

Emperor penguins, what does their future hold? A first step into the distribution modelling of the species

by

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Preface

I would like to extend my extreme gratitude towards my supervisors' Doreen Boyd and Geertje van der Heijden for their extraordinary guidance and support during the process of sculpting this dissertation



(McCrae, 2019): Atka emperor colony (located near the Neumayer research station) huddling during a harsh Antarctic storm.

Abstract

Emperor penguins are an extremely unique and fragile species, living in one of the most desolate biomes on the planet. Unfortunately, the ever-escalating process of climate change sees environments around the globe transform. Antarctica is one of the most fragile regions on the planet and one that has been highlighted to be dramatically affected by climate change. These changes to the environment emperor penguins call home will undoubtedly have impacts on the species, but to this day it is still uncertain as to how much and what kind of an impact this will have. With the unique beauty of this bird species observed nowhere else globally, it is key to strive to fully understand them and attempt to conserve their majestic elegance. Used extensively and prosperously by other ecological modellers due to its countless benefits, a Species distribution models (SDM's) was developed to analyse and project the range shift of emperor penguins under different future climate scenarios. Utilising quantitative secondary data for current emperor colony occurrence and a variety of environmental variables of a high spatial resolution, a series of scenarios were run through Maxent. With the models success in predicting emperor colony occurrence in the current environment to a high degree of accuracy (AUC: 0.973), it was proposed that: Scenario 1 (the Antarctic environment in 2050 under RCP 4.5) was projected to have a slight increase in the total area of predicted presence uniformly around Antarctica and scenario 2 (complete loss of sea ice under current environmental conditions) determined emperors would have a slightly increased environmental range. Results of the SDM concluded that looking to the future under all environmental scenarios would see an overall increase in the predicted presence of emperor penguins. These results contradict much of academic literature, thus it is key to fully understand the limitations of their conclusions. Across all scenarios, the models are predicting an increase in the species environmental niche, but due to the lack of biotic variables, such as food availability, the model cannot accurately depict the species. In addition to this, the physiology and dispersal ability of the species is disputed, suggesting they may not be able to follow the projected niche of the model. Ultimately the limitations of the study restrict its representativeness to the species, thus the results should be interpreted with this in mind.

The work highlights areas that need to be developed, allowing for the acquisition of more reflective results. Firstly, the development and utilisation of an advanced aerial surveying capability (RPAS) to allow for more data collection, combined with the application of more climate models to be run for the region of Antarctica; something that is lacking and hinders future distribution modelling on the peninsula. In addition to this the GPS tracking of large proportions of individuals, giving a better

understanding of the dynamics of the bird's life and proving or disproving the results of studies such as this. The model itself (Maxent) was not tailored specifically for the study species, therefore a bespoke model needs to be developed just focus solely on Emperor Penguins, to better reflect the species and its unique environment.

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1.0 Introduction

Antarctica is one of the most barren and isolated landscapes on the planet, situated at the bottom of the globe it experiences periods of both constant darkness and sunlight (BAS, 2006; USCIA, 2011). In addition, this naked and seemingly lifeless environment experiences extreme weather events, with winds blowing at storm force up to 199mph (Parish, 1988; Parish & Waight, 1987) and temperatures falling to -89.2°C (Turner, et al., 2009). This oddly surreal and deadly Martian like environment is home to a unique species of bird, the emperor penguin. Arguably one of the most mysterious species of bird on the planet, displaying inquisitive human-like behaviour from a species that could not be further from homo sapiens. Under the waves emperors are efficient and elegant birds, gliding through the cold seas performing a beautiful quartet for the acquisition of food; on land however they become clumsy waddling towers of blubber, silhouetting the baron Antarctic landscape that they call home. Unfortunately, much of scientific knowledge agrees that future climate change will have implications amongst the species, with an indicated reduction in their population (Kato, et al., 2004; Barbraud & Weimerskirch, 2001; Alhatem & Saavedrad, 2018) with some such as Jenouvrier, et al., (2019) suggesting their extinction. As with many other species of animals SDM's are frequently used to assess these changes in future environments, attempting to predict alterations at hand (Ehrlen & Morris, 2015; Raxworthy, et al., 2003; McCune, 2016). Unfortunately, this is not the case with emperor penguins, with little to no work surrounding species distribution modelling of the species, a gap in the academic knowledge that is becoming increasingly important. Conservation is considered an important application of SDM (Seo, et al., 2008; Franklin, 2013; Guisan, et al., 2013) and something that many species will be in dire need of in the coming decades (Scott, et al., 2005; Scott, et al., 2010). This is especially true for emperor penguins, as these predicted damming effects on the species will need to be mitigated for, but more importantly, fully understood to maintain this beautiful bird. One of the main aspects of this study surrounds the development of a species distribution model, a method of predicting the presence of penguins looking to the future. From there it will be utilised to predict the range of penguins under future scenarios, assessing the overall outlook for the species, detailing any conservation efforts and areas of improvement if needed.

