particular is about 25 times the length of the elephant seal's actual body (Helm 1983). Although squid are a significant part of the southern elephant seal's diet, they do eat other types of prey. During their first year of life, they include krill in their diet (Berta et al. 2015). Adults also eat fish and are even known to occasionally prey on penguins (Miranda-Filho et al. 2007). As southern elephant seals experience different growth phases, the relative growth of their pancreas also changes. These changes are believed to reflect changes in diet as the animal grows (Bryden 1971).

Throughout their range, different populations of Southern elephant seals have shown different demographic trends. Some populations have been stable for decades. Others saw declines during the late 1960s that lasted through the 1970s (Ballance et al. 2006). During both the 1950s and 1990s, populations of southern elephant seals declined throughout their breeding range in the Southern Ocean. These decreases have been attributed to environmental change and anthropogenic disturbances have been ruled out as possible causes. Recently, some of their populations have begun to recover (Miranda-Filho et al. 2007). As long-lived marine mammals, factors affecting their demographic patterns are expected to have a delayed impact on population size. Such regime shifts, abrupt decreases from one steady state to another, is typical of elephant seals (Weimerskirch et al. 2003).

Some contaminants pose a threat to Southern elephant seals. Analysis of excrement has shown that mercury concentrations biomagnify, or increase with trophic level. As elephant seals feed at high trophic levels, they are at greater risk from mercury than species feeding at lower levels (Yin et al. 2008). Organic contaminants also pose a threat. Recent evidence suggests that many organochlorine (OC) compounds, including the pesticide DDT, are increasing in the southern hemisphere via atmospheric transport. Research has shown elephant seal pups and juveniles to accumulate organic contaminants via transfer from the placenta and lactation. Like metal contaminants, organics pose a threat to Southern elephant seals through diet because of their high trophic level. Recent research has shown DDT concentrations in the southern hemisphere to be one to two orders of magnitude less than those detected in pinnipeds in the northern hemisphere (Miranda-Filho et al. 2007). However, as concentrations of some organic contaminants continue to increase in the southern hemisphere, they could pose a greater threat to elephant seals and other animals at high trophic levels (Aono et al. 1997).

Antarctic Fur Seal

The Antarctic fur seal (*Arctocephalus gazella*) (Figure 10) is a member of the taxonomic family Otariidae, and like others in this family, is characterized by external ear flaps known as pinnae and the ability to rotate their hind flippers to move on land (Berta et al. 2015). Like other fur seals, this species has more fur and relatively thinner blubber than other pinnipeds, suggesting they rely more on their fur for thermal insulation and use blubber primarily as a means of storing energy (Liwang et al. 2012b).

Antarctic fur seal pups are about six kilograms at birth (Schulz and Bowen 2005), and are born within a week of their mothers coming ashore to the breeding rookery (Costa et al. 1985). At the time of birth, the percentage of body fat on mother Antarctic fur seals is close to 22%, roughly half that of elephant seals' 40% at parturition (Boness and Bowen 1996). Lactation for Antarctic fur seals differs from that of other members of the family Otariidae. The mother's milk if about 40% fat, which is considered a high content compared to other otariids (Costa et al. 1985). The lactation period is much shorter than most other otariid species, typically lasting about four months with little variation in duration. Lactation also differs in that it is abrupt for Antarctic fur seal, as opposed to a gradual weaning seen in other species of otariids, where pups begin entering the water and supplementing milk with nearshore prey. Antarctic fur seal pups have been shown to wean themselves and leave the breeding colony while their mothers are feeding at sea (Trillmich 1996). This rapid, self-weaning helps Antarctic fur seal pups avoid a period of postweaning fasting seen in many species of phocids (Berta et al. 2015).

The Antarctic fur seal is an opportunistic forager. Its diet consists largely of fish and Antarctic krill, but they are known to also prey on penguins (Yin et al. 2008). When compared to other species of pagophilic seals, the Antarctic fur seal was found to have high dietary overlap with leopard seals, with a prey overlap value of 67.9 on the dietary similarity index (Casaux et al. 2011). Like leopard seals, Antarctic fur seals are considered top predators. Even so, and despite a high prey overlap, fur seal pups are preyed on by leopard seals. For Antarctic fur seals, leopard seals are competition and predators (Boveng et al. 1998).

Figure 10. Antarctic fur seal (*Arctocephalus gazella*) from smallest to largest: pup, adult female, adult male. (Illustration by Pieter Folkens © 1989).

As with many other otariids, Antarctic fur seals are not as well adapted for deep diving as phocids. The spleen of a fur seal is not as large proportionally as the spleen of a phocid, and their blood contains lower concentrations of hematocrit and hemoglobin (Mottishaw et al. 1999). A comparative analysis of marine mammals and sea birds found most dives by Antarctic fur seals to be between 6 and 48 meters deep, typically lasing 0.7 to 1.7 minutes in duration. However, they have been known to dive as deep as 101 meters and hold their breath up to 5 minutes (Schreer & Kovacs 1997). While many pinnipeds often exhale before diving, Antarctic fur seals consistently dive with their lungs full and exhale during the latter stage of the ascent (Hooker et al. 2005).

