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Impacts of global climate change on birds and marine mammals in Antarctica

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Abstract Birds and marine mammals in Antarctica, especially penguins and seals, are top consumers and critical elements of the Southern Ocean ecosystem. As a region undergoing rapid global change, new challenges will be posed to the survival of these vertebrates species. Global climate change causes many alterations, such as ocean temperature rise, altered sea ice distribution, and abnormal climate events along with effects of intensive human activities, such as fishing. These not only directly affect the spatiotemporal distributions and population dynamics of Antarctic birds and marine mammals but also indirectly influence them via modification of their food resources. At present, the impact of climate change on birds and marine mammals in the Antarctica is focusing on a number of species in a few areas. Response mechanisms of these species are still very limited and therefore require further long-term and continuous monitoring and research.

Keywords Antarctica, birds, marine mammal, global climate change

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1 Introduction

Given its unique geographic location, Antarctica is regarded as an ideal place to study global climate change and ecological response. The Scientific Committee on Antarctic Research (SCAR) has listed the priority of scientific issues to include climate change, ecosystem structure, and biodiversity. As upper trophic level consumers in the food web in the Southern Ocean, seabirds and marine mammals are important components of the ecosystem (Croxall et al., 1992; Huang et al., 2014). Despite the harsh environmental conditions, the biomass of Antarctic seabirds and marine animals is large owing to the impressive primary productivity and efficient trophic transfer. Although the species diversity is not great, population sizes are large. The latest surveys from 2017 show that the Adélie penguin (*Pygoscelis adeliae*) population in Eastern Antarctica has reached 5.9 million, with a global population of 14–16 million. Because this penguin breeds in ice-free coastal areas and forages in the adjacent Southern Ocean, associated with sea ice, it is very sensitive to climate and environmental changes. Thus, this species is considered as an "indicator of climate change" (Baroni and Orombelli, 1994; Sun et al., 2000a). Emperor penguins (*Aptenodytes forsteri*) breed at 46 locations in the Antarctica, numbering ~595000 birds (Fretwell et al., 2012). In regard to seals, that 50% of the total global seal population and 80% of the global biomass of pinnipeds are found in the Southern Ocean further reflects the high productivity of the region (Laws, 1984). In addition, large cetaceans are widely distributed in the Southern Ocean, with the most abundant during summer (Croxall et al., 1992; Costa and Crocker, 1996). The huge number of Antarctic seabirds and marine

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mammals has attracted commercial development exploitation. Over the past two centuries, alteration of the distribution and population change of Antarctic seabirds and marine mammals has been largely caused by direct and indirect human over-exploitation of marine resources (Croxall et al., 1992; Weimerskirch et al., 1997). For instance, about 1.2 million seals were killed before 1882 and more than a million whales were taken before 1975 (Chen et al., 1992). Birds and marine mammals in Antarctica are now protected by the international conservation legislations, such as the "Antarctic Treaty System", "Convention for the Conservation of Antarctic Marine Living Resources", "Convention for the Conservation of Antarctic Seals" and "International Convention for the Regulation of Whaling" (Maffei, 1997; IUCN, 2017). Furthermore, massive hunting has now been effectively curbed. However, because of the long life and slow propagation of Antarctic seabirds and marine mammals, they are more susceptible to changes of the sea environment and ecosystem caused by climate change (Croxall et al., 1992; Sun et al., 2004).

Studies have confirmed that global average temperature is climbing, leading to temperature, wind speed and precipitation shifts, which have been amplified in polar regions (IPCC, 2007; Korczak-Abshire, 2010). The Antarctica is one of the most sensitive areas for response and feedback to global change, and the major environment has undergone rapid and significant change (Korczak- Abshire, 2010). Observational data indicate that the Antarctic Peninsula has experienced major warming over the last five decades (1951–2000), and this has shortened annual sea ice duration (Vaughan et al., 2003). Along the western peninsula, average annual air temperature recorded at scientific bases during the past five decades has increased by 3.4°C, with the sharpest increase in winter, as much as 6.0°C (Turner et al., 2005); these are as much as 10 times the equivalent figures for global temperatures (Vaughan et al., 2003). These changes have already resulted in a 40% decrease of sea-ice coverage in the Bellingshausen Sea (McClintock et al., 2008) and disintegration of ice shelves along both the eastern and western Antarctic Peninsula (Cook and Vaughan, 2010).

In such a fragile and sensitive area like the Antarctica, the food web is relatively simple and any small change can have important implications (IPCC, 2007; Korczak-Abshire, 2010). These changes will bring new challenges to the survival of Antarctic wildlife. The reduction in extent and duration of sea ice would drastically change the availability and connectivity existing habitats, which in turn may increase regional-scale biotic homogenization and the extinction of less-competitive species (Lee et al., 2017). Moreover, for some Antarctic animals, their abundance, phenology, behavior, morphology, physiology and activity patterns would be affected by the reduced sea ice owing to changes in food resources (Trathan et al., 2007; Korczak-Abshire, 2010). With acceleration of global change, Antarctic birds and marine mammals will be confronted with many aspects of the aforementioned impacts, divisible into two major types: changes in their critical habitat mainly caused by sea ice reduction, and alteration of food webs (Forcada, 2008; Sydeman et al., 2015).

The reduction of extent and seasonal duration of sea ice influences species most dependent on the ice to complete their reproductive cycle. However, less ice-dependent species probably benefit from this reduction over the short term (Siniff et al., 2008). Nevertheless, with modification of the Southern Ocean food web caused by climate change, these species may also soon suffer from change in food resources (Siniff et al., 2008).

Studies of global change effects on Antarctic large vertebrates have mainly treated seabirds and marine mammals (Barbraud and Weimerskirch, 2006; Forcada et al., 2008; Korczak-Abshire, 2010; Huang et al., 2014; Cimino et al., 2016). Based on related literature published by Chinese researchers and international scholars, this paper presents a review of the effects of global change on Antarctic birds and marine mammals and their response mechanisms.

2 Birds and marine mammals in Antarctica

2.1 Major birds

Antarctic seabirds refer to those species for which most of their life stages or important life activities, such as breeding or overwintering, are completed in the Antarctic region (south of latitude 60°), including Sphenisciformes, Procellariiformes, Charadriiformes, and Pelecaniformes. Sphenisciformes rely on ocean and land throughout their lives, including activities such as predation, reproduction, and migration. There are seven species of penguins in the Antarctica, including the emperor, Adélie, chinstrap (*P. antarctica*) and gentoo (*P. papua*) penguins. These have a circumpolar distribution, with the king (*A. patagonicus*), macaroni (*Eudyptes chrysolophus*) and southern rockhopper (*E. chrysocome*) penguins mainly in the sub-Antarctic. Procellariiformes in the Antarctica include the following: Cape petrel (*Daption capense*), white-chinned petrel (*Procellari aequinoctialis*), southern giant petrel (*Macronectes giganteus*), snow petrel (*Pagodroma nivea*), blue petrel (*Halobaena caerulea*), sooty shearwater (*Ardenna grisea*), Antarctic prion (*Pachyptila desolata*), white-headed petrel (*Pterodroma lessonii*), southern fulmar (*Fulmarus glacialoides*) and Antarctic petrel (*Thalassoica antarctica*) in Procellariidae; wandering albatross (*Diomedea exulans*), black-browed albatross (*Thalassarche melanophrys*) and light-mantled sooty albatross (*Phoebetria palpebrata*) in Diomedeidae; and Wilson's storm-petrel (*Oceanites oceanicus*), and black-bellied storm petrel (*Fregetta tropica*) in Hydrobatidae. These birds have a strong flying ability and most are in the higher latitude circumpolar ocean and islands. The Antarctic shag

(*Phalacrocorax bransfieldensis*) in Pelecaniformes and snowy sheathbill (*Chionis alba*) in Charadriiformes occur only in the northern Antarctic Peninsula. However, the other four species of Charadriiformes, the south polar skua (*Stercorarius maccormicki*), brown skua (*C.antarctica*), Antarctic tern (*Sterna vittata*) and Arctic tern (*S. paradisaea*), have a circumpolar distribution in the Antarctica. Among the aforementioned birds, the black-browed albatross, light-mantled sooty albatross, and emperor penguins are classified as "near-threatened", whereas macaroni penguins, southern rockhopper and wandering albatross are classified as "vulnerable" by the International Union for Conservation of Nature (IUCN, 2017).