1.1 Aim's:

The aim of this project is to further enhance the academic understanding of emperor penguins geographical range across Antarctica, attempting to predict their distribution under future climate scenarios.

1.2 Objective's:

Objective 1:

Collate a database of high-quality environmental variables; such as average temperature, wind speeds, precipitation levels etc. All of which have shown impacts on the distribution of the species and will be utilised within a species distribution model (SDM).

Objective 2:

Utilising Maxent, create and run an SDM assessing the geographical range of emperor penguins under environmental variables seen in the present day.

Objective 3:

Run the optimum SDM on a number of different future environmental scenarios: Scenario 1 (Antarctica in 2050 under projected conditions for RCP 4.5), Scenario 2 (Antarctica under a complete loss of sea ice); all whilst reflecting upon conservation.

2.0 Literature Review

2.1 Introduction

Antarctica is widely considered the most inhospitable location on planet Earth (Singh & Dutta, 2011; Polar Research Board, 2011). It has a mean annual temperature ranging between -10°C to -60°C (Bureau of Meteorology, 2016), accompanied by extremely low humidity, precipitation and frequent extreme blizzards (Mishra, et al., 2011). With record low temperatures of -89.2°C recorded (Scambos, et al.,2013), it would not be inexcusable to assume such a location is void of all life. Extraordinarily however, this 14 million km2 slab of ice is home to one of the most unique animal species on the planet, the Emperor Penguin (Aptenodytes forsteri). With their first recorded sighting sometime between 1773 and 1775 and official classification by George Robert Gray in 1844 (Borborglu & Boersma, 2013) they are the most ancient of all living penguin species. During the millions of years of their existence, they have against all odds called this dark, dry and cold expanse of ice home. Surviving countless threats, spanning from the merciless environmental conditions experienced during incubation seasons to their predatory hunting by southern giant petrels and leopard seals (Green & Williams, 1986). Such an improbable species being the only animal on Earth to breed through the Antarctic winter, with no active defence mechanism from predators, nor the natural environment, is extremely vulnerable to even the slightest of changes (Barbraud & Weimerskirch, 2001). Unfortunately, the future of our planet and Antarctica is worryingly ambiguous, and If climate change proceeds to advance at the rate it has been then it is suggested the future of this species lies perilously uncertain. With such little known about the effects future climate change will have on the species it is difficult to envisage how they will respond, many suggesting a reduction in populations (Abadi, et al., 2017; Jenouvrier, et al., 2014) and others speculating its entire eradication (Jenouvrier, et al., 2009). It is vitally important to fully understand and predict the changes facing emperors; not only to allow for a greater understanding of the species and the processes affecting it, but also in the hopes to best mitigate any damming future changes and conserve the species under the worst scenarios. Just because the emperor is

defenceless and seems to serve no anthropogenic purpose, does not mean its future should be disregarded.

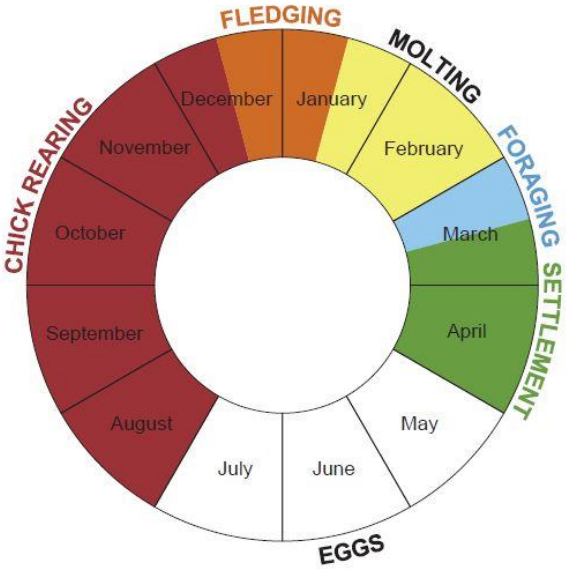


Figure 1: Annual cycle of the emperor penguin (Borborglu & Boersma, 2013)