In the early 19th century, commercial exploitation drove Antarctic fur seals to the brink of extinction (Boveng et al. 1998). Nearly 1,000,000 were harvested from South Georgia alone (Mori & Butterworth 2004). Since the 1950s, however, they have recovered, with the population at South Georgia Island increasing from under 10,000 in the 1950s to nearly 1,000,000 in the early 1990s (Ballance et al. 2006). And on Livingston Island, their numbers grew from 32 in 1959 to about 19,000 in 1987 (Boveng et al. 1998). However, research in the 1990s suggests that competitive release has been responsible for the recovery of Antarctic fur seals more than recovery from post-sealing exploitation alone (Ballance et al. 2006).

Commercial whale hunting in the 20th century is considered the greatest exploitation of wildlife in human history. It’s estimated that approximately 1.8 million whales were harvested from the Southern Ocean by commercial whaling (Ballance et al. 2006). A study in the 1970s calculated that the whales harvested consumed about 150 million tons of krill every year (Laws 1977). As a result of whaling, this surplus of krill allowed populations of other species of krill predators to increase, including Antarctic fur seals (Ballance et al. 2006).

In addition to their populations, Antarctic fur seals have seen increases in their breeding range, expanding to locations where they were not previously seen (Ballance et al. 2006). This could lead fur seals to be exposed to new contaminants. Concentrations of organic contaminants such as DDT in the blubber of whales were shown to be increasing from 1984 to 1994 (Aono et al. 1997). In addition, a study found that octochlorine B8-1413 occurred at higher concentrations in the southern hemisphere than in the northern (Vetter et al. 2001). As Antarctic fur seals expand their range into areas where whales were historically more common, they may be exposed to these same contaminants.

Contaminants

Despite their interconnectedness, the Southern Ocean’s sectors experience only limited input from water and air masses originating from lower latitudes because of oceanic and atmospheric circulation forming a series of natural barriers (Bargagli 2008). The Antarctic Circumpolar Current acts as an isolating mechanism by diverting heat flowing from the equator and causing the buildup of the Antarctic ice cap (American Museum of Natural History 2014). In addition, the remote location and hostile environment of Antarctica and the Southern Ocean give the perception of being untouched by human disturbances, but this is not true. Since the 1970s, the recurring appearance of the “ozone hole” over Antarctica and regional warming of the Antarctic Peninsula demonstrate that the Southern Ocean and Antarctica are not completely unaffected by anthropogenic disturbances occurring in other regions of the world (Bargagli 2008).

Atmospheric transport is one source of organic contaminants in the Southern Ocean. Anthropogenic actions, such as fuel combustion and waste incineration, are the main sources of contaminants in the Antarctic and its biota (Bargagli 2008). Under ambient temperatures, some persistent organic pollutants (POPs) evaporate (volatilize) from water, soil, and vegetation and enter the atmosphere. Once in the air, they are unaffected by reactions that may break them down and can be transported long distances before being redeposited. According to the theory of cold condensation and global fractionation, this cycle of volatilization and deposition can be repeated many times (Wania & Mackkay 1993). Some POPs can even be redistributed across the globe. Once they reach polar regions, they condense and settle. Over time, POPs can reach relatively high levels in high latitude environments because the cold temperatures can reduce or even completely stop evaporation (Bargagli 2008).

Atmospheric transport is also the source of many of the metal contaminants detected in the Southern Ocean and Antarctica. Mercury (Hg) is considered one of the most serious contaminants in polar ecosystems, such as coastal areas in the Antarctic (Ebinghaus et al. 2002). Mercury most often enters the atmosphere in its gaseous, elemental form from anthropogenic and natural sources. Once it's deposited in aquatic ecosystems, mercury is partly re-emitted into the air, where it assumes characteristics or POPs and other global pollutants (CITE). While mercury considered a serious threat to the Southern Ocean, the presence of other metals such as copper (Cu), nickel (Ni), and lead (Pb) in the southern hemisphere have been attributed to anthropogenic activities. These metals enter the atmosphere when they are released by fossil fuel combustion and production of non-ferrous metals (Bargagli 2008).

There are several pathways through which marine mammals are exposed directly. These include food consumption, mother-to-offspring transfer via gestation and lactation, absorption directly through skin, and inhalation (O'Shea et al. 1998). Bioaccumulation and biomagnification are two processes by which contaminants enter the bodies of organisms. Bioaccumulation is the accumulation of contaminants in an organism's tissues as a result of uptake from the abiotic environment and the organism's diet, while biomagnification is the increase of the concentration of contaminants along successive trophic levels in a food web (Ali & Khan 2019). This paper divides contaminants into two main categories, those that are composed of metal, and those that are organic compounds. Metal contaminants include mercury, lead, cobalt, and nickel, while organic contaminants are represented by dichlorodiphenyltrichloroethane, toxaphene, polychlorinated naphthalenes, and chlorofluorocarbons.

Concentrations of many metal and organic contaminants in organisms of Antarctica and the Southern Ocean are lower than levels documented in related species in temperate regions and the Arctic. However, most species in the Southern Ocean are endemic and have evolved in isolation, and so may be more vulnerable to harmful effects of such contaminants. Since 1964, a series of legal procedures have been implemented to help preserve the Antarctic and the Southern Ocean. One such example would be the Protocol on Environmental Protection to the Antarctic Treaty, formed in 1991, as a means of recognizing the scientific values of the Southern Ocean, such as better understanding its endemic species and global processes. However, while this Protocol establishes guidelines for human activities in the Southern Ocean and Antarctica, the impact of anthropogenic contaminants is likely to increase as human population growth and industrial development continue in the southern hemisphere (Bargagli 2008). Understanding the impacts contaminants such as these have on marine mammals could prove vital in developing effective conservation strategies.