2.2 Marine mammals

Pinnipeds and whales are the two groups of marine mammals found in the Southern Ocean. The former are semi-aquatic, with most of their lives in the water, but come ashore or haul out on sea ice to rest, molt, breed or escape from predators. Whales are exclusively aquatic. Six species of pinnipeds inhabit the Antarctica, including the leopard (*Hydrurga leptonyx*), Weddell (*Leptonychotes weddellii*), crabeater (*Lobodon carcinophagus*), Ross (*Ommatophoca rossii*), southern elephant (*Mirounga leonina*), and Antarctic fur (*Arctocephalus gazella*) seals (Costa and Crocker, 1996; Geraci and Lounsbury, 2009). The first four species are endemic to the Antarctica and mainly live on the pack-ice region surrounding the Antarctic continent (Geraci and Lounsbury, 2009). The latter two species are generally found somewhat further north, using island beaches as a haul-out site for breeding instead of ice, but are known to forage in waters south of the Antarctic convergence into the marginal ice zone (Costa and Crocker, 1996).

In addition to seals, the Southern Ocean is also a critical feeding ground for many cetaceans, including six species of baleen whales, such as the blue (*Balaenoptera musculus*), fin (*B. physalus*), sei (*B. borealis*) , dwarf minke (*B. acutorostrata*), Antarctic minke (*B. bonaerensis*) and humpback (*Megaptera novaeangliae*) whales. Some species in Odontoceti, i.e., the sperm (*Physeter catodon*), Arnoux's beaked (*Berardius arnuxii*), southern bottlenose (*Hyperoodon planifrons*), killer (*Orcinus orca*) and long-finned pilot (*Globicephala melas*) whales, and southern right whale (*Lissodelphis peronii*) and hourglass (*Lagenorhynchus cruciger*) dolphins (Costa and Crocker, 1996; Moore et al., 1999; Deborah et al., 2004).

Cetaceans occur throughout the Southern Ocean. They usually make long migrations for feeding during summer in the Southern Ocean. Their population density decreased substantially after commercial whaling (Croxall et al., 1992). This, coupled with the harsh climate in the Southern Ocean, hampers detailed investigation of their ecology and its relation to the dynamics of sea ice and climate (Forcada, 2008). Therefore, assessing the impacts of climate change on them presents many difficulties and uncertainties (Stenson et al., 2016).

3 Influence of climate change on birds and marine mammals in Antarctica

3.1 Habitat change

Sea ice is an important habitat for birds and pinnipeds in the Antarctica, providing a platform for their breeding, fostering, foraging and molting (Massom and Stammerjohn, 2010). The Antarctica is rapidly warming, making air and water temperatures rise. This has caused the duration, thickness, and extent of sea ice to change substantially in certain regions, such as Bellingshausen and Amundsen seas (Vaughan et al., 2003; Mulvaney et al., 2012; Li et al., 2016) . Furthermore, the large-scale extent of sea ice has a relationship with the global climate system, such as the El Niño – Southern Oscillation (ENSO) and Southern Annular Mode (SAM) (Stammerjohn et al., 2008; Huang et al., 2014). Change of sea ice, such as its seasonal range, delay in formation, and faster melt in spring, can greatly threaten the survival of certain species whose life is strongly dependent on the ice (Moore and Huntington, 2008).

Among seabirds, penguins have become a focus of attention because of their widespread distribution in the Antarctica and unique biological habits. They are considered "indicator species". Similar to marine mammals, Antarctic penguins have varying dependencies on sea ice. It is generally believed that emperor and Adélie penguins have greater dependence on sea ice, whereas the gentoo penguin is only sea ice tolerant (Ainley et al., 2017). However, spatiotemporal variation in the distribution of sea ice has various influences on penguin populations (Emmerson and Southwell, 2008; Massom et al., 2009). The impacts of climate change vary by region, which is crucial to change of penguin habitat. Based on the maximum entropy (MaxEnt) model and satellite remote sensing data, the distribution dynamics of suitable chick-rearing habitats of three types of penguins over 1982–2010 have been determined by fitting analysis using sea ice concentration and sea surface temperature as climate niche parameters (Cimino et al., 2013). The results indicate that extent and locations had greatly changed; extent decreased in the north and increased in the south. The sharpest decrease was near the western Antarctic Peninsula where it is warming the fastest, which is consistent with the trend of population demographics in that area (Cimino et al., 2013). In addition, upon analysis of changes in the historical habitat of two species of Procellariidae, Grecian et al. (2016) indicated that Antarctic prions, which is mainly in the Antarctica, have moved considerably southward in the non-breeding season over the past 100 years. However, there was no obvious change of the broad-billed prion (*P. vittata*), whose distribution was north of 60° latitude.

Based on survey results and climate data, scenarios building are also an important approach to predicting the trend of the habitat change of birds in the future. This change over the next 50 years has been predicted using three Intergovernmental Panel on Climate Change (IPCC) scenarios (Barbraud et al., 2011). The results show that the response of Southern Hemisphere birds in the subtropics, sub-Antarctic, and Antarctica to environmental change is a frequency-dependent nonlinear relationship. With the increase in sea surface temperature and reduction of sea ice, species that live in the northernmost Southern Ocean suffered least from climate change, while southernmost species showed a significant declining trend (Barbraud et al., 2011). The effects of habitat loss on various bird species in the Antarctica will also vary. According to the four climate-change scenarios proposed in the fourth IPCC Assessment Report, the habitat of emperor and Adélie penguins north of latitude 70° will disappear under a temperature rise of 2°C. This is equivalent to 50% of the total habitat of the emperor penguin and 70% of that of the Adélie penguin. Habitat of the emperor penguin at higher latitudes (>73°) will increase. Overall, these changes may be beneficial to emperor penguins, but the Adélie penguin will be at a disadvantage because this species has limited tolerance to polar night and increased snow (Ainley et al., 2010). Suitable breeding habitat for the Adélie penguin is also predicted to have this trend, expected to diminish by ~20% over the next 40 years. However, over the same period, new breeding sites formed on the Antarctic continent may somewhat slow the speed of decrease of the population (Cimino et al., 2016). Some birds that are expert in remote migration, such as Diomedeid and Procellariid species, are generally considered to be less affected by local habitat loss (Constable et al., 2014). However, they also respond to climate change with variable tendencies (Inchausti et al., 2003; Jenouvrier et al., 2005; Nevoux et al., 2010), although driving mechanisms remain unclear.

Local small and large populations in a large area have a certain heterogeneity in their response to habitat loss (Robertson et al., 2014; Ropert-Coudert et al., 2015; Widmann et al., 2015). Continuous monitoring and comparison of the six populations of emperor penguins in the western Ross Sea from 1983 to 2005 show that small populations are more sensitive to reduction of sea ice extent, there being no major effect on the overall level of the entire regional population (Barber-Meyer et al., 2008). After surveys of 70 penguin breeding habitats on the Antarctic Peninsula over 30 years, results indicated that the population of Adélie penguins at all locations is declining. The chinstrap penguins showed declines in the Antarctic Peninsula region though not at all locations, while numbers of gentoo penguins have increased rapidly with their range gradually expanding southward. This multilevel dynamic model cannot be explained by the single "sea ice hypothesis" (Lynch et al., 2012). Indeed, the recovery of whales, i.e. major trophic competitors, may be involved. Therefore, when evaluating the influence of habitat loss, the integration of regional survey data is essential to understand the dynamics of an entire species. To better reveal conservation hotspots, one should also assess impacts from regional and global perspectives.

The reliance on sea ice among the six species of pinnipeds in the Antarctica varies greatly. Weddell, crabeater, Ross and leopard seals are as pack-ice species, and are particularly sensitive to changes of sea ice because they need that ice for most or at least the critical stage of their life history, such as breeding, resting and molting. The southern elephant and Antarctic fur seals are ice-tolerant seals that breed, rest and molt farther north, on islands in the sub-Antarctic. Therefore, depending on life-history characteristics, population strategies and regional distributions, pinnipeds in the Antarctica have variable responses to change of sea ice extent caused by climate change (Siniff et al., 2008). Habitat extent is declining long-term on the West Antarctic Peninsula: 47% of suitable habitat for the pack-ice seals was lost from 1979 to 2011. This could cause directional changes in distribution and density of Weddell, crabeater and leopard seals (Forcada et al., 2012).