Emperor penguins themselves have one of the most unique lifestyles of all birds and arguably all species across Antarctica. Presented in figure 1 is the annual cycle of emperor penguins. The cycle starts with adults returning to their previous colony location after a period of exploration and foraging. During this period, usually occurring in March, sea ice is stable enough to sustain the development of a colony. Once back at the colony location settlement of the emperors ensues over the proceeding four to six weeks. During this time the discovery of a mate and courtship is performed by individuals, resulting in the laying of eggs by the females around May to early June. Once laid the egg is passed to the male, allowing the female to begin her testing endeavour to forage in surrounding sea ice. In late July to early August the father's incubation efforts pay off and the well-guarded egg finally hatches. Over the whole period of fertilisation and incubation, it is well documented that males fast for roughly 115 days (Kooyman, et al., 2018), during this time they losing 45-50% of their body mass (Prevost, 1961). As highlighted by Kooyman (2018) there is some variation in fasting times, with the Cape Washington colony observed to have been feeding before the chick has laid. This a result of night feeding, an unusual behaviour that most emperors seem averse to carrying out (Ainley & Ballard, 2012). If this is the case, then some males fast for around 65 days and still successfully accommodate the hatching of their chick. This would prove more beneficial for the chick as the father can provide sustenance whilst the mother is away, both increasing chick survival rates and reducing chances of egg abandonment. During this rearing period, interesting behavioural traits have been observed. Emperors are seen to be territorial when raising chicks, with multiple instances of chicks and eggs being stolen from other breeding pairs causing a reduction in their fasting period. As a result, the opportunity for multiple birds participating in the rearing process of an individual chick increase (Kooyman, et al., 2018), this again providing beneficial for the development of the chicks and colony health overall.

Once the females return, they provide much-needed sustenance for the chick with the males handing over possession of the chick to the mother, allowing them to forage for themselves after their fast. This process of the Mother and Father relaying to foraging sites to feed the chick and

themselves continues till the youngling has developed their adult coat; allowing them to thermoregulate and forage for themselves. Prior to this a chick' s coat is not suited to extreme conditions experienced when foraging or unprotected from adults, thus they are extremely vulnerable to the harsher Antarctic weather events. Evidence of this was seen during the 2016 Halley Bay colony collapse when chicks with undeveloped feathers perished as the underlying colony ice broke off into the sea (Fretwell & Trathan, 2019). From September the chicks necessitate so much energy that both parents are required to forage simultaneously for the child to sustain energy needs. By December the chicks start to fledge and by early January the vast majority of the emperors have abandoned their colony. An annual moult occurs at the breeding ground but most adults do not attend. The juveniles that have just fledged typically spend the next years of their lives travelling hundreds of miles from their breeding ground and only returning after 3-5 years for the cycle to repeat itself.

In recent years the livelihood of this species has come to be queried. The issue lies within the adjustments of global temperatures as a result of climate change, endangering the suitability of sea ice for penguin settlement and food source, but also the rate at which it develops. This rate of ice development and depletion ultimately limits the time for emperors to complete their intricate and delicate breeding process, being one of the most important parts of the species lifecycle (Borboroglu & Boersma, 2013). Consequently, to understand the impacts facing emperor penguins one must study the trends of climate change and the effects it has had and may continue to have on the species.

2.2 Climate Change

With evidence amassed from more than 50 years of scientific research and observations, it is undoubtedly clear that climate change is a major threat to life on earth (Hodson, 2012). With much of climate change, anthropogenic or not, closely attributed to fossil fuel-based development (Giles-Carnero, 2013), emission levels are continuing to rise; and with the direct and most influential impact of these emissions causing an increase in global temperature. A recent report by the IPCC (2018) assessed the impacts of global warming 1.5°C above pre-industrial levels on emperor penguins. Although these are not current levels it is with high confidence that continuing current trends it will reach this 1.5°C increase between 2030-2052 (IPCC, 2018). Although seemingly small, such an increase in temperature could not only have drastic effects to Antarctica's fragile environment but also lead to the possibility of extinction of species (Jenouvrier, et al., 2019) as a result of their heightened sensitivity to temperature change (Alhatem & Saavedra, 2018). Emperors face this threat as many of the processes they rely upon are extremely susceptible to temperature

fluctuations (Ice extent, foraging sites etc.). The report suggests that temperatures could increase up to 2°C above pre-industrial levels, with some such as Rapp (2008) & Stern (2006) speculating increases from 3-5 °C. This would put even more stress on the species and further highlighting the increased uncertainty of their future.

2.2.1 Past Climate Impacts on the Species

Over the lifespan of emperor penguins as a species, many unique climate-changing events have been observed, as a result, the species has experienced impacts from previous events. Paleoecological records have offered vital information on how the species responded to different rates and degrees of change (Dawson, et al., 2010), but with the inability to acquire such records, assessing previous works proves equally as beneficial, and it becomes clear that penguins have been influenced by such climate changes.

