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# Climate Change and Penguin Populations: What We Know and What We Can Learn

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## ABSTRACT

Climate change is a complex concept that poses many severe threats to life on Earth as we know it. The environment is at risk of warming and more extreme weather events that will be detrimental too many organisms and forms of life. The polar regions, including the Arctic and Antarctica, are especially in jeopardy as they see faster warming rates than many other regions of the planet. This is causing peril upon many organisms and ecosystems in these areas, including penguins. While penguins are not the only organisms at risk of endangerment or extinction as a result of climate change, they are affected by it in uniquely complex ways depending on the species and their geographic location. Studying these differences and understanding how they are responding to changes in their environments is critical to avoid species endangerment and extinction. Furthermore, limiting further environmental damage and pushing for successful conservation efforts in penguin populations will aid in bringing stability to their ecosystems and the other species that exist in them.

## Introduction

Climate change is a global phenomenon with great ramifications, almost all of which have negative effects on each of the Earth's systems. These systems and the ways in which they are affected by climate change are greatly intertwined and it is critical to recognize this to understand and combat the threats that climate change poses to Earth's oceans, lands, polar regions, atmosphere, species and more.

Climate change, as defined by NASA, is "a long-term change in the average weather patterns that have come to define Earth's local, regional and global climates," and "these changes have a broad range of observed effects that are synonymous with the term." (NASA Science, n.d.). The effects of climate change are often discussed in relation to one or more of Earth's systems; higher temperatures that result from climate change typically affect the hydrosphere through ocean warming, the cryosphere through the melting of ice sheets, the geosphere through forest fires, droughts and other land-based weather events and the biosphere through the consequences of these changes on numerous species (NASA Science, n.d.).

The polar regions, which include both the Arctic and Antarctic regions, are highly studied as they are among the most severely affected regions of the world. The Antarctic peninsula, West Antarctica and some of East Antarctica have shown significant warming and are projected to continue warming at rapid rates, higher than those of other regions of the world (IPCC, 2023). Antarctic glaciers and major ice sheets have been losing mass and are predicted to continue to do so as air and water temperatures rise and rainfall increases at coastal regions (IPCC, 2023). Snowfall has and is predicted to increase as well (1PCC, 2023). Together, these will have many downstream effects on the environment and biodiversity of the Antarctic regions.

Many microbes, plants, animals, and humans will feel the effects of climate change and will likely need to adapt in order to survive. Climate change may heavily impact penguins as most of them live in Antarctica and on sub-Antarctic islands (Australian Antarctic Program, 2022), both of which are continuing to warm faster than the global rate, experiencing glacier melting, ocean warming and shrinking sea ice (Robinson, 2022). Penguins undergo many

changes related to their own behavior, genetics, and population dynamics as a result of the effects of climate change. Additionally, they need to respond to a shift in the availability of many of their main food sources and prey as the ocean warms and sea ice is lost. Considering and understanding these changes and how they may differ based on a species by species basis is critical for conservation efforts.

## Food Supply and Foraging

### Food Supply

Penguins primarily feed on small fish and krill (Australian Antarctic Program, 2022). Adélie Penguins (*Psygoscelis adeliae*) and Emperor Penguins (*Aptenodytes forsteri*) are two of the most common species living in Antarctica (Antarctica Penguins: Pictures, Facts and Information, n.d.). The Ross Sea is a known breeding site of both Adélie and Emperor penguins and both are believed to be dependent on food sources from the Ross Sea, such as plankton, krill and silverfish. The food web of the Ross Sea is influenced by the qualities of the sea ice habitat, which is threatened by climate change-related warming (Hong et al., 2021). Adélie penguins are known as a krill-dependent species but have exhibited differences in their primary food source based on the colony location. Colonies located on Cape Hallett of Antarctica consumed 95% Antarctic and ice krill, while those located on Inexpressible Island consumed a much higher proportion of Antarctic silverfish than krill (Hong et al., 2021). This suggests that the differences in prey availability by geographical location and ease of foraging greatly impact the diet of Adélie penguins. Emperor penguin colonies at various sites in Antarctica primarily consumed Antarctic silverfish, likely because they hatch and grow under sea ice which is more common near these colonies (Hong et al., 2021). Changes in the sea ice may therefore disturb this food source and force Emperor penguin colonies to rely more on krill for food or to move their breeding colonies. In marginal ice zones of the Southern Ocean around Antarctica, lowered abundance of krill at the ice edge led to Adélie penguins shifting to primarily consume silverfish (Saenz et al., 2020). When sea ice broke, the Adélie penguins diet switched back to primarily krill (Saenz et al., 2020), demonstrating that krill abundance as prey for the Adélie penguins is correlated with sea ice conditions.