The Weddell seals live most of the time in regions close to the Antarctic continent (Shirihai and Jarrett, 2006). This species occurs principally where there is fast ice and, during the winter, makes breathing holes where the ice is thin by using their teeth (Stirling, 1969). They gather near cracks of fast ice to breed, rest and molt (Siniff et al., 2008). Therefore, the sea ice changes caused by climate change will have a strong impact on the critical habitats required for their survival and reproduction. Siniff et al. (2008) stated that the continuing decline in number of Weddell seals at Arthur Harbour, Antarctic Peninsula is considered to be related to a reduction in the amount of fast ice necessary for breeding there.

The mating and pupping season of the crabeater seal begins in spring, with a reproductive peak in October or even through early November, with the specific time varying greatly by region (Southwell et al., 2003). During this period, females must choose floating ice floes suitable for their size and physical characteristics (Siniff et al., 1979). The size of ice floes must be large enough to not break up until pups are weaned in ~4–6 weeks, because they cannot enter the water early. In addition, because the crabeater seal is possibly the most vulnerable of the four pack-ice seal species to predation, some special physical structure (such as bumpy) and adequate ice size will help protect them and their pups by leopard seals or killer whales (Visser et al., 2008). Thus, climate change can affect critical habitat of the crabeater seal by influencing the amount and topography of floating ice.

Leopard seals also need floating ice to breed, rest and molt. However, unlike the crabeater seal, they can use many different types and sizes of floating ice, and can even use a small piece of iceberg. Therefore, the sea ice change caused by climate change appears not to be a problem for their critical habitats as compared with other pack-ice seals

(Siniff et al., 2008). Nevertheless, the leopard seal is also prey of killer whales (Ainley et al., 2005) and those whales have been known to create waves that displace seals from floating ice (Visser et al., 2008). Therefore, if possible, this species also tends to inhabit larger and more protective floating ice (Siniff et al., 2008).

The southern elephant seal and Antarctic fur seal mainly breed, rest and molt on land of islands in the sub-Antarctic, so excess spring pack ice prevents their access to critical grounds. The disappearance of sea ice coupled with the retreat of ice fields and glaciers may create additional land for their molting, pupping and breeding. Therefore, the decreasing sea ice caused by climate change may be beneficial for completing their life history, and both these species may respond in ways opposite to the pack-ice species. However, they might also be affected most directly by changes in their food resources owing to other factors, such as fisheries (Siniff et al., 2008).

The biology of the Ross seal, including its distribution, population, and diet composition, is still very unclear. Therefore, the impacts of global change on this species remains unknown. Climate change may impact this species through the size of ice floes, which provide a crucial breeding platform or protection during the breeding and molting period (Siniff et al., 2008).

3.2 Change of population dynamics

As noted, various Antarctic birds (especially penguins) and seals can be considered "indicator species" given their sensitivity to environmental change. The fecal droppings of these species affect the soil and terrestrial catchments surrounding their colonies, and coupled with accumulation in datable layers, can provide excellent means to study change of the Antarctic ecological environment (Sun et al., 2000a, 2000b; Sun and Xie, 2001; Sun et al., 2002, 2004; Hu et al., 2013). Using fecal sediments, Sun et al. (2000a, 2004) established historical population dynamics of penguins and seals at King George Island, Antarctica, and studied their relationships with climate change. The results for the Adélie Penguin show decreasing numbers under cold conditions of the neoglacial period of 2300–1800 years ago. However, 1800–1400 years ago, when the climate was relatively warm, the number of penguins increased. Conditions either side of the optimum for the species, either too warm or too cold negatively affect penguin survival, reducing their population (Smith et al., 1999; Sun et al., 2000a; Sun and Xie, 2001; Hu et al., 2013). Research into sediments of Mochou Lake, Larsemann Hills, East Antarctica, show that the number of penguins has been declining overall for the past 2000 years, and this trend is consistent with the harsh climate in this area (Liu et al., 2007).

Using wavelet analysis, Jenouvrier et al. (2005) showed that the populations of the southern fulmar, snow petrel and emperor penguins in Terre Adélie over the past 40 years have fluctuated with a periodicity of 3–5 years, which is consistent with the change of sea-ice extent as affected by the Southern Oscillation. In another model, which synthesized anomalous atmospheric temperature in the Antarctic Peninsula region also related to the Southern Oscillation, results showed that populations of 13 bird species fluctuated in concert. Among these species, population dynamics of the chinstrap and gentoo penguins were negatively correlated with the Southern Oscillation Index. The larger the temperature anomaly (the higher the temperature in summer of the previous year and lower in winter), the smaller the population. However, population dynamics of the south polar skua and brown skua were opposite to those of the penguins (Petry et al., 2016). Considering the impact on food resources, another model indicated the major drivers of population change among three penguin species on King George Island (Lima and Estay, 2013). These included climate warming, change of sea ice extent for Adélie and gentoo penguin populations, and change of krill density for the chinstrap penguin population (Lima and Estay, 2013).

Nevertheless, it appears that in most models constructed to date trends in population trends have been explained only by local climate parameters. They ignore factors that could affect populations such as the dispersal capacity of species, genetic diversity, and phylogeographic structure (Younger et al., 2016a). Geographic analysis of king penguin populations using restriction site associated DNA (RAD) data suggested that genetic variance is very small, even for thousands of kilometers between populations. This indicates substantial gene flow between different breeding colonies (Clucas et al., 2016); this is also true for emperor and Adélie penguins (Roeder et al., 2001; Younger et al., 2017). At a smaller scale, there is also major gene flow between populations of the chinstrap penguin on the Scott Archipelago and adjacent Antarctic Peninsula, which can buffer the effect of decline in local populations (Freer et al., 2015); see also Shepherd et al. (2005) for regional patterns in the Ross Sea. Therefore, when establishing conservation programs and predicting the influence of climate change on species, we must consider the effect of strong dispersal capacity on fluctuation of local populations (Dugger et al., 2010; LaRue et al., 2013) and then strengthen the study of other species.

Adaptive characteristics of species formed during prolonged evolution and historical population dynamics are also an important influence on existing populations. Comparative genome analysis of Adélie and emperor penguins presume that their populations increased over the past 1000000 to 100000 years. However, the populations of these two penguins had different trends in glacial-interglacial cycles. Combined with comparative analysis of positive selection genes in genomes between species, results indicate that they have different adaptabilities to long-term climate change (Li et al., 2014). Based on coalescent diagnosis of mitochondrial genes and carbon isotopic dating of sedimentary fossils, the emperor penguin apparently was distributed in three isolated sanctuaries during the last glacial maximum ~25,000 years ago, forming a unique genealogy group and a population decline to its minimum. Then, during the warming of the Holocene, each genealogy group spread to new habitats, among which the group in the Ross Sea refuge increased most rapidly while maintaining its genetic uniqueness (Younger et al., 2015). At the same time, the Weddell seal, which was distributed sympatrically with the emperor penguin and also depends on fast ice, remained stable in terms of population, which might be related to their limited dispersal ability (Younger et al., 2016b).

Habitat quality is another key driver for penguin dispersal, and therefore can affect local population numbers. Research into the king penguin on Crozet Archipelago indicates that its populations in high-quality habitats have a larger inbreeding index and stronger geographic population structure, further indicating that a decline in habitat quality will promote the spread of this species. Hence, the impact of habitat quality differences on local population numbers must be considered in predicting trends of population dynamics (Cristofari et al., 2015). Conversely the improvement of habitat can encourage dispersal, as in the Adélie penguin in the Ross Sea (Emslie et al., 2007; Dugger et al., 2010; LaRue et al., 2013). Projections based on paleontological records also suggest that it is very difficult to accumulate genetic mutations that adapt to short-period rapid warming for penguins that have a long generation and slow microevolution speed. If penguins are to cope with complex environmental changes and use new niches to maintain existing habitat, they will need high phenotypic diversity. However, the specialization of species such as penguins limits their potential phenotypic change, so they tend to spread rather than adapt to environmental change such as habitat degradation (Shepherd et al., 2005; Forcada and Trathan, 2009).