A study carried out by Barbraud & Weimerskirch (2001), analysed the population of an emperor colony situated near Dumont d'Urville Station. With population data from 1952-2000, they concluded that the colony had suffered a 50% decline in its population as a result of a decrease in adult survivability during the 1970s. This decrease was attributed to the greater winter fluctuation experienced through the course of the 1970s, with temperatures averaging -14.7°C in comparison to -17.3°C of the 1960s. If a change in temperature due to a fluctuating climate could have such a long-lasting effect 40 years ago, then furthermore extreme climate changes post-1970 could have more profound effects. Interestingly Barbraud & Weimerskirch's work highlighted a seemingly delicate balance regarding the extent of sea ice and penguin survival, with sea surface temperature (SST) and the accompanying sea ice extent, accounting for 86.9% of the survival variation. When less sea ice was experienced by the penguins there was a reduction in the availability of Prey (Krill, Fish, Squid) settling under the ice. Thus with a far greater extent of sea ice, there would be an abundance of food available, resulting in greater emperor survivability. This demonstrated ice food relationship may prove valuable, Interestingly however it was seen that increased sea ice extent in the winter negatively affected hatching success, as greater distances and thus time was needed for the mother to acquire adequate food for the father and chick (Barbraud & Weimerskirch, 2001), resulting in a higher risk of fatality for both parties.

A paper by Trathan (2011) detailed some effects of a rapid population reduction owed to climate-changing events on the species. With the colony on emperor island observed to have a continuous decline from 150 breeding pairs in 1970 to 20 pairs in 1999, and the complete loss of the colony observed in 2009. Interestingly the study details the same climate-changing event in 1970 that were observed in Barbraud & Weimerskirch's paper; however, the colony locations were in completely

different positions on the peninsula, somewhat discounting local climate fluctuations and more directly pointing to the effect of regional or global climate change. As both colonies experienced the same climate-changing event but had different responses this raises the question, what makes a colony more or less susceptible to the effects of climate change? In addition to this, the variables observed in this report differ from the norm, with Trathan utilising mean annual air temperature as the independent variable as opposed to sea surface temperature used in the majority of other papers. But as the variables are so similar this should not have caused any adjustments within the results.

A further paper by Fretwell & Trathan published in 2019 details the drastic events in 2016, when the Brunt ice shelf was destroyed by extreme weather events causing the loss of 5-9% of the global emperor breeding population; roughly 14,000-25,000 breeding pairs. The early onset of the breakup and loss of sea ice is widely accepted to be the reason for the breeding colony loss (Barbraud & Weimerskirch 2001; Barbraud et al., 2011) partially due to the underdeveloped nature of the chicks swimming feathers (Fretwell & Trathan, 2019). But exactly why the early breakup of sea ice occurred is still speculated by academics. Fretwell & Trathan themselves draw attention to an El Nino event that directly preceded the breakup of ice, being the strongest in 60 years. But without sufficient evidence to corroborate, it leaves uncertainty as to if El Nino is attributed to climate change or not, with their relationships still being actively researched with conflicting views on its impacts (Colins et al., 2010). However the frequency of such Southern oscillation events is predicted to increase, and catastrophic weather events are likely to become more recurrent with increased greenhouse gas emissions (Cai et al., 2015). There are other causes that more directly allude to climate change. In September of 2016, the average atmospheric pressure of the month was the lowest in 30 years, with the average wind speed and annual temperature being higher than normal. Not only this but it was stated that “The timing of strong wind events in relation to key aspects of breeding will almost certainly be important” (Fretwell & Trathan, 2019 p.137), with prolonged strong winds causing the breakup and dispersal of sea ice, especially during breeding months. This suggests that wind speed plays a potentially more prominent role in the distribution of the species than is commonly detailed. This is, however, a balance, as with increased wind speeds brings coastal upwelling, beneficial for providing foraging sites for colonies (Crawford, 2007; Morrison, et al., 2015). Much of the concern for the individuals over the disappearance of the colony in this paper can be subdued by the knowledge that a close colony located at the Dawson-Lambton Glacier, some 50km away, had seen a drastic increase in its population. This potentially suggests that under extreme conditions, even though emperors are breeding site faithful, they will relocate for survival. However, the number of penguins arriving at Dawson are nowhere near as many as those lost at the previous colony (Fretwell

& Trathan, 2019). With this event occurring in 2016, to this day there has not been much of a resurgence of the colony. This was attributed to strong winds hollowing the reforming ice impacting its integrity, however, something the paper failed to consider is the food supply. The collapse of the ice shelf would induce the collapse of the local food sources inhabiting this sea ice (Fretwell & Trathan, 2019; Ducklow, et al., 2007; Montes-Hugo, et al., 2009), and in subsequent years if the sea ice had not developed then there would be no food, thus no reason to restart the colony. This is tied to the primal response of the penguin, a response seen in wolves and other animals. When there is a short supply of food the species will not reproduce until there is an upsurge in or an abundance of prey. Of late there have been a few breeding pairs sighted, so it would suggest that potentially these food stocks underneath the sea ice may have grown to a more sustainable size to support a breeding colony.