Since 1970, krill abundance in the Western Antarctic Peninsula (WAP) and the adjacent Scotia Sea has declined by as much as 80% and is associated with reductions in sea ice in these regions (Trivelpiece et al., 2011). Krill is one of many species that heavily depend on sea ice for reproduction and as a habitat. Due to the shrinking of sea ice from global warming, their opportunities for reproduction dwindle and their general abundance decreases as well. As sea ice and krill availability have declined, so have populations of both chinstrap and Adélie penguins. There is great evidence that supports the hypothesis that as sea ice continue to decline as a result of climate change, chinstrap and Adélie penguin populations will decline as they are dependent on krill availability which is dependent on sea ice presence (Trivelpiece et al., 2011). Sea ice loss due to warming temperatures bodes very ill for the future projections of krill species and all other species that rely on them as a food source, including penguin species.

Many studies have predicted less abundance and declines in krill biomass as surface warming in the ocean continues. Results of studies that measured krill oxygen consumption rates demonstrate that changes in water temperature may greatly impact the krill life cycle and physiology, as both are highly dependent on their environment (Michael et al., 2021). The warming of Southern Ocean waters are likely to increase the metabolic rates of krill which will affect their ability to grow and reproduce; their growth appeared hindered and krill raised in higher temperature water were smaller than average (Michael et al., 2021).

Overall, both ocean surface warming and sea ice loss have negative consequences on the size, reproduction and general amount of krill available in waters near Antarctica and near penguins. Four penguin colonies in the Ross Sea and their diets were investigated to better understand the relationship between their diets and sea-ice dynamics. Adélie penguins in the Ross Sea region primarily feed on krill and Antarctic silverfish, and the availability of both food sources and other less common ones such as bald racked and other fish species are associated with sea-ice

dynamics (Maccapan et al., 2023). While adult penguin diet has been shown to vary based on prey availability and foraging conditions specific to a particular colony, penguin chick diet variability is less understood as they are dependent on adult penguins to feed them. A penguin chick's diet consists of what its parents hunt, cough up and feed into their beaks during the process of regurgitation. The adult penguins partially digest the food during transport as well. It was observed that chicks consumed more krill than fish or other prey but the percentage of krill in their diet was dependent on the amount and persistence of sea-ice found in foraging areas (Maccapan et al., 2023). When sea ice persisted, chicks also received less fish than adults, further demonstrating that sea-ice persistence is critical and that a lack of sea ice alters the penguin chicks diet, potentially threatening their survival. Threats to sea-ice from climate change may continue to have these detrimental effects on penguins and their chicks.

In addition to climate change, krill are also suffering because of human intervention as around 440,000 tons of krill have been captured by human fisheries in 2020 (Savoca et al., 2024). These numbers' estimates only increase in future projection and 40% of krill are projected to die off by the end of the 21st century (Savoca et al., 2024). It is estimated that as a species, they may collapse by the end of 2300 (Savoca et al., 2024). The loss of krill would be catastrophic for countless species that rely on them as food, including many penguin species and populations. Penguins play a diverse role in their respective ecosystems and if these trends continue, their endangerment and extinction may be imminent. Climate change has a widespread effect over countless species and many species connected to the penguins may experience severe consequences from both penguin decrease and from the external pressures of climate change. Penguins coexist in an intertwined ecosystem where every consequence on one species is another consequence for another.

## Foraging

Climate change and its affects on sea-ice formation and melt and ocean temperatures also impact the foraging behavior of penguins, also known as the way they hunt and collect food. Adélie penguins show major differences in their method of foraging based on sea ice presence near their habitats and foraging areas. During an ice free season, they were walking less and diving more to forage and the duration of their foraging trips also differed by the amount of sea ice present (Watanabe et al., 2020).

Chinstrap penguins also exhibit changes in their diving behavior based on environmental conditions. Chinstrap penguins are specialized krill foragers and use krill as a food source almost exclusively (Salmerón et al., 2023). Low sea-ice reduces food availability for krill larvae and therefore a decrease in overall krill abundance. To respond to low krill availability due to sea-ice loss, chinstrap penguins need to dive much deeper and more frequently to forage. Their foraging efforts essentially become less efficient due to sea-ice loss, which also has negative downstream effects on their breeding success and overall survival (Salmerón et al., 2023). If climate change trends continue, sea-ice loss and lack of krill availability will be a huge threat to chinstrap penguins as well.