Heavy Metal-based contaminants

Heavy metals are defined as having an atomic number, or number of protons, greater than 20 and an elemental density greater than 5 g cm^{-3} (Ali and Khan 2018). They are often divided into two general categories: essential and non-essential. Essential heavy metals are needed in very low quantities by organisms and are vital for biological systems to function properly (Roy 2010). Non-essential heavy metals, however, are not known to be involved in any biological functions (Ali and Khan 2019).

Cobalt and nickel represent essential metals because past studies have shown them to be vital components of aquatic ecosystems but can be hazardous to organisms in high concentrations (Eisler 1998). Past research on pinnipeds in the northern hemisphere has shown that higher concentrations of anthropogenic nickel increases the likelihood of stillbirths in ringed seals living in Finland (*Pusa hispida saimensis*), an adverse effect that high nickel concentrations could potentially have on pinnipeds in the Southern Ocean as well (Hyvärinen and Sipilä 1984). Cobalt is important for phytoplankton growth, and past research comparing the dissolution of natural and anthropogenic cobalt in seawater found anthropogenic particles to be significantly more soluble (0.78%) than natural cobalt particles (0.14%) (Thuróczy et al. 2010). As naturally occurring cobalt has a residence time of four to sixteen years, an influx of anthropogenic cobalt with higher solubility could impact the production of phytoplankton in the Southern Ocean (Sañudo-Wilhelmy et al. 2002).

Non-essential metals are represented in this study by mercury and lead because these are considered two of the “most notorious” non-essential heavy metals (Ali and Khan 2019). Data on the effects of non-essential metals on marine mammals is limited except for mercury. Multiple studies of mercury in different species of marine mammals have been conducted, allowing biologists to develop a more complete understanding of its impacts on these organisms (Krishna et al. 2002). Lead also represents non-essential heavy metals because it has been used in many industrial products, including gasoline and paints prior to a ban in 1978, and are still prevalent in many regions of the world. The effects of both non-essential metals have been extensively studied in humans, and have been linked to brain abnormalities in infants. Lead has also been linked to increased likelihoods of shorter life expectancies (Roy 2010). Because the effects of mercury are so extensively studied, and its impacts on humans and other mammals are similar, it could also exhibit the same adverse effects in Southern Ocean marine mammals. Lead could also be detrimental in that lowered life expectancies and abnormal brain developments would be difficult for marine mammals to adapt to because of their k-selected reproduction strategy (MacArthur and Wilson 1967).

Essential Heavy Metals

Cobalt

Cobalt (Co) is an essential metal that aids in the growth and distribution of several different groups of phytoplankton, the basis of the marine food web (Thuróczy et al. 2010). As an essential element, cobalt is naturally occurring in marine environments, with erosion of land surfaces and wind transport being major sources. However, not all cobalt occurs in the oceans naturally, with anthropogenic sources such as agricultural and industrial activities (Sunda and Huntsman 1995), including combustion and incineration (Bargagli 2008). Both natural and anthropogenic sources of cobalt enter the oceans as dust that is deposited on the surface via atmospheric transport (Thuróczy et al. 2010).

In some areas of the Southern Ocean, levels of cobalt were found to be relatively low. In the Weddell Sea, levels of Co measured to be 51 ppm are relatively high. Cobalt is enriched when water that's been upwelled combines with water along the continental shelf because of input processes occurring in sediments along the shelf (Sañudo-Wilhelmy et al. 2002).

Low levels of cobalt in comparison to other metals, such as copper, nickel, and zinc, in the waters around Antarctica have led some to conclude that the concentrations of such metals are the result of natural processes. Even so, anthropogenic processes still have an impact on the levels of cobalt and other metals in Antarctic waters (Sañudo-Wilhelmy et al. 2002). Trace metals can enter the environment though combustion and incineration (Bargagli 2008). The average residence time of cobalt once it enters the environment is four to sixteen years. Such a long residence time may be the result of biological uptake. This is because cobalt is incorporated into organic matter by phytoplankton during primary production (Sañudo-Wilhelmy et al. 2002).

In organisms at higher trophic levels, such as leopard seals, Weddell seals, and crabeater seals, studies found concentrations of cobalt to be highest in kidneys, followed by liver and muscle. In the same study, concentrations of cobalt in the liver and kidneys were shown to have a significant coassociation (Szefer et al. 1994). These results are in line with cobalt's nature as a trace metal, as some such metals are known to concentrate up the trophic system, especially in marine mammal kidneys and livers (Szefer et al. 1994). This, combined with its residence time of several years, means cobalt could pose a threat to marine mammals of the Southern Ocean.

Nickel

Nickel (Ni) is a trace metal that, in its pure form, has a silvery white color and is insoluble in water (Eisler 1998). It's considered essential to animals because it's present in fetuses and newborns, is homeostatically regulated, is part of some metalloproteins, and the metabolic pool of nickel is influenced by hormonal substances or pathologic processes (Eisler 1998). Nickel can enter water sources either naturally through physical weathering of rocks and soil, or through anthropogenic activities such as industrial waste discharge (USEPA 1986; WHO 1991). The main anthropogenic sources of nickel in waterways include production of nickel, metallurgical processes, and fossil fuel combustion and incineration (USEPA 1986). Production of other non-ferrous metals are another source of nickel, particularly in the southern hemisphere (Bargagli 2008).