Ultimately this report presents an example of the drastic impacts of climate-changing events and highlights the vulnerability of the species. Not only this but it draws to the potential course of action emperors may take if future colonies become endangered; migration to other colonies for example. Fundamentally, as stated by Fretwell and Trathan (2019), the understanding of how environmental drivers' impact upon breeding colonies remains a key challenge for the species and is something this dissertation aims to investigate.

Forcada & Trathan (2009)'s paper on the southern ocean penguin responses to climate change, reinforced by work from Meredith & King (2005) highlights that the distributional range of both emperor and adelie penguins has shifted polewards and contracted as a result of El Niño. Although El Niño events seem to stand independent from climate change, many such as NASA (2016) & Cho (2016) believe that climate change almost certainly affects El Niño. Unfortunately, this is hard to quantify due to the variation between El Niño year on year (Cho, 2016; Colins et al., 2010).

Huang et al (2016) assessed historic emperor colony in Amanda Bay during the Little Ice Age. During this history, a period of unique global cooling caused emperor penguins to experienced in increase in population size, with the colder temperatures affecting sea ice extent, breeding habitats and prey availability (Huang, et al., 2016) thus boosting the productivity of the colony. Ultimately this again

strengthens the notion that emperor penguins have been affected by climate-changing events in the past to varying effects.

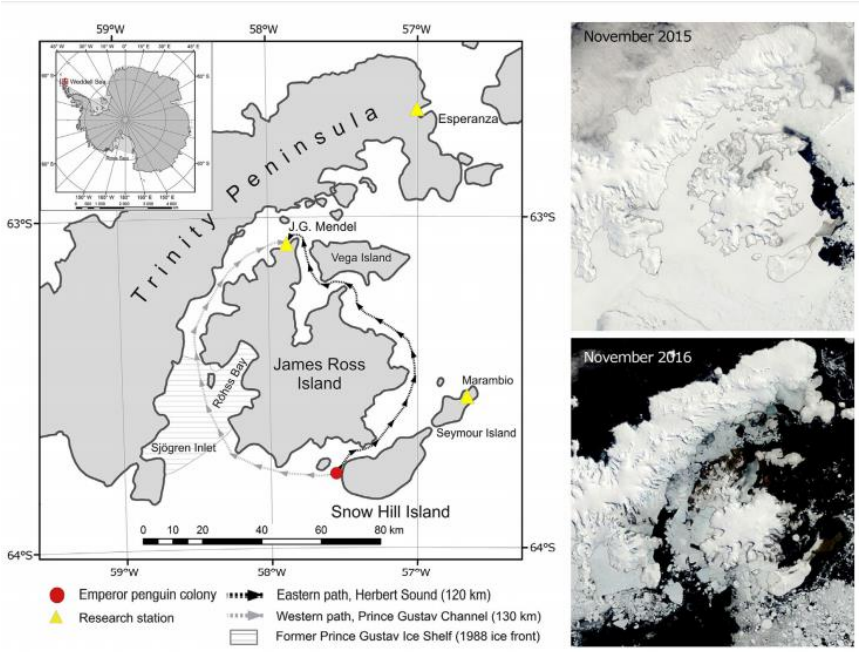


Figure 2: Map of potential migration paths and sea ice situation in the north-east Antarctica (Hrbáček, et al., 2018)

The evidence of such changes as a result of climate change are not always as obvious and do not always take the form of distribution shifts or population changes. A paper by Hrbáček, et al., (2018) assessed the most recently discovered emperor colony on Snow Hill (Coria & Moltalti, 2000; Todd, et al., 2004). With the colony home to 2100 breeding pairs (Fretwell, et al., 2012, Jenouvrier et al., 2014) it is fairly well established. Hrbáček's study assesses the roaming distance of certain individuals in reflection to a change in sea ice coverage. Throughout the history of this colony, there have always been individuals who travelled extreme distances, but usually, they are scarce with only several penguins per decade witnessed (Hrbáček, et al., 2018); with one sighted as far as 140km from the colony in the late 1990s (Coria & Montalti, 2000). Recently there have been no sightings of emperor's in the area since 2004, until now when a pair of Juvenile emperors were spotted off the northern side of James Ross Island, walking along the coast of the Prince Gustav Channel roughly 120-130 km from the nearest Snow Hill colony. There are only two paths they could have taken around James Ross Island to be spotted here. They would have either had to have travelled East or West of the island and in normal Arctic conditions on foot, this would have been impossible. However, due to recent changes in climate, the Eastern Ice shelf (Prince Gustov Shelf) previously blocking migration to the East, collapsed in 1995 opening the up to migration. Not only this but more recently in 2016 a warm austral spring was observed causing the breakup of sea ice to the north of the island, this significant sea ice retreat (Figure 2) was concluded to have been the most probable cause of the sighting of the two individuals; The reason for such a venture by the emperors are still unknown but it is recognised that a Juveniles first venture from their colony can be the longest and most adventurous (Kooyman & Ponganis, 2007; Borboroglu & Boersma, 2013). The observations and assumptions in this work suggest that individual penguins can traverse distances of at least 250km, this presenting the flexibility of emperors at sea becoming a valuable asset if