Unlike seabirds, whose reproductive energy investment is limited to egg laying and incubation, marine mammals have a long gestation period whose final stage requires substantial energy expenditure by females (Gelatt et al., 2001; Forcada, 2003; Salas et al., 2017). The gestation period of Antarctic seals normally lasts from the end of one summer to the start of the next (Chen et al., 1992). Then, during lactation, mothers must transfer even more energy to their offspring. Post-parturient female Weddell seals, with an average weight of 405 kg, can lose >45% of their body weight during this period (Tedman and Greeb, 1987; Testa et al., 1989). The lactation period for the true seals (Weddell, Ross, crabeater, leopard, and southern elephant seals) in the Antarctica lasts about one month. During this period, females usually stop feeding and mainly rely on their accumulated energy reserve in the form of a lipid layer during the gestation stage to maintain their bodily metabolism (Wheatley et al., 2008; Campagna et al., 2010). This period lasts approximately four months for the Antarctic fur seal. During the lactation period in that species , females need to feed frequently and then convert most of the energy input into milk to suckle their offspring. Therefore, the global changes altering environmental conditions and food availability will have greater effects on the reproduction success of pinnipeds, thereby influencing their population dynamics.

The population dynamics of Weddell seals are closely related to environmental conditions (Siniff et al., 2008; Garrott et al., 2012). The relationship between those dynamics and climate to some degree can be explained by the change of sea ice caused by climate change. Cameron and Siniff (2004) reporting one aspect of long-term research on Weddell seals in McMurdo Sound, showed that relationships with several ice-related influences on population trends, behavior and physiology have become obvious. For Weddell seals, the change of sea ice (extended or depleted) will have a negative influence on their population. After a large portion of the Ross Ice Shelf broke off in late 2000, a large number of icebergs blocked the usual advection of sea ice from McMurdo Sound, which increased the extent, thickness and seasonal persistence of fast ice. As a result, female adults breeding there temporarily decreased, with fewer pups born. It was not until 2006 that the effect of the icebergs completely disappeared and the number of young pups born each year returned to previous levels. There are as well other factors, such as food availability that can affect these seals (Salas et al., 2017). On the contrary, a reduction in the amount of fast ice in Arthur Harbour, Antarctic Peninsula can decrease locations required for the breeding of Weddell seals, which has caused their number to gradually decline in the past few decades (Siniff, et al., 2008). In addition, Testa et al. (1991) found a relationship between the population dynamics of Weddell seals and ENSO by linking climatological patterns to those dynamics.

The crabeater seal usually breeds on ice floes. The size and physical characteristics of those floes have a great effect on their breeding success. Among the four species of pack-ice seals in the Antarctica (Weddell, Ross, crabeater and leopard seals), the crabeater seal may be the most vulnerable to predation, with leopard seals and killer whales constantly threatening individuals in all age classes (Siniff et al., 2008). In almost every region of the Southern Ocean, a very large proportion (60%–70%) of crabeater seals have scars that indicate escape from predators (Siniff and Stone, 1985). Therefore, in the area where ice floes have decreased or are continuing to do so, the population of crabeater seals may decline because of a reduction of breeding platforms and sites protected against their predators (Siniff et al., 2008; Costa et al., 2010). Forcada et al. (2012) indicated that crabeater seals were more abundant where sea ice concentration was high and pack ice was closer to the shelf break, and the distribution and population density decreased with the loss of apparently suitable habitat for this species. In addition, the reduction of sea ice seriously affects the survival and breeding performance of seals by reducing their food supply (Pistorius et al., 1999), which would affect change of seal population dynamics.

Fluctuation in seal demography has a strong relationship with SAM (Forcada et al., 2005, 2008). The SAM modulates the availability of Antarctic krill (*Euphausia superva*), a keystone species and one of the main foods of crabeater and a few other seal species, by impacting the local ecosystem (Meredith et al., 2008). McMahon et al. (2015) showed that yearling survival of southern elephant seals on Heard Island correlated with the SAM. Using results of long-term research of a declining population of Antarctic fur seals in the South Atlantic, Forcada and Hoffman (2014) found that climate change caused by SAM conditions, typically associated with high sea surface temperature, decreased prey availability for this species and drastically reduced pup birth rate and body mass. Over the 27 years from 1985 to 2012, the average birth weight of female pups declined by 7.8% (Forcada and Hoffman, 2014). In addition, continuous food pressure has reduced survival and breeding rates of young seals, and increased the age of first breeding for females (Eberhardt，2002; Forcada and Hoffman, 2014).

3.3 Change of food resources

In birds, the utilization of different food resources is a critical factor affecting their ability to cope with climate change. The sympatric species gentoo and chinstrap penguins have major differences in the specificity of food. Chinstrap penguins almost exclusively feed on krill, whereas >20% of the gentoo penguin’s diet is contributed by several fish species. This could be one of the reasons why these two species have shown an opposite trend with a decline in the availability of krill (Polito et al., 2015). Food supplementation experiments for Adélie penguins suggest that the weight of chicks which included 17% of three-year old silverfish (*Pleuragramma antarcticum*) in their diet was 5% heavier than chicks feeding only on krill. This increase in weight may compensate the decline of parental feeding frequency caused by food shortages and negative effects of reduced suitable habitat for chicks caused by snowfall (Chapman et al., 2011). Stable isotope analysis of historical samples of two species in Procellariidae, which mainly feed on zooplankton, indicated that ^{15}N in their food had a significant downward trend over the past century. This may be associated with the decline of marine productivity caused by climate change, or with alteration of trophic levels by change of food species (Ainley et al., 2006; Grecian et al., 2016). In recent years, the regional decline of marine productivity has become the major influence on the survival of birds in the Antarctica (Lea et al., 2006).

In regard to seals, frequent EI Niño events were likely associated with low-availability of krill for foraging females during the breeding period. This has resulted in extreme reductions in Antarctic fur seal pup production over 20 years at South Georgia (Forcada et al., 2005). However, EI Niño has had opposite effects on the southern elephant seal. Oscillations caused by EI Niño boost the abundance of squid, one of the main prey species of that seal. This appeared to create more abundant food for both mother and offspring and aid survival of yearlings in the Macquarie Island population (McMahon and Burton, 2005).

The change of sea ice caused by climate change poses a new challenge to the survival of Antarctic wildlife by influencing the local food web (Korczak-Abshire, 2010). Decreasing food will affect the breeding parameters of seals, such as female reproductive success and the birth weight and survival rate of pups, which will eventually affect their population dynamics. Using research into Weddell seals in Erebus Bay over two decades, Hadley et al. (2007) indicated that the pup birth rate was lower when sea ice extent was greater in the previous year’s summer, and that greater sea ice extent during this post-weaning period would reduce the foraging success of pregnant females. The reason for this (decreased foraging success with more pack ice) may have something to do with reduced open water available for phytoplankton blooms and primary productivity (Arrigo and van Dijken, 2004), which would eventually affect the availability of fish (Siniff et al., 2008). In support of this mechanism, using research over a 30-year period in the Ross Sea, Proffitt et al. (2007) proved that foraging success of pregnant Weddell seals (reflected by weaning mass of their pups the following year) increased during summers with reduced sea-ice cover. As a principal food of Weddell seals, silverfish along the western Antarctic Peninsula is decreasing because of climate change (Ruck et al., 2014). In addition, the apparent population decrease of these seals around Victoria Land is considered to be related to change in its food, such as the recent depletion by commercial fishing of the Antarctic toothfish (*Dissostichus mawsoni*), another major prey species of Weddell seals (Ainley et al., 2015; Salas et al., 2017).