Despite being essential to organisms, nickel can have many harmful effects. It can enter the bodies of animals, including humans, by being ingested, inhaled, and absorbed through skin

(Mushak 1980; USEPA 1975, 1980, 1986; Sigel and Sigel 1988; WHO 1991; USPHS 1993). Compounds containing nickel can even damage DNA and proteins and inhibit cellular antioxidant defenses (Rodriguez et al. 1996). For mammals, nickel is known to bioaccumulate, as its concentration generally increases with age (Eisler 1998). Trophic position and reproductive state, on the other hand, do not seem to significantly influence the effects of nickel (Outridge and Scheuhammer 1993).

Nickel can also be concentrated up the trophic web in aquatic environments. It's known to be especially prevalent in the kidneys of marine mammals. This was demonstrated in a study comparing different metal concentrations in crabeater, leopard, and Weddell seals. Results found the kidneys of all three species to have higher levels of nickel than other body tissues. A previous study found Antarctic Ross seals to have nickel concentrations in the liver to be as high as four to eight micrograms per gram dry weight (Szefer et al. 1994).

Non-Essential Heavy Metals

Lead

Lead (Pb) is a heavy metal that serves no biological function in organisms (Majer et al. 2014). It can form many compounds, some organic and others inorganic (Jakimska et al. 2011). Lead is one of many contaminants that reaches the Southern Ocean through atmospheric transport from lower latitudes (Majer et al. 2014). Deposition of lead in Antarctica has occurred during two separate time intervals, with the first lasting from 1891 to 1908 primarily from non-ferrous metal production and coal combustion, and the second from 1948 to 1994 corresponding to use of additives containing lead being used in automobile gasoline (Bargagli 2008). Anthropogenic activities such as incinerating garbage and fuel usage are some of the main sources of lead (Bargagli et al. 1998). Over 75% of anthropogenic lead in the atmosphere is the result of using leaded gasoline (Yin et al. 2008).

Lead can elicit many toxic effects in organisms. It can disrupt functions at the cellular level, including attacking bonds with sulfur carboxylic and amine groups of proteins and remove phosphate from compounds (Jakimska et al. 2011). In vertebrates, lead forms higher concentrations in hard tissues in animals, such as bones and hair, than in soft tissues such as internal organs (Yamamoto et al 1987). Lead concentrations have been found to be generally uniform in the tissues in which they occur, and while it's not known to biomagnify along the

Southern Ocean food chain (Yin et al. 2008), bioaccumulation of lead is documented (Majer et al. 2014).

Lead is also known to impair mammal immune systems, as evidenced by increased rates of tumors, lesions, and ulcers (LeBeuf et al. 2014). For marine mammals, lead exposure can also cause behavioral disturbances that negatively affect survival rates, growth, metabolic processes, and even learning (CITE). In addition, inorganic compounds containing lead are carcinogenic (Jakimska et al. 2011).

Currently, lead concentrations in the Weddell Sea are about half the level measured in other ocean environments (Sañudo-Wilhelmy et al. 2002). However, Antarctica can act as a sink for gaseous and particulate trace contaminants, including lead (Majer et al. 2014). In addition, many of the sources of lead contaminants in the southern hemisphere are linked to increasing human presence (Bargagli et al. 1998). As many species in the Southern Ocean have low fecundity, they are sensitive to lead exposure (Majer et al. 2014). In addition, lead has been reported to have a residence time lasting up to 20 years (Sañudo-Wilhelmy et al. 2002). This means that once lead enters the Southern Ocean, it can remain for decades.

Mercury

Mercury (Hg) is a non-essential heavy metal, meaning it is not a component in the tissues of organisms (Szefer et al. 1993). It’s volatile, insoluble, and inert in the presence of atmospheric oxidants (Sprovieri et al. 2002). Mercury is emitted into the atmosphere mainly by anthropogenic activities, including fuel combustion, mining, and smelting (Jakimska et al. 2011). While in the atmosphere, mercury occurs mostly in its gaseous, elemental form Hg^0. After mercury is deposited in terrestrial or aquatic ecosystems, it is partially re-emitted into the air, where it takes on features of persistent organic pollutants (Bargagli 2008).

Mercury is considered one of the most serious contaminants in the polar regions due to depletion events occurring in coastal areas around Antarctica (Ebinghaus et al. 2002). When it enters an organism, it can disrupt many cellular functions. Like lead, mercury attacks bonds with sulfur, as well as carboxylic and amino groups of proteins in enzymes. It can also remove phosphate from compounds or catalyze their decomposition. Studies of various marine vertebrates, including seabirds, sea turtles, and marine mammals, have shown mercury to adversely impact the central nervous and endocrine systems, leading to impaired reproductive and osmoregulatory functions (Jakimska et al. 2011).

For mammals specifically, mercury is one of many contaminants, both metal and organic, linked to impaired immune systems, as evidenced by increased incidences of lesions, tumors, and ulcers in beluga whales of the St. Lawrence River Estuary (LeBeuf et al. 2014). It can also cause motor deficits and behavioral impairment in mammals, leading to lethargy and even anorexia (Krishna et al. 2002). Analysis of animal excrements show mercury concentrations increase with the trophic position of organisms in a food web, a process known as biomagnification (Yin et al. 2008). Mercury is not only passed from one organism to another through predation. It can also be transferred from mothers to their offspring, either through the placenta or milk (Malcolm et al. 1994). Any potential health concerns mercury poses to the Southern Ocean's marine mammals is intensified not only by biomagnification, but also because the regions of the troposphere located over the Earth's polar regions has been found to be a reactive environment for mercury (Sprovieri et al. 2002). In addition, anthropogenic emissions of mercury in the southern hemisphere are increasing. As mercury levels in Antarctic organisms increase, Antarctica may become a sink for global mercury, further harming marine mammals in the Southern Ocean (Bargagli 2008).