discussing possible relocation sites and the maximum distance viable for a colony. Allowing for an in-depth understanding of the intricacies of selecting new breeding habitats; something that was successfully carried out on king Penguins in the South Shetland Islands, (Petry, et al., 2013, Juares et al., 2017).

Climate changing events in the past have had varying effects on emperor Penguins, ranging from distribution shifts to colony eradication. The overall consensus of many of these works reviewed is that historically increasing temperatures in both land and sea as a result of climate fluctuations have caused a reduction in penguin populations, sometimes attributed to a decrease in sea ice. However, as emphasised in an array of different papers it seems that the actual cause of such population declines is not simply the temperatures increasing, but in fact, is the secondary effects of such increasing temperatures. With rising temperatures, the early and drastic reductions in sea ice would be observed (Abram, et al., 2010; Curran, et al., 2003) potentially restricting the ability for a colony to complete a full breeding cycle. In addition, these temperature changes have impacts on species food availability. The influence of El Nino Southern oscillations is suggested in a few of the papers discussed. This raises questions as to how much of an impact they have and whether or not they should be further included in the work, something perhaps not taken into account previously. As with most theories, without sufficient data, many of these proposed reasons for population changes are riddled with uncertainty, with limited datasets and relevant work carried out something that many of the discussed papers suggest.

2.2.2 Future Climate Impacts on the Species

Current academic literature does not present any severe future shifts in observed trends. The IPCC's AR5 (2014) further encapsulates the environmental conditions and changes expected to be seen in the future. In this report they adopted the Representative Concentration Pathway (RCP), presenting four different 21st-century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations (Figure 3, IPCC, 2014). Transposing these emissions directly to temperature (Figure 4) it can be seen that the most likely outcome is an increase in temperature, ranging from a best-case scenario 1°C increase to worst-case 4°C. Even if RCP 2.6 (best case scenario) was observed in the future there is little to no doubt that emperor penguins would be affected as a result of such temperature changes (Jenouvrier, et al., 2019), the question is how much of an effect would these future changes have on the species?

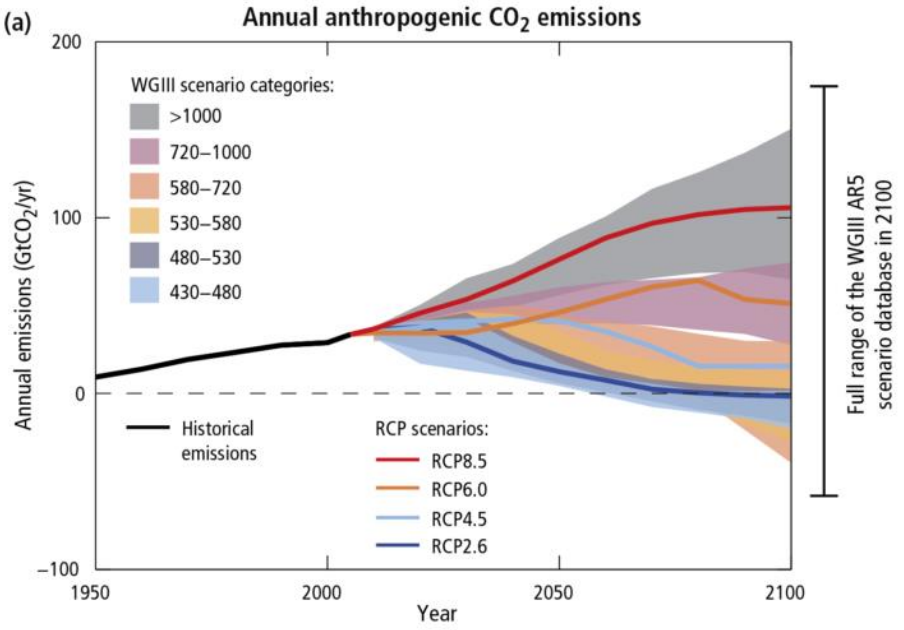


Figure 3: CO_2 RCP scenario trajectory (IPCC, 2014)