The crabeater seal has evolved into a specialist in its foraging habits and predation on abundant Antarctic krill and ice krill (*E. crystallorophias*) in the Southern Ocean. Krill contributes 90% to the crabeater seal diet (Forcada et al., 2012). In accord with this diet specialization, this seal has a uniquely adapted, sieve-like tooth structure specifically to filter krill from seawater (Adam, 2005). Major changes in the Southern Ocean, especially to sea ice cover, will influence the available biomass of krill and impact the crabeater seal (Croxall et al., 2002) and other species. The change of sea-ice extent is a key influence on krill stock (Atkinson et al., 2004). Antarctic krill are strongly dependent on sea ice, particularly during winter when young krill feed under that ice, where they can obtain plentiful microbial organisms and protect themselves from predators (Fraser and Hofmann, 2003; Atkinson et al., 2004). Thus, krill prevalence will decrease with the disappearance of local sea ice (Atkinson et al., 2004). Therefore, the region where sea ice has and will continue to decrease should reveal reduced crabeater seal abundance (Siniff et al., 2008).

In addition, the local marine web has changed because of overfishing by humans of large predators in the Southern Ocean, especially whales, seals and fish (Laws, 1977; Reid et al., 2006; Ainley and Blight, 2009; Korczak-Abshire, 2010; Marschoff et al., 2012; Barrera-Ora et al., 2017). Because of the quantities of large fish and baleen whales killed by humans, seal populations were decimated but now are recovering. At present, the Antarctic krill fishery is increasing its catch amount and the fishing method is becoming more advanced. The annual per capita human consumption of Antarctic krill held steady around 120000 tons for 17 years until 2009, but has recently increased to >200000 tons (Nicol et al., 2012). In addition, the rapid decline of sea ice near the Antarctic Peninsula has created more open waters, which will promote fishery expansion either in time or in space (Forcada et al., 2012). Therefore, it is critical to further strengthen research into fishery impacts on these species.

The leopard seal is one of the largest predators in Antarctica and its diet changes seasonally and spatially, with a particular focus on crabeater seal pups in spring, switching to fledgling penguins when they go to the sea in late summer. The leopard seal sometimes feeds mainly on krill during winter (Siniff et al., 2008). In addition, fish are a common prey for this species and can be consumed year round. Therefore, given the diversity of food resources for leopard seals, the impact of climate change on food of this species is relatively weak (Forcada, 2008). Even so, this seal is also facing the risk of decreasing prey abundance with change of the food chain during periods of abnormal climate. Furthermore, the dispersal of leopard seals after reproduction is often accompanied by the change of sea ice driven by climate change (Testa et al., 1991; Jossop et al., 2004). In years with higher temperature and smaller ice extent, this type of dispersal will also change. The number of leopard seals migrating to breeding grounds of penguins and Antarctic fur seals in the Antarctica and sub-Antarctic will decrease rapidly. This situation is related to the decrease of krill abundance in penguin breeding grounds caused by higher water temperature and smaller sea ice extent (Fraser and Hofmann, 2003), which may reduce food for the leopard seal (Forcada, 2008).

The change of food resources caused by climate change may also modify the ratio of heterozygosity in the population of marine mammals. Forcada and Hoffman (2014) showed that climate change has caused breeding female heterozygosity of Antarctic fur seals in the South Atlantic to increase by 8.5% per generation over the last two decades. It appears that females with greater heterozygosity are better adapted to less prey availability conditions caused by climate change and, as a result, have better breeding performance.

4 Other impacts on Antarctic birds and marine mammals

The change of physical environment caused by global change, such as the retreat of sea ice extent and increase of water and air temperature, will fast-forward the geographic expansion of marine fisheries (Forcada et al., 2012). More intensive fisheries in the Southern Ocean may not only directly injure marine birds and mammals by strikes or incidental catches (Arnold et al., 2006; Riddle, 2009) but also may disrupt the equilibrium of certain marine ecosystems and thereby change the food density and distribution of marine birds and mammals. This will in turn modify their feeding grounds. Meanwhile, long-range atmospheric transport and increased human activities in certain areas of the Antarctic continent and Southern Ocean, such as those of people visiting the Antarctica as either tourists or researchers that are part of a national Antarctic program, will increase the risk of physical disturbance, disease and pollution (Geraci and Lounsbury, 2009; Pook, 2009; Wang et al., 2012; Zhang et al., 2015).

In recent years, several disease have been identified in Antarctic birds and seals (Grimaldi et al., 2011, 2015; Varsani et al., 2014). The canine distemper virus found in crabeater seals was possibly introduced by Greenland sled dogs (Bengtson et al., 1991). *Babesia* sp. have been found parasitizing the blood of the chinstrap penguin for the first time in 2016, with an infection rate >20%. This type of disease, which is transmitted via blood sucking of Antarctic ticks, may seriously affect the survival of birds in the Antarctica, which lack corresponding immune defenses (Montero et al., 2016). Epidemiology surveys of gentoo and chinstrap penguins during 2008–2013 showed that a new type of adenovirus is widely prevalent among their populations (Lee et al., 2016). Are these new diseases associated with climate change? What is their prevalence in other Antarctic birds and marine mammals? What is the effect on animal fitness? These will be important questions in analyzing the reasons for population dynamics change and forecast study. In the Antarctic terrestrial ecosystem, some species respond to climate warming while coping with increasing non-native species introduced by humans, especially in sub-Antarctic regions (Walther et al., 2002). In addition, they may confront continuous competition from temperate invasive species and increased predators which could be blocked by large-scale sea ice or water temperature and never meet them (Pook, 2009).

Birds and pinnipeds that feed in the sea and return to land to live and breed are the upper trophic level consumers in the ecosystem. Increased vessels and other vehicles not only influence the hearing and communications of marine mammals (Riddle, 2009) but also bring more pollution such as heavy metals and persistent organic pollutants, which may enter the bodies of birds and marine mammals via the food chain and have far-reaching effects (Gadamus, 2013).

Comparison of the number of erythrocytic nuclear abnormalities (ENAs) in populations of three penguin species shows that the Adélie penguin has the largest proportion of ENAs and significant geographic differences with populations of the chinstrap penguin. However, the gentoo penguin did not show the same tendency, implying that species exhibit different environmental resilience at the cellular level (De Mas et al., 2015). Coupled with the different baseline of cell metabolic level across species (Ibañez et al., 2015), these factors should be considered when assessing the risks of species in their response to environmental changes.

The population ecology of penguins and seals is closely related to changes of climate and environment in Antarctica and the Southern Ocean. To better understand population development trends of supernatants in the Southern Ocean ecosystem under the influence of future global change, it is useful to research ecological change of penguins and seals over historical periods. In the past, research into ecological change concerning penguins and seals in the Antarctica has been based on field investigation and satellite remote sensing, but this has lacked long-term ecological change data. However, Sun et al. (2000a), Hodgson and Johnston (1997), Emslie and Patterson (2007) analyzed the relative population size of penguins and seals and change of trophic level in the diet of penguins using biological remains (fecal sediments, seal hair, penguin tissues, and eggshells) found in lacustrine sediments and abandoned penguin lair deposits. They studied relationships between the population development history of penguins and seals and climate change, such as the variation of glaciers and human activity. This indicated that sediments with a time sequence, such as biological feces, seal hair, penguin eggshells, and bone fragments and feathers in the sediments, are effective means to study changes of the ecological environment in the Antarctica during a historical period.

Overall, global change has caused many alterations to Antarctic birds and mammals, but the impact has mainly been on a number of species in a few areas, and the response mechanisms of these species remain very limited. This demands further long-term and continuous monitoring and research.