Organic Contaminants

Organic contaminants can be classified in different ways, with some subjective to the opinions of authors while other classification methods have a more scientific basis. One system of classification can group certain chemicals together, while another may not. This is exemplified in a series of studies in 1998, which divided contaminants into four groups: lipophilic organics, toxic metals, agricultural contaminants, and plasticizers and industrial solvents. Using this method to categorize organic contaminants, dichlorodiphenyltrichloroethane (DDT) is classified as a lipophilic organic and not an agricultural contaminant despite being used historically as an insecticide (O'Shea, Reeves, and Long 1998).

This research paper arranges organic contaminants into two categories: those that were historically used as pesticides, and those that have been used for industrial processes. DDT and toxaphene represent organic contaminants connected to pesticides because both have been historically used to protect agricultural crops from insect pests (Smith 1991; WHO 1984) and are still in use in the southern hemisphere (Larsson et al. 1992, Ritter et al. 1995). Organic contaminants with industrial origins in this capstone are chlorofluorocarbons (CFCs) and polychlorinated napthalenes (PCNs). Both have been used in manufactured products since the 1930s (Corsolini et al. 2002; Alleman et al. 2001). CFCs were first detected in the Antarctic region in the late 1970s (Bargagli 2008), while PCNS were documented in Antarctic organisms in 2002 (O'Shea, Reeves, and Long 1998). Although the specific impacts of these industrial-based organic contaminants on the Southern Ocean are limited, research on them in other regions can offer insight into how they may affect marine mammals of the Southern Ocean.

Organic Contaminants Originating as Pesticides

Dichlorodiphenyltrichloroethane

Dichlorodiphenyltrichloroethane (DDT) is one of the first organochlorine pesticides developed (Smith 1991). Its use in agriculture in tropical regions during the relatively warmer, wetter growing season facilitates its rapid dissipation (Ritter et al. 1995). DDT enters the Antarctic marine environment via atmospheric transport (Larsson et al. 1992). As DDT is transported from tropical regions to higher latitudes, it is continuously deposited and re-evaporated (Ritter et al. 1995).

DDT is a persistent organic pollutant (POP), meaning it persists in the environment for more than six months. It's also known to bioaccumulate in organisms because it has a lipophilic nature and easily partitions into the fats of organisms (Ritter et al. 1995). DDT is considered a well-studied contaminant, and there is already a large body of evidence that exposure has adverse effects on a wide variety of species. General effects of DDT on vertebrates include tremors and even fetal death in pregnant females (O'Shea, Reeves, and Long 1998). Other non-lethal effects of DDT exposure include altered behavior and reproduction, likely the result of DDT altering hormones, enzymes, and calcium metabolism (Science Applications International Corporation 1998). It is also known to biomagnify, meaning organisms at higher trophic levels are likely to have higher concentrations than their prey species (Ritter et al. 1995). When DDT does degrade, it produces dichlorodiphenyldichloroethylene (DDD) and dichlorodiphenyldichloroethylene (DDE), both of which, like DDT itself, are lipid soluble, able to biomagnify, and can persist in the environment for years (O'Shea, Reeves, and Long 1998).

For marine mammals such as pinnipeds and cetaceans, DDT’s lipophilic nature means it tends to be stored mainly in their blubber (O’Shea, Reeves, and Long 1998). DDT often enters the bodies of marine mammals through food consumption, and can cause many ailments, including vitamin and thyroid deficiencies, as well as weakened immune systems that leave them more susceptible to infectious microbes (Ritter et al. 1995). DDT is one of many pesticides that has been linked to increased incidences of lesions, tumors, and ulcers in cetaceans and other mammals (LeBeuf et al. 2014). Exposure to DDT and other POPs has already been connected to populations declines in many species of marine mammals in the Northern Hemisphere (Reijnders 1986, Duinker 1985, Martineau et al. 1987). DDT concentrations in the blubber of whales in the Southern Ocean have already been shown to have increased between 1984 and 1994 (Aono et al. 1997). Studies of Antarctic air samples in the 1990s show continued transport of DDT to the southern polar region (Larsson et al. 1992). In the polar climate of the Southern Ocean, combined with reduced biological activity compared to lower latitudes and relatively less exposure to sunlight, cause DDT and other POPs to increase in persistence. This increases the threats DDT poses to Southern Ocean wildlife, which include immune deficiencies (Ritter et al. 1995).

Toxaphene

Toxaphene is a persistent organic pollutant (POP) that appears as a yellow, waxy solid with an odor similar to chlorine (Montgomery 1993). As a POP, it has a semi-volatile nature, allowing it to occur in either a vapor phase or be adsorbed onto particles in the atmosphere (Ritter et al. 1995). Toxaphene is one of the earliest organochlorine insecticides, having been in use in the United States since 1949 (WHO 1984). Between 1947 and 1987 approximately 454,000 metric tonnes of toxaphene were produced in the United States, and about 181,000 metric tonnes in other countries (Voldner & Ellenton 1987). Beginning in the 1970s, however, it was banned in the US. Today, it is now banned or restricted in most countries around the world (Ritter et al. 1995). However, toxaphene is still in use in some countries, particularly in South America, which have historically been some of the heaviest users of toxaphene (Bargagli 2008). The reason for its prevalence is a general lack of knowledge regarding alternative insecticides among farmers in countries that still use it, such as Honduras (Ritter et al. 1995).