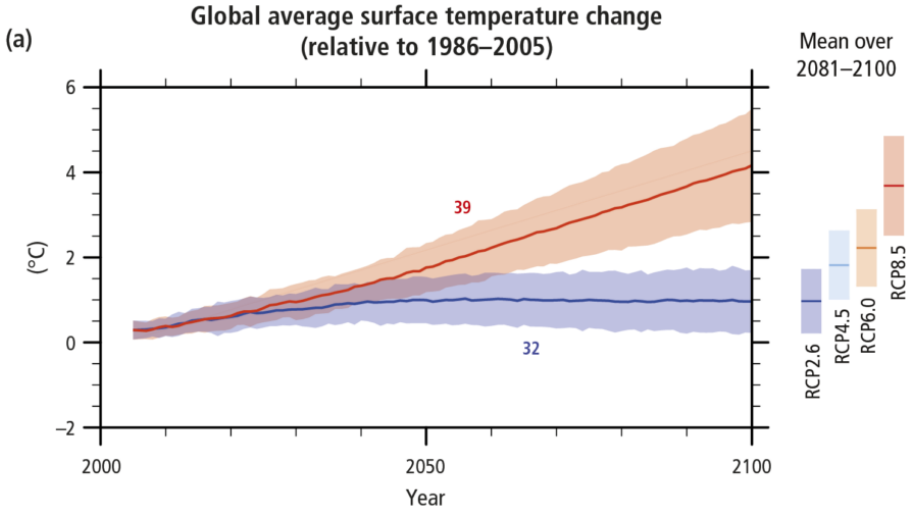


Figure 4: Global average surface temperature change RCP projections (IPCC, 2014)

A study by Alhatem & Saavedra in (2018) proposed the hypothesis that increasing future temperatures due to climate change would negatively impact emperor populations. By collecting both temperature and population data and running it through statistical analysis packages they concluded that over time temperatures increasing will harm emperors, specifically on their breeding populations. Whilst comparing temperature anomalies to fluctuations in populations trends were observed. Firstly, Coulman Island colonies experienced a drastic decline in 2005 with an

accompanying increase in temperature of 0.94 °C (Alhatem & Saavedrad, 2018). The reason for such a decrease may however be more complex than discussed. As proposed by both Jenouvrier et al (2009) and Ainley et al (2010) they believe that increases in global temperatures will cause reductions in sea ice, resulting in profound consequences on emperor populations. This suggests that the change in temperatures may not directly impact emperor penguins but indirectly via its effect on other crucial aspects of emperors lives. As it stands 87% of Antarctica's glaciers have retreated (Cook, et al., 2005) accompanied by an increased frequency of reduction events, with 2016's Antarctic sea ice extent decreasing 46% faster than mean rates, and with 25% greater area of reduction (Turner, et al., 2017). If the IPCC RCP's are followed then there is no doubt that sea ice extent on the peninsula will decline further, raising serious concerns for both colony locations and food availability (Huang, et al., 2016).

Focusing on the future effects of climate change it is not surprising that the increased frequency of warm events will result in the further reduction in sea ice extent and cause a reduction In population's (Jenouvrier, et al., 2009), with these trends in sea ice shifting, Turner (2009) predicts that the annual average sea ice extent will reduce by 33%. If this is the case the most likely response observed by emperor's would be the dispersal of the species (Forcada & Trathan, 2009; Jenouvrier, et al., 2019). Unfortunately, it is hard to quantify exactly how much of an effect this will have on them, as presented by the IPCC's RCP's there is much variation between future emission projections meaning the effects on emperor populations could vary dramatically. The IPCC, (2018) and other academic papers do their best to project future trends but it must be kept in mind that the huge number of variables and uncertainties affect the validity of results. With this in mind, they are still the most reliable and robust projection's available, thus many works utilise them.

Demographic models have been employed in the past with attempts to determine changes in populations. Jenouvrier (2012) constructed one to predict population trajectories from 2000-2100 with relation to sea ice extent. Although well supplied with information there is knowledge to suggest that sea ice is not the only factor affecting these penguins, with wind speed, food sources and precipitation playing a role (Kooyman, 1993; Trathan, et al., 2011; Ainley, et al., 2010). Perhaps the aim of this study was a bit too narrow in its focus, as the results become less significant as many other factors not included could have impacts on the species. This decision potentially reflects how there are far too many variables that contribute to the penguin population or distribution dynamics. This paper concluded that not only would reduce sea ice have an effect on emperor populations but heavy and persistent sea ice would also have a detrimental effect on the species. As for projections, Jenouvrier concluded that by 2100 a population drop of 81% would be experienced around the Terre Adelies region. The uncertainty of models is further highlighted in this paper, as one projected an