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References

Adam P J. 2005. *Lobodon carcinophaga*. Mamm Species, 772: 1–14

Ainley D G, Ballard G, Karl B J, Bugger K T. 2005. Leopard seal predation rates at penguin colonies of different size. Antarct Sci, 17: 335–340

Ainley D G, Hobson K A, Crosta X, et al. 2006. Holocene variation in the Antarctic coastal food web: linking δD and $\delta^{13}C$ in snow petrel diet and marine sediments. Mar Ecol Prog Ser, 306: 31–40

Ainley D G, Blight L K. 2009. Ecological repercussions of historical fish extraction from the southern ocean. Fish and Fish, 10(1): 13–38

Ainley D, Russell J, Jenouvrier S, et al. 2010. Antarctic penguin response to habitat change as Earth's troposphere reaches 2 degrees C above preindustrial levels. Ecol Monogr, 80(1): 49–66

Ainley D G, LaRue M A, Stirling I, et al. 2015. An apparent population decrease, or change in distribution, of Weddell seals along the Victoria Land coast. Mar Mammal Sci, 31(4): 1338–1361

Ainley D G, Woehler E J, Lescroël A. 2017. Birds and Antarctic sea ice// Thomas D N. Sea Ice. London: John Wiley and Sons, Ltd, 570–582

Arrigo K R, van Dijken G L. 2004. Annual changes in sea ice, chlorophyll a, and primary production in the Ross Sea, Antarctica. Deep Sea Res PT II, 51: 117–138

Arnold J M, Brault S, Croxall J P. 2006. Albatross populations in peril: A population trajectory for black-browed albatrosses at South Georgia. Ecol Appl, 16(1): 419–432

Atkinson A, Siegel V, Pakhomov E, et al. 2004. Long-term decline in krill stock and increase in slaps within the Southern Ocean. Nature, 432: 100–103

Barber-Meyer S M, Kooyman G L, Ponganis P J. 2008. Trends in western Ross Sea emperor penguin chick abundances and their relationships to climate. Antarct Sci, 20(1): 3–11

Baroni C, Orombelli G. 1994. Abandoned penguin rookeries as Holocene paleoclimatic indicators in Antarctica. Geology, 22(1): 23–26

Barbraud C, Weimerskirch H. 2006. Antarctic birds breed later in response to climate change. P Natl Acad Sci USA, 103(16): 6248–6251

Barbraud C, Rivalan P, Inchausti P, et al. 2011. Contrasted demographic responses facing future climate change in Southern Ocean seabirds. J Anim Ecol, 80(1): 89–100

Barrera-Ora E, Marchoff E, Ainley D. 2017. Changing status of three notothenioid fish at the South Shetland Islands (1983–2016) after impacts of the 1970–80s commercial fishery. Polar Biol, doi: 10.1007/s00300-017-2125-0

Bengtson J L, Boveng P, Franzén U, et al. 1991. Antibodies to canine distemper virus in Antarctic seals. Mar Mamm Sci, 7(1): 85–87

Cameron M F, Siniff D B. 2004. Age-specific survival, abundance, and immigration rates of a Weddell seal (*Leptonychotes weddellii*) population in McMurdo Sound, Antarctica. Can J Zool, 82: 601–615

Campagna C, Lewis M, Baldi R. 2010. Breeding biology of southern elephant seals in Patagonia. Mar Mammal Sci, 9(1): 34–47

Chen W Q, Zheng C L, Zhang Q X. 1992. Marine mammals. Qingdao: Qiaodao Ocean Universtiy Press (in Chinese)

Chapman E W, Hofmann E E, Patterson D L, et al. 2011. Marine and terrestrial factors affecting Adélie Penguin *Pygoscelis adeliae* chick growth and recruitment off the western Antarctic Peninsula. Mar Ecol Prog Ser, 436: 273–289

Cimino M A, Fraser W R, Irwin A J, et al. 2013. Satellite data identify decadal trends in the quality of Pygoscelis penguin chick-rearing habitat. Global Change Biol, 19(1): 136–148

Cimino M A, Lynch H J, Saba V S, et al. 2016. Projected asymmetric response of Adélie penguins to Antarctic climate change. Sci Rep-UK, 6: 28785

Clucas G V, Younger J L, Kao D, et al. 2016. Dispersal in the sub-Antarctic: king penguins show remarkably little population genetic differentiation across their range. Bmc Evol Biol, 16: 211

Constable A J, Melbourne-Thomas J, Corney S P, et al. 2014. Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. Global Change Biol, 20(10): 3004–3025

Cook A J, Vaughan D G. 2010. Overview of areal changes of the ice shelves on the Antarctic Peninsula over the past 50 years. The Cryosphere, 4: 77–98

Costa D P, Crocker D E. 1996. Marine mammals of the Southern Ocean. Antarct Res Ser, 70: 287–301

Costa D P, Huckstadt L A, Crocker D E, et al. 2010. Approaches to studying climate change and its role on the habitat selection of Antarctic pinnipeds. Integr Comp Biol, 50(6): 1018–1030

Cristofari R, Trucchi E, Whittington J D, et al. 2015. Spatial Heterogeneity as a Genetic Mixing Mechanism in Highly Philopatric Colonial Seabirds. Plos One, 10(2): e0117981

Croxall J P, Callaghan T, Cervellati R, et al. 1992. Southern ocean environmental change: effects on seabird, seal and whale population [and Discussion]. Philos T R Soc B, 38: 319–328

Croxall J P, Trathan P N, Murphy E J. 2002. Environmental change and Antarctic seabird populations. Science, 297: 1510–1514

Deborah T, Chester E T, Moore S E, et al. 2004. Seasonal variability in whale encounters in the Western Antarctic Peninsula. Deep Sea Res PT II, 51: 2311–2325

De Mas E, Benzal J, Merino S, et al. 2015. Erythrocytic abnormalities in three Antarctic penguin species along the Antarctic Peninsula: biomonitoring of genomic damage. Polar Biol, 38(7): 1067–1074

Dugger K M, Ainley D G, Lyver P O B., et al. 2010. Survival differences and the effect of environmental instability on breeding dispersal in an Adélie penguin meta-population. Proc Natl Acad Sci, 107(27): 12375–12380

Eberhardt L L. 2002. A paradigm for population analysis of long-lived vertebrates. Ecology, 83: 2841–2854

Emmerson L, Southwell C. 2008. Sea ice cover and its influence on Adélie Penguinreproductive performance. Ecology, 89(8): 2096–2102

Emslie S D, Patterson W P. 2007. Abrupt recent shift in $\delta^{13}C$ and $\delta^{15}N$ values in Adélie penuin eggshell in Antarctica. Proc Natl Acad Sci, 104(28): 11666–11669

Emslie S D, Coats L, Licht K. 2007. A 45,000 yr record of Adélie penguins and climate change in the Ross Sea, Antarctica. Geol, 35: 61–64

Forcada J, Trathan P N, Reid K, et al. 2005. The effects of global climate variability in pup production of Antarctic fur seals. Ecology, 86: 2408–2417

Forcada J, Trathan P N, Reid K, et al. 2006. Contrasting population changes in sympatric penguin species in association with climate warming. Global Change Biol, 12(3): 411–423

Forcada J. 2008. The impact of climate change on Antarctic megafauna// Duarte C M. Impacts of global warming on polar ecosystem. Bilbao: Fundación, 84–112

Forcada J, Trathan P N, Murphy E J. 2008. Life history buffering in Antarctic mammals and birds against changing patterns of climate and environmental variation. Global Change Biol, 14: 2473–2488

Forcada J, Trathan P N. 2009. Penguin responses to climate change in the Southern Ocean. Global Change Biol, 15(7): 1618–1630

Forcada J, Trathan P N, Boveng P , et al. 2012. Response of Antarctic pack-ice seals to environmental change and increasing krill fishing. Biol Conserv, 149: 40–50

Forcada J, Hoffman J I. 2014. Climate change selects for heterozygosity in a declining fur seal population. Nature, 511: 462–465

Freer J J, Mable B K, Clucas G, et al. 2015. Limited genetic differentiation among chinstrap penguin (*Pygoscelis antarctica*) colonies in the Scotia Arc and Western Antarctic Peninsula. Polar Biol, 38(9): 1493–1502

Fraser W R, Hofmann E E. 2003. A predator's perspective on causal links between climate change, physical forcing and ecosystem response. Mar Ecol Prog Ser, 265: 1–15

Fretwell P T, LaRue M A, Morin P, et al. 2012. An Emperor Penguin Population Estimate: The First Global, Synoptic Survey of a Species from Space. Plos One, 7(4): e33751

Gadamus L. 2013. Linkages between human health and ocean health: a participatory climate change vulnerability assessment for marine mammal harvesters. Int J Circumpol Heal, 72(72): 759–765

Garrott R A. Rotella J J, Siniff D B, et al. 2012. Environmental variation and cohort effects in an Antarctic predator. Oikos, 121: 1027–1040

Gelatt T S, Davis C S, Siniff D B, et al. 2001. Molecular evidence for twinning in Weddell seals (*Leptonycotes weddellii*). J Mammal, 82(2): 491–499

Geraci J R, Lounsbury V J. 2009. Risk of marine mammal die-offs in the Southern ocean//Kerry K R, Riddle M J. Health of Antarctic wildlife: A challenge for science and policy. German: Springer Berlin Heidelberg, 13–34