As a POP, toxaphene is highly resistant to degradation by biological or chemical processes (Ritter et al. 1995). Toxaphene is also highly insoluble in water and able to reach new locations through atmospheric transport (WHO 1984). Once it enters the environment, toxaphene can be deadly to organisms. The most common form of exposure to toxaphene is through food (WHO 1984). It is able to accumulate in biological tissues, bioaccumulate, and biomagnify in organisms, increasing in concentration as it moves up the trophic levels (Smith 1991). Studies of animals in laboratory settings have even found evidence that toxaphene is carcinogenic (IARC 1979).

Past studies have found toxaphene to be one of several POPs responsible for immune deficiencies in wildlife, including marine mammals. Seals have already been found to experience vitamin and thyroid deficiencies when consuming prey contaminated with POPs such as toxaphene, which leaves them vulnerable to infectious microbes and even reproductive disorders. There is also evidence that some POPs, including toxaphene, are connected to immunotoxic and reproductive effects in wildlife. While toxaphene has not been directly linked to these effects, residues have been detected in the air in the Arctic (Ritter et al. 1995). As the use of toxaphene continues in some countries, these harmful impacts may become more common in marine mammals of the Southern Ocean.

Organic Contaminants Originating from Industrial Processes

Chlorofluorocarbons

Chlorofluorocarbons, also known as CFCs, are anthropogenically emitted transient tracer contaminants (Alleman et al. 2001). They are chlorinated hydrocarbons that are resistant to atmospheric breakdown and have been found to have the potential to deplete the stratosphere’s ozone and induce global warming. Chlorofluorocarbons have been used in refrigeration, metal and electronics, and mobile air conditioning systems (National Research Council Committee on Toxicology et al. 1996). Since the 1930s, they have become widely dispersed in the World Ocean and exhibit a quasi-uniform increase (Alleman et al. 2001). Since the late 1970s, the recurring appearance of the “ozone hole” above Antarctica indicates that the continent and the Southern Ocean are both affected by anthropogenic inputs, including CFCs (Bargagli 2008). In fact, the chlorine that forms CFCs contributes to their ability to deplete the ozone (National Research Council Committee on Toxicology et al. 1996).

Concentrations of CFCs in and around the Southern Ocean can vary by location. Water in the Georgia Basin has been found to have higher concentrations of CFC than waters of the Argentine Basin (Whitworth III et al. 1991. These CFC-rich waters of the Georgia Basin are believed to originate from the boundary region between the Antarctic Circumpolar Current and the Weddell Gyre located east of the Antarctic Peninsula (Whitworth III et al. 1991). Conversely, the water in the Argentine Basin has lower CFC concentrations because it is actually Weddell Sea Deep Water that has been circulating for longer than in the Georgia Basin (Whitworth III et al. 1991).

Many studies of chlorofluorocarbons focus on their atmospheric impacts. However, there are some studies of the negative effects that exposure can have on organisms. The main form of exposure to CFCs is inhalation. Research has found that inhalation of CFCs and other chlorinated hydrocarbons can make the hearts of mammals more sensitive to epinephrine than they otherwise would be. This can lead to cardiac arrhythmias and even death. This is because CFCs decrease the threshold for epinephrine-induced arrhythmias by reducing the cardiovascular system’s ability to respond to stress (National Research Council Committee on Toxicology et al. 1996).

Compared to other organic contaminants, the effects of CFCs on marine mammals in the Southern Ocean are not as well known. However, because of their relatively recent introduction into the ocean, chlorofluorocarbons are useful for tracing the movement of deep-water masses that have recently been exposed to the atmosphere (Locarnini et al. 1993). Understanding how CFCs are transported between different sectors of the Southern Ocean is vital for determining if any marine mammal populations are more vulnerable to this class of organic contaminants.

Polychlorinated naphthalenes

Polychlorinated naphthalenes (PCNs) are a group of 75 organic compounds that possess the naphthalene ring system, meaning chlorinate atoms can substitute hydrogen atoms. They have low flammability, electrical properties, and are thermally stable (Corsolini et al. 2002). Like other persistent organic pollutants, PCNs are lipophilic and hydrophobic (Green and Larson 2016). They have been commercially in use since the 1930s, and are released as byproducts of chlorinating processes, combustion, magnesium refineries, and waste incineration (Corsolini et al. 2002). Although the processes responsible for releasing PCNs into the environment are documented, their actual distributions are not as well-known. What is known is that PCNs are sometimes released into the environment by polychlorinated biphenyls (PCBs) and are likely transported together (Corsolini et al. 2002).

Different PCN compounds have different properties. Those with lower chlorinations are more volatile than high-chlorinated counterparts and can reach polar regions through atmospheric transport (Corsolini et al. 2002). Regardless of the specific compound, PCN exposure is either oral or inhalation (Van de Plassche and Schwegler 2002). PCNs are known to bioaccumulate in organisms and have been detected in tissues of organisms around the world, including the Southern Ocean (Järnberg et al. 1997; Falandysz et al. 1996; Crookes and Howe 1993).

There are fewer studies of PCNs in Antarctica than in other regions. A study by Corsolini et al. (2002) was the first ever to document PCNs in Antarctic organisms. In this study, PCN concentrations were found to be higher in organisms at higher trophic levels, such as Weddell seals, than their prey species, proving that PCNs biomagnify up the food web (Corsolini et al. 2002). Because of their lipophilic nature, PCNs tend to accumulate in the blubber of marine mammals (O'Shea, Reeves, and Long 1998).