King penguins experience changes in their foraging efficiency as well due to climate change and fluctuations in their environments. The success of their foraging depends greatly on different aspects of their local environment including temperature, wind, rain, snow and ocean currents, all of which are influenced by climate change (Le Bohec et al., 2008). Poor sea ice cover and high sea surface temperature led to king penguins foraging for longer at much deeper levels (Le Bohec et al., 2008).

Climate change resulting in warmer ocean temperature and changes in sea ice dynamics alter foraging patterns and typically make foraging trips longer for multiple species of penguins in different regions of Antarctica due to prey being more difficult to find, also a downstream effect of climate change on this environment.

## Breeding and Overall Survival

Climate change has rippling downstream effects on the breeding patterns and success of penguins as well, which contributes to their survival rates and success. Chinstrap penguins are central foragers during breeding that primarily rely on krill. This means that during breeding, their foraging is typically restricted to somewhere close enough for them to go on a foraging trip and continuously return to their nest site to feed the offspring or incubate (Salmerón et al., 2023). Loss of sea ice and changes in krill availability have led to longer trips and deeper dives, generally less efficient foraging trips. This has significant impacts on their breeding success as they return to their nests to feed their chicks less frequently. Chick survival and overall population size can be threatened by this.

King penguins have a breeding season of 12 months and increases in summer temperatures pose a serious threat to their reproductive capabilities (Le Bohec et al., 2008). Similarly to the chinstrap penguins, the decrease of available prey nearby has caused them to have longer dives for food and return to their chicks at the nest less frequently. Low breeding success amongst king penguin colonies was also observed when sea surface temperatures were higher than usual, as this affected food availability. Some even chose to abandon their reproductive ventures all together, likely to prioritize their own survival and conserve energy and food reserves (Le Bohec et al., 2008). King penguin populations see a 9% drop in their adult survival with an increase of 0.26°C in sea surface temperature and the Intergovernmental Panel on Climate Change (IPCC)-2007 predicted an increase of 0.2°C per decade for the next two decades. As climate change alters foraging conditions and habitats for king penguin populations, they will likely be forced to move in order to see increased survivability and breeding success (Cristofari et al., 2018). Colony loss will cause a decrease in population size and many will be forced to disperse and colonize new areas where foraging, breeding and survivability is easier. It is estimated that 70% of king penguin breeding pairs will need to relocate by 2100, 49% are projected to lose their habitat completely and 21% will see a change in habitat due to foraging conditions becoming near impossible (Cristofari et al., 2018). Overall, there will likely be huge changes in geographical distribution of the king penguins based on a change in sea surface temperature alone. There may be even more drastic changes caused by other effects of climate change such as changes to sea-level, changes in ocean productivity due to ocean acidification and changes in biotic interactions.

Adélie penguins also experience major changes from climate change. Adélie penguin populations live in many different regions of Antarctica, which is undergoing climate change in an asymmetric fashion. Much of the continent and inland is experiencing cooling while the West Antarctic Peninsula and its nearby bodies of water are experiencing warming. Climate has always influenced the distribution patterns of penguins, but climate change is hypothesized to cause a different response in different populations of Adélie penguin based on their geographic distribution. Adélie penguins nests are built on snow and ice free terrain to keep their eggs and chicks dry, so changes in precipitation and snowmelt will likely lead to nest site flooding that may drown eggs and chicks and lead to population decline (Cimino et al., 2016). Adélie penguin populations were positively affected (increased survival, population growth) by warming and negatively affected by cooling (decreased survival, population declines) but further warming in Antarctica is likely to be unsustainable or beneficial for Adélie penguins (Cimino et al., 2016). As a result, it is likely that colonies will shift to areas more favorable for their survival, those with less climate variability and better conditions for nesting sites.

Adélie penguins' migration patterns are also affected by climate change. These penguins migrate around 8,000 miles in a circular pattern utilizing sea ice (Waters, 2023). They are highly dependent on the patterns of the sea ice and the movement of the water as it impacts both themselves and their prey (Ralls, 2024). However, as sea ice has decreased by 60% in roughly 3 years, these penguins have needed to alter their migration patterns and lengths (Ralls, 2024).