Grecian W J, Taylor G A, Loh G, et al. 2016. Contrasting migratory responses of two closely related seabirds to long-term climate change. Mar Ecol Prog Ser, 559: 231–242

Grimaldi W, Jabour J, Woehler E J. 2011. Considerations for minimising the spread of infectious disease in Antarctic seabirds and seals, Polar Rec*,* 47(240): 56–66

Grimaldi W W, Seddon P J, Lyver P O'B, et al. 2015. Infectious diseases of Antarctic penguins: current status and future threats. Polar Biol*,* 38(5): 591–606

Hadley G L, Rotella J J, Garrott R A. 2007. Evaluation of reproductive costs for Weddell seals in Erebus Bay, Antarctic. J Anim Ecol, 76: 448–458

Hodgson D A, Johnston N M. 1997. Inferring seal population from lake sediments. Nature, 387(6628):30–31

Hu Q H, Sun L G, Xie Z Q, et al. 2013. Increase in penguin populations during the Little Ice Age in the Ross Sea, Antarctica. Sci Rep-UK, 3(7463): 2472

Huang T, Sun L G, Wang Y H, et al. 2014. Paleodietary changes by penguins and seals in association with Antarctic climate and sea ice extent. Chinese Sci Bull, 59(33): 4456–4464

Ibañez A E, Najle R, Larsen K, et al. 2015. Haematological values of three Antarctic penguins: gentoo (*Pygoscelis papua*), Adélie (*P. adeliae*) and chinstrap (*P. antarcticus*). Polar Res, 34: 25718

Inchausti P, Guinet C, Koudil M, et al. 2003. Inter-annual variability in the breeding performance of seabirds in relation to oceanographic anomalies that affect the Crozet and the Kerguelen sectors of the Southern Ocean. J Birds Biol, 34(2): 170–176

IPCC. 2007. Climate Change 2007-the physical science basis.

Observations: snow, ice and frozen ground. Cambridge: Cambridge University Press, 337–385

IUCN. 2017. Red List of Threatened Species. [2017-08-08]. http://www.iucnredlist.org

Jenouvrier S, Weimerskirch H, Barbraud C, et al. 2005. Evidence of a shift in the cyclicity of Antarctic seabird dynamics linked to climate. P Roy Soc B-Biol SCI, 272(1566): 887–895

Jossop M J, Forcada J, Reid K, et al. 2004. Winter dispersal of Leopard seals (*Hydrurga leptonyx*): environmental factors influencing demographics and seasonal abundance. J Zool, 263: 251–258

Korczak-Abshire M. 2010. Climate change influences on Antarctic bird populations. Papers on Global Change IGBP, 17(1): 53–66

Varsani A, Porzig E L, Jennings S, et al. 2015. Identification of an avian polyomavirus associated with Adélie penguins (*Pygoscelis adeliae*). J Gen Virol, 96(Pt 4): 851–857

LaRue M A, Ainley D G, Swanson M, et al. 2013. Climate change winners: receding ice fields facilitate colony expansion and altered dynamics in an Adélie Penguin metapopulation. Plos One, 8(4): e60568

Laws R M. 1977. Seals and whales of the Southern Ocean. Philos T R Soc B, 279: 81–96

Laws R M. 1984. Seals// Laws R M. Antarctic Ecology. London: Academic Press, 62l–7l5

Lea M A, Guinet C, Cherel Y, et al. 2006. Impacts of climatic anomalies on provisioning strategies of a Southern Ocean predator. Mar Ecol Prog Ser, 310: 77–94

Lee S Y, Kim J H, Seo T K, et al. 2016. Genetic and Molecular Epidemiological Characterization of a Novel Adenovirus in Antarctic Penguins Collected between 2008 and 2013. PloS One, 11(6): e0157032

Lee J R, Raymond B, Bracegirdle T J, et al. 2017. Climate change drives expansion of Antarctic ice-free habitat. Nature, 547: 49–54

Li C, Zhang Y, Li J, et al. 2014. Two Antarctic penguin genomes reveal insights into their evolutionary history and molecular changes related to the Antarctic environment. Gigascience, 3(1): 27

Li T, Ding Y F, Zhao T C, et al. 2016. Iceberg calving from the Antarctic Nansen Ice Shelf in April 2016 and its local impact. Sci Bull, 61(15): 1157–1159

Lima M, Estay S A. 2013. Warming effects in the western Antarctic Peninsula ecosystem: the role of population dynamic models for explaining and predicting penguin trends. Popul Ecol, 55(4): 557–565

Liu X D, Sun L G, Xie Z Q, et a1. 2007. A preliminary record of the historical seabird population in the Larsemann Hills, East Antarctica, from geochemical analyses of Mochou Lake sediments. Boreas, 36(2): 182–197

Lynch H J, Naveen R, Trathan P N, et al. 2012. Spatially integrated assessment reveals widespread changes in penguin populations on the Antarctic Peninsula. Ecology, 93(6): 1367–1377

Maffei M C. 1997. The international convention for the regulation of whaling. The Int J Mar Coastal Law, 12(3): 287–305

Marschoff E R, Barrera-Oro E R, Alescio N S, et al. 2012. Slow recovery of previously depleted demersal fish at the South Shetland Islands, 1983–2010. Fish Res, 125/126(4): 206–213

Massom R A, Hill K, Barbraud C, et al. 2009. Fast ice distribution in Adélie Land, East Antarctica: interannual variability and implications for emperor penguins Aptenodytes forsteri. Mar Ecol Prog Ser, 374: 243–257

Massom R A, Stammerjohn S E. 2010. Antarctic sea ice change and variability–physical and ecological implications. Polar Sci, 4, 149–186

McClintock J, Ducklow H, Fraser W. 2008. Ecological responses to climate change on the Antarctic Peninsula. Am Sci, 96: 302–310

McMahon C R, Burton H R. 2005. Climate change and seal survival: evidence for environmentally mediated changes in elephant seal, *Mirounga leonina*, pup survival. P Roy Soc B-Biol Sci, 272: 923–928

McMahon C R, New L F, Fairley E J, et al. 2015. The effects of body size and climate on post-weaning survival of elephant seals at Heard Island. J Zool, 297(4): 301–308

Meredith M P, Murphy E J, Hawker E J, et al. 2008. On the interannual variability of ocean temperatures around South Georgia, Southern Ocean: Forcing by El Niño/Southern Oscillation and the Southern Annular Mode. Deep Sea Res PT II, 55: 2007–2022

Montero E, Miguel Gonzalez L, Chaparro A, et al. 2016. First record of *Babesia* sp in Antarctic penguins. Ticks Tick-Borne Dis, 7(3): 498–501

Moore M J, Berrow S D, Jensen B A, et al. 1999. Relative abundance of large whales around South Georgia (1979–1998). Mar Mammal Sci, 15: 1287–1302

Moore S E, Huntington H P. 2008. Arctic marine mammals and climate change: impacts and resilience. Ecol Appl, 18(2): S157–S165

Mulvaney R, Abram N J, Hindmarsh R C A, et al. 2012. Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history. Nature, 489: 141–144

Nevoux M, Weimerskirch H, Barbraud C. 2010. Long- and short-term influence of environment on recruitment in a species with highly delayed maturity. Oecologia, 162(2): 383–392

Nicol S, Foster J, Kawaguchi S. 2012. The fishery of Antarctic krill-recent developments. Fish Fish, 13: 30–40

Petry M V, Valls F C L, Petersen E D S, et al. 2016. Breeding sites and population of seabirds on Admiralty Bay, King George Island, Antarctica. Polar Biol, 39(7): 1343–1349

Pistorius P A, Bester M N, Kirkman S P. 1999. Survivorship of a declining population of southern elephant seals. *Mirounga leonine*, in relation to age, sex, and cohort. Oecologia, 121: 201–211

Polito M J, Trivelpiece W Z, Patterson W P, et al. 2015. Contrasting specialist and generalist patterns facilitate foraging niche partitioning in sympatric populations of *Pygoscelis* penguins. Mar Ecol Prog Ser, 519: 221–237