Currently, contamination levels of PCNs in Antarctica are lower than in other locations (Corsolini et al. 2002). However, while some sites in Antarctica are only a few parts per billion (ppb), other areas have PCN concentrations as high as hundreds of parts per billion (Corsolini et al. 2002). Because of the limited number of studies, the specific impacts are not well known. However, studies of other POPs have shown that the impacts on marine mammals depend on several factors, including migration. Marine mammals that migrate to areas impacted by anthropogenic activities are exposed to PCNs and other POPs more so than species that do not migrate (Corsolini 2009). Because research of PCNs in the Southern Ocean region is relatively young, further studies are needed to determine the specific impacts of these contaminants on its marine mammals.

Contaminants in Southern Ocean Marine Mammals

Antarctica was once thought to be unpolluted because of its distance from human activities (Dick 1991). However, research has shown this to be inaccurate. In fact, the Antarctic region has seen the largest human-induced perturbations of the marine ecosystem in the entire world (Mori & Butterworth 2004). Currently, concentrations of metal and persistent organic contaminants in the biota of Antarctica and the Southern Ocean are below concentrations documented to have significant biological effects on taxonomically related species in temperate regions and the Arctic Ocean. However, many of the anthropogenic activities that contribute to these contaminants are increasing in the southern hemisphere. This includes burning fossil fuels, which contributes to increased concentrations of mercury (Jakimska et al. 2011), lead (Bargagli et al. 1998), and nickel (Bargagli 2008). Some organic contaminants in the Antarctic and Southern Ocean have also shown increases over time, including DDT during the 1990s (Larsson et al. 1992), where the polar climate and reduced biological activity allow POPs such as this to persist even longer than they would at lower latitudes (Ritter et al. 1995). Because most organisms in the Southern Ocean are endemic and possess unique ecophysiological features from evolving in isolation, they are potentially more vulnerable to contaminants than those living in other regions (Bargagli 2008). And that includes marine mammals.

Contaminants affecting marine mammals often originate from agricultural pesticides, especially contaminants that are organic in nature, while other contaminants can be traced to other anthropogenic activities such as industrial solvent production. Contaminants typically enter the bodies of marine mammals through four main pathways: directly through food consumption, absorption through the epidermis, inhalation, and mother-to-offspring transmission through gestation and lactation. Food consumption, which includes drinking milk, and prenatal transfer from mother to offspring are believed to be the two most significant means by which marine mammals are exposed. This is especially concerning because some contaminants biomagnify as they pass through the food web, and many marine mammals feed at high trophic levels (O’Shea, Reeves, and Long 1998).

Various species of marine mammals in the Southern Ocean are known to have been exposed to contaminants, either metal or organic. Different species are exposed to different contaminants, and the effects can vary, as can how they are studied and what they reveal. A study in 2013, for example, revealed that blue whales and other mysticetes produce plugs of ear wax that record some contaminants chronologically, including mercury and organic pesticides, which can be used to create lifetime profiles of individual whale exposure (Trumble et al. 2013). Between 1984 and 1994 concentrations of the lipophilic organochlorine DDT were found to be increasing in the southern hemisphere (Aono et al. 1997). This is problematic for cetaceans because of their k-selected population structure (MacArthur and Wilson 1967), including Antarctic minke whales, which do not reach sexual maturity until four to five years old and produce only a single calf annually (Ichii et al. 1998).

Killer whales are potentially more vulnerable to contaminants that are biomagnified through the food web, such as the lipophilic DDT (O'Shea, Reeves, and Long 1998), because they feed at higher trophic levels than other marine mammals (Berta et al. 2015). Some Antarctic killer whales are known to migrate to subtropical waters near Brazil and Uruguay (Durban and Pitman 2011), placing them at risk of exposure to contaminants that they otherwise would not.

Pinnipeds are also exposed to various contaminants. Multiple studies of Weddell seals that focused on metals in tissues found that metal contaminants tended to have the highest concentrations of metals in the liver, with the kidneys and muscle having lower concentrations (Szefer et al. 1993, Szefer et al. 1994, Yamamoto et al. 1987). One study found different tissues in Weddell seals to have different metals. They discovered that tissues in the liver and kidneys tended to have the highest accumulations of mercury, while bone and hair tissues had higher levels of lead and nickel (Yamamoto et al. 1987). Like other metal contaminants, these enter marine mammals and other organisms through food consumption, respiration, or being absorbed through the skin (Jakimska et al. 2011).

One study compared concentrations of various metal contaminants between Weddell, leopard, and crabeater seals. They discovered that in all three species, the kidneys to contain the highest concentrations of nickel and cobalt in all three species when compared to other body tissues. The concentrations of nickel, in $\mu g/g^{-1}$ dry weight for the kidneys of crabeater, leopard, and Weddell seals averaged 0.32, 0.16, and 0.20, respectively. Cobalt concentrations, also in $\mu g/g^{-1}$ dry weight for the kidneys of crabeater, leopard, and Weddell seals averaged 0.23, 0.21, and 0.20, respectively (Szefer et al. 1994).

Previous studies found some trace metals in aquatic environments to be concentrated through the trophic system, especially by the lipid-rich liver and kidneys of marine mammals (Anas 1974, Eisler 1984, Ray 1984). This may explain why some of the contaminants in this study are found in higher concentrations in some tissues than in others. Other studies of cetaceans, particularly killer whales in the northern hemisphere, have found mercury levels to being higher in their liver (Law et al. 1997, Endo et al. 2006, Endo et al. 2007), while their blubber saw accumulations of organic compounds (Law et al. 1997; Haraguchi et al. 2009).