Emperor penguins also face similar challenges in their survival and breeding. Climate change led to a record low sea ice extent in Antarctica that began in spring of 2022 and continued, leading to matching of 2021's all-time low in December (Fretwell et al., 2023). Some regions of the Bellingshausen Sea experienced a 100% loss of sea ice concentration which led to a regional breeding failure of emperor penguin colonies. Emperor penguin colonies relies

on sea ice for all of its life cycle but particularly for breeding when they lay eggs from May to June that hatch after 65 days before the chicks are able to leave the nest a few months later around December and January. Due to this long breeding process, the sea ice on which nests are built must remain stable to support them. In 2022, multiple breeding colonies were not successful which was unprecedented (Fretwell et al., 2023). Typically, breeding failure is caused by random or localized sea ice destabilization so widespread sea ice loss is likely a strong reason behind this widespread failure. Breakage or damage to sea ice before emperor penguin chicks grow waterproof feathers can cause them to drown (Strickland, 2022), so loss of sea ice may also harm chicks even if nesting and breeding was initially successful. While sea ice dynamics cannot be completely predicted, it is likely that they will continue to be affected by climate warming in a negative way, with negative consequences on emperor penguin breeding as well. It is projected that emperor penguin populations may decline from 27%-47% by 2050 (enouvrier et al., 2021). This could even increase to a 98% decrease in population, essentially extinction, by 2100 (Strickland, 2022).

## Considerations For the Future and Conservation Efforts

Penguins not only have a significant presence in their respective ecosystems but may also be particularly relevant to scientists and the study of climate change in general. They are a good model taxonomic group since their ecology and genetic history has been heavily studied and is well known. As there are many different species and populations that are each influenced by temporal variability, prey availability and more, they are good study subjects (Trathan et al., 2015). Their foraging is somewhat constrained and less adaptable than some other sea birds which is an additional controlled variable for studying the effects of climate change. Understanding changes in penguin populations can help scientists study their ecosystems as well. Additionally, climate change and warming can affect different species in different ways; Emperor and King penguin populations will likely see declines in breeding success and adult survival in warm events while Adélie penguin colonies decline where there are heavy winds and snow accumulation (Trathan et al., 2015). These differences can help elucidate exactly how climate change is affecting different species.

Newer technology such as genetic sequencing and -omics technologies may also improve our studies and understandings of climate change and biodiversity. As observed so far, penguins and other animals threatened by climate change may change their behaviors as a response to their changing environmental conditions. They also may adapt genetically, expressing different genes in different ways to be better suited for survival (Santos et al., 2024). Experimental evolution studies look at genetic or phenotypic changes in natural populations that are experiencing variation in their environment. These studies can provide insight on how quickly evolution and adaptation may occur and in what ways, how different variables relate to or drive these evolutions and deepen our understanding of selection and adaptation within populations (Santos et al., 2024). Extinction is more likely to be avoided if populations move geographically to more favorable conditions, as many penguin populations are doing, and undergo evolutionary adaptation (Hoffmann et al., 2011). A sequencing study showed that the emperor penguin seemed to be undergoing selection for TRPM8 gene, a temperatures sensing gene that is likely contributing to its survival and breeding success in an environment that is becoming increasingly cold (Pirri et al., 2022). Coupled with behavioral studies, experimental evolution studies could greatly improve our understanding of how penguins could adapt and survive the threat of climate change.

Penguins not only have a significant presence in their respective ecosystems and environments, but are also of great interest to human scientists. Penguins are considered an indicator species, which means that their conditions represent the health of their ecosystem overall (Changing Life: Ocean - Antarctic and Southern Ocean Coalition, n.d.). Declines in their populations would have many negative effects on their ecosystem and on its ability to be studied. Any negative changes in their population numbers or behaviors are often indicative of other species' troubles and unfavorable environmental conditions. If many penguin populations are in trouble, many ecosystems are as well.

Although humanity has dealt deleterious effect on penguins, they have also provided plenty of conservation efforts to preserve the species. Many organizations have placed efforts into the restoration and maintenance of penguins. The Global Penguin Society and WWF are both organizations that work not only to conserve the penguin

species, but also to educate and establish protected penguin areas. For instance, the Galápagos Conservancy has established protected areas for penguins that will contribute to their conservation (Galápagos Conservancy, 2022).

In summation, penguins face many challenges from climate change which ultimately cause negative effects to their populations, which are decreasing and in trouble. If these trends are to continue, they may cause severe drops in population numbers and possibly even more extremely, extinction. The dangers include many factors such as krill depletion, reduced sea ice, and many other effects of climate change. These may also have cascading effects on many species in the same ecosystem, as penguins serve as an indicator species and are heavily intertwined in their ecosystems and food webs. While there are many efforts to preserve the penguin species, such as conservation organizations and the establishment of protected areas, penguins are in an endangered state. This will only worsen if no external support is provided and efforts to reverse climate change occur. Penguins are one of many species suffering from the unnatural phenomenon of the manmade climate change, and it will require an equal or greater manmade effort to restore the penguin populations.

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