Pook M. 2009. Antarctic climate, weather and the health of Antarctic wildlife//Kerry K R, Riddle M J. Health of Antarctic wildlife: A challenge for science and policy. German: Springer Berlin Heidelberg, 13–34

Proffitt K M, Garrott R A, Rotella J J, et al. 2007. Exploring linkages between abiotic oceanographic processes and a top-trophic predator in an Antarctic ecosystem. Ecosystems, 10: 119–126

Reid K, Davis D, Staniland I J. 2006. Spatial and temporal variability in the fish diet of Antarctic fur seal (*Arctocephalus gazella*) in the Atlantic sector of the Southern Ocean. Can J Zool, 84: 1025–1037

Riddle M J. 2009. Huamn-mediated impacts on the health of Antarctic wildlife//Kerry K R, Riddle M J. Health of Antarctic wildlife: A challenge for science and policy. German: Springer Berlin Heidelberg, 13–34

Robertson G, Wienecke B, Emmerson L, et al. 2014. Long-term trends in the population size and breeding success of emperor penguins at the Taylor Glacier colony, Antarctic. Polar Biol, 37(2): 251–259

Roeder A D, Marshall R K, Mitchelson A J, et al. 2001. Gene flow on the ice: genetic differentiation among Adélie penguin colonies around Antarctica. Mol Ecol, 10: 1645–1656

Ropert-Coudert Y, Kato A, Meyer X et al. 2015. A complete breeding failure in an Adélie penguin colony correlates with unusual and extreme environmental events. Ecography, 38: 111–113

Ruck K E, Steinberg D K, Canuel E A. 2014. Regional differences in quality of krill and fish as prey along the Western Antarctic Peninsula. Mar Ecol Prog Ser, 509: 39–55

Salas L, Nur N, Ainley D, et al., 2017. Coping with the loss of large, energy-dense prey: a potential bottleneck for Weddell Seals in the Ross Sea. Ecol Appl, 27(1): 10–25

Shepherd L D, Millar C D, Ballard G, et al. 2005. Microevolution and mega-icebergs in the Antarctic. Proc Natl Acad Sci, 102 (46): 16717–16722

Shirihai H, Jarrett B. 2006. Whales, dolphins, and other marine mammals of the world. New Jersey: Princeton University Press

Siniff D B, Stirling I, Bengtson J L, et al. 1979. Social and reproductive behaviour of Crabeater seals (*Lobodon carcinophagus*) during the austral spring. Can J Zool, 57: 2243–2255

Siniff D B, Stone S. 1985. The role of the Leopard seal in the tropho-dynamics of the Antarctic marine ecosystem//Siegfried W R, Condy P R, Laws R M. Antarctic nutrient cycles and food webs. Berlin: Springer, 498–515

Siniff D B, Garrott R A, Rotella J J, et al. 2008. Projecting the effects of environmental change on Antarctic seals. Antarct Sci, 20(5): 425–435

Smith R C, Ainley D, Baker K, et al. 1999. Marine ecosystem sensitivity to historical climate change. BioScience 49(5): 393–404

Southwell C, Kerry K, Ensor P, et al. 2003. The time of pupping by pack-ice seals in East Antarctica. Polar Biol, 26: 648–652

Stammerjohn S E, Martinson D G, Smith R C, et al. 2008. Trends in Antarctic annual ice retreat and advance and their relation to ENSO and Southern Annular Mode Variability. J Geophys Res, 113: C03S90

Stenson G B, Buren A D, Koen-Alonso M. 2016. The impact of changing climate and abundance on reproduction in an ice-dependent species, the Northwest Atlantic harp seal, *Pagophilus groenlandicus*. ICES J Mar Sci, 73(2): 250–262

Stirling I. 1969. Tooth wear as a mortality factor in the Weddell seal (*Leptonychotes weddelli*). J Mammal, 50: 559–565

Sun L G, Xie Z Q, Zhao J L. 2000a. A 3,000-year record of penguin populations. Nature, 407(6806): 858

Sun L G, Xie Z Q, Zhao J L. 2000b. The lake sediment of Ardley Island, Antarctic: Identification of penguin-dropping amended soil. Chin J Polar Res, 12(2): 105–112

Sun L G, Xie Z Q. 2001. Changes in lead concentration in Antarctic penguin dropping during the past 3,000 year. Environ Geol, 40(10): 1205–1208

Sun L G, Zhu R B, Xie Z Q, et al. 2002. Emissions of nitrous oxide and methane from Antarctic Tundra: role of penguin dropping deposition. Atmos Environ, 36(31): 4977–4982

Sun L G, Liu X D, Yin X B, et al. 2004. A 1,500-year record of Antarctic seal populations in response to climate change. Polar Biol, 27: 495–501

Sydeman W J, Poloczanska E, Reed T E, et al. 2015. Climate change and marine vertebrates. Nature, 350(6262): 772–777

Tedman R, Greeb B. 1987. Water and sodium fluxes and lactational energetics in suckling pups of Weddell seal (*Leptonychotes weddellii*). J Zool, 212: 29–42

Testa J W, Hill S E B, Siniff D B. 1989. Diving behavior and maternal investment in Weddell seals (*Leptonychotes weddellii*). Mar Mammal Sci, 5: 399–405

Testa J W, Oehlert G, Ainley, et al. 1991. Temporal variability in Antarctic marine ecosystems: periodic fluctuations in the period seals. Can J Fish Aquat Sci, 48: 631–639

Trathan P N, Forcada J, Murphy E J. 2007. Environmental forcing and Southern Ocean marine predator populations: effects of climate change and variability. Philoso T R Soc B, 362: 2351–2365

Turner J, Colwell S R, Marshall G J, et al. 2005. Antarctic climate change during the last 50 years. Int J Climatol, 25: 279–294

Varsani A, Kraberger S, Jennings S, et al. 2014. A novel papillomavirus in Adelie penguin (*Pygoscelis adeliae*) faeces sampled at the Cape Crozier colony, Antarctica. J Gen Virol, 95: 1352–1365

Vaughan D G, Marshall G J，Connolley W M，et al. 2003. Recent rapid regional climate warming on the Antarctic Peninsula. Climatic Change, 60(3): 243–274

Visser I N, Smith T G, Bullock I D, et al. 2008. Antarctic peninsula Killer whales (*Orcinus orca*) hunt seals and a penguin on floating ice. Mar Mammal Sci, 24: 225–234

Walther G R, Post E, Convey P, et al. 2002. Ecological responses to recent climate change. Nature, 416: 389–395

Wang P, Zhang QH, Wang T, et al. 2012. PCBs and PBDEs in environmental samples from King George Island and Ardley Island, Antarctica. Res Advances, 2: 1350–1355

Weimerskirch H, Brothers N, Jouventin P. 1997. Population dynamics of wandering albatross *Diomedea exulans* and Amsterdam albatross *D. amsterdamensis* in the Indian Ocean and their relationships with long-line fisheries: Conservation implications. Biol Conserv, 79(2–3): 257–270

Wheatley K E, Bradshaw C J, Harcourt R G, et al. 2008. Feast or famine: evidence for mixed capital-income breeding strategies in Weddell seals. Oecologia, 155(1): 11–20

Widmann M, Kato A, Raymond B, et al. 2015. Habitat use and sex-specific foraging behavior of Adélie penguins throughout the breeding season in Adélie Land, East Antarctica. Movement Eco, 3: 30

Younger J L, Clucas G V, Kooyman G, et al. 2015. Too much of a good thing: sea ice extent may have forced emperor penguins into refugia during the last glacial maximum. Global Change Biol, 21(6): 2215–2226

Younger J L, Emmerson L M, Miller K J. 2016a. The influence of historical climate changes on Southern Ocean marine predator populations: a comparative analysis. Global Change Biol, 22(2): 474–493

Younger J L, van den Hoff J, Wienecke B, et al. 2016b. Contrasting responses to a climate regime change by sympatric, ice-dependent predators. BMC Evol Biol, 16(1): 61

Younger J L, Clucas G V, Kao D, et al. 2017. The challenges of detecting subtle population structure and its importance for the conservation of emperor penguins. Mol Ecol, 1–15

Zhang Q H, Chen Z J, Li Y M, et al. 2015. Occurrence of organochlorine pesticides in the environmental matrices from King George Island, west Antarctica. Environ Pollut, 206:142–149