Further studies may reveal similar contaminant distributions in their counterparts in the Southern Ocean.

Organic contaminants are also potential threats to the Southern Ocean's marine mammals, including the southern elephant seal. One study looked at various persistent organic pollutants in southern elephant seal blubber, including DDT, in nanograms per gram. The results showed concentrations of DDT to be approximately 106 ng/g^{-1} of lipid, one to two orders of magnitude lower than levels in the blubber of pinnipeds in the northern hemisphere. Even so, the fact that DDT was at detectable levels demonstrates that the remoteness of Antarctica and the Southern Ocean does not prevent exposure of contaminants, and long-range transport of it and other organic contaminants occur primarily through aerial transport (Miranda-Filho et al. 2007).

Antarctic fur seals, as members of the genus *Arctocephalus*, have thinner blubber than other pinnipeds, suggesting they rely on their fur for insulation and rely on blubber for energy storage (Liwang et al. 2012). Because of this, lipophilic contaminants like DDT may not be as much of a threat to fur seals as they are to other marine mammals of the Southern Ocean. However, they are still potentially vulnerable to metal contaminants. One study found Antarctic fur seals have some of the highest concentrations of metals found in marine vertebrates. Although the seals in this study displayed no observable pathological symptoms and appeared healthy, concentrations of some of the metals detected in their livers were higher than any previous study of this species had recorded, including mercury, with an average concentration of 215 mg Hg pet kilogram dry weight (Malcolm et al. 1994).

Even within a single species, contaminant exposure can vary. Location and demographics can influence the level of exposure marine mammals in the Southern Ocean experience. One study of Weddell seals found that those living on King George Island, located at latitude 62°° S, had concentrations of DDT between 11 and 19 μg/kg, one order of magnitude lower than DDT concentrations sampled in other sites in Antarctica between 69°and 78° S, implying that some organic contaminant levels vary with geographic site (Vetter et al. 2003). Demography can also influence exposure. Research has found that male Weddell seals south of Elephant Island, which is located at latitude 61° S, had higher concentrations of DDT and other organic contaminants than females from the same population. Concentrations measured in 1981 found male Weddell seals to have concentrations as high as 186 nanograms per gram of lipid, while the maximum in females was 101 ng/g^{-1} of lipid (Kawano et al. 1984).

The same study found concentrations of contaminants in southern elephant seals to be higher in juveniles than in pups and higher still in adult elephant seals, and that pups accumulate contaminants via transplacental and lactational transfer from their mothers. On Elephant Island, the concentration of DDT in pups averaged 79.95 ng/g^{-1} lipid, while for juveniles it was 123.50, 182.59 for adult females, and 192.85 in adult males that were subdominant. Dominant males could not be analyzed in this study (Miranda-Filho et al. 2007). Transfer through lactation is a confirmed route by which the offspring of many species of marine mammals are exposed to lipophilic contaminants, including humpback and blue whales in the Gulf of St. Lawrence in Canada (Metcalfe et al. 2004). This type of transfer has also been documented in killer whales along the Pacific coast of Japan (Haraguchi et al. 2009). Although these cetacean studies were conducted in regions outside the Southern Ocean, they focused on species that are native to the area, suggesting the possibility of similar trends in Southern Ocean whales of these species.

The harmful effects of contaminants in the Southern Ocean are not always confined to the organisms exposed to them. Sometimes, they can have significant impacts on the environment itself. This can be seen in CFCs, which contribute to the depletion of ozone above Antarctica (Alleman et al. 2001). As ozone is depleted, it causes temperatures to increase. In some regions of the Southern Ocean, such as the Antarctic Peninsula, temperatures have risen by 2.8 ° C (American Museum of Natural History 2014). This in turn affects El Niño Southern Oscillation (ENSO), an oceanographic and meteorological event is characterized by increased surface temperatures, which prevents upwelling of deeper, nutrient-rich waters. As temperatures increase, ENSO events are likely to become more frequent and intense, which would most likely lower productivity in the Southern Ocean significantly affect marine mammals (Berta et al. 2015). As temperatures increase, the rate of snow and ice melt also increases, and contaminants that have accumulated in them could enter the marine environment as runoff, further increasing concentrations (Bargagli 2008).

Marine mammals are exposed to many different environmental contaminants, some of which are persistent, fat-soluble, and able to accumulate through food webs. Understanding the risks these contaminants pose, whether they are composed of metal or organic, is difficult because it requires a systematic approach that involves extrapolating from model species and laboratory experiments (O’Shea, Reeves, and Long 1998). This is further complicated by the fact that logistics and ethics make studying marine mammals difficult and costly (Berta et al. 2015).

Even so, understanding the effects of contaminants on marine mammals is vital to successful conservation. Without this knowledge, scientists will not be able to inform policy makers and managers. Additionally, this could lead to a loss of genetic diversity within species and perhaps even the extinction of entire species. Understanding how marine mammals are affected by these contaminants will allow any harmful impacts they may have, either on individuals or entire populations, to be recognized and investigated before they become more widespread. Such information would be gained from studies of the tissues of the marine mammals to develop accurate models and techniques to be available to be applied to any threatened or endangered species to understand how they would be affected by such contaminants, both at the individual and population levels (O'Shea et al. 1998).

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