increase in population over much of the century, this discounted but the study as the ensemble suggested otherwise. Interestingly Jenouvrier also observed how the seasonality has an effect on the impact, with observable effects occurring at differing times of any given seasonal cycle (Jenouvrier, 2012), suggesting the time of year may vary the impacts of climate-changing events; with summer months having an amplifying effect on the effects of climate change. This may not have that much of an effect but it is something to consider and is rarely touched upon in other academic works. An update to this paper was provided by Jenouvrier, et al., (2019), building upon the previous study and concluding that under a business as usual emissions state, 80% of the emperor colonies are predicted to be extinct by 2100. A prominent impact that fundamentally highlights both the drastic changes they will face and the requirement for conserving the species.

With the severe effects climate change has on ecological processes (Trathan, et al., 2011) and its inarguable predicted increase into the future, one of the major issues for the species is its shifting of sea ice trends. Currently the breeding cycle of an emperor penguin just about fits within the lifecycle of Antarctic sea ice, however with future temperatures on the rise these breeding and ice cycles will go out of phase. With an earlier spring and the onset of ice occurring later and ending earlier the ability for chicks to survive reduces, as showed by archive reports from Dion Island (Trathan, et al., 2011). With a change in the breeding seasons, the giant petrels (a predator already known to attack chicks) would become more prevalent and further threaten emperor chicks (Trathan, et al., 2011; Kato & Ichikawa, 1999). There will also be a shift in the trends of food stocks, not only a reduction in the availability of food due to less sea ice but also the location of foraging areas within the range of emperor Colonies (Trathan, et al., 2011). As sea ice retreats earlier, it encroaches on the more vital time in chick-rearing when it is of upmost importance that the mother returns with plentiful food for herself and the youngling. As ice retreats earlier or even vanishes entirely there will come a time when the mothers of the family will struggle to find adequate food for both herself and the chick. It is speculated by some such as (Cheung, 2008) that with a total loss of sea ice prey stocks could disappear. If future projections are correct and there is a total loss of sea ice then issues with colony breeding sites would also arise (Cheung, 2008). The possible relocation of emperors is discussed in academic literature, Fretwell (2009) presents an instance where a colony residing on Mertz Glacier's tongue had to naturally relocate due to the tongue's loss in 2010. Unfortunately, as documented emperors are site fateful and their long life and loyalty to their breeding sites could prove to be a future issue if relocation was required. If they were to relocate it could prove to be a challenge due to their natural lack of agility (Trathan, et al., 2011; Skutch, 1935), limiting them to areas of more subdued terrain and elevation. In this case, it is suggested that moving to lower-lying accessible land would not necessarily be a valid long term survival option for the species (Trathan, et al., 2011).

Some aspects of the emperor penguin's lifecycle are poorly understood, one example is the interactions of juvenile under ice habits. Further understanding this is suggested to provide an insight into the important and poorly understood part of the life cycle, is essential to predicting their response to climate change (Labrousse, et al., 2019).

The future effects of climate change will impact emperor penguins, worsening with a high degree of certainty progressing to the future. Academic literature varies drastically in its opinions on exactly how much of an impact climate change will have, with some such as Walther (2005) suggesting it may drive population expansion rather than retraction. Utilising projected climate data from sources such as IPCC, the majority of current literature has suggested that the most prominent impacts penguins will face are those of drastically reduced sea ice. The reduction in sea ice itself does not seem to be the main contributor to the future concerns of the species, but it provokes changes that are. A loss in access and availability of food sources, loss of breeding sites and in turn shift in breeding cycles are all predicted as major risks to emperors if changes in our climate continue as planned. It is key that to utilise a variety of different assumptions and simulations when predicting future statuses of the species, the IPCC's RCP's may prove to be a brilliant building block as they contain a range of well-educated scenarios that can be built upon and integrated into the dissertation. Although these computer simulations and extrapolation techniques are widely regarded as reliable and significant It must be kept in mind that these are still predictions, and as a result are not exact insights into the future. Thus It was ensured that any future predictions be verified to the highest standard and assessed within the context and knowledge that they are well educated 'predictions' and nothing more

With these climate-changing events predicted to have varying effects on emperor penguins, it is key to mitigate the impacts of these events on the species via conservation.

2.3 Conservation

Species conservation is important, especially with unprecedented climatic changes currently affecting the distribution of many species; potentially resulting in numerous extinctions over the next century (Naia Morueta-Holme, 2010). Research by Dawson (2010) & Cardillo (2005) showed that extinction risk is highly correlated with body mass, with larger species requiring more time to recover from demographic reductions in population sizes (Matthews et al., 2010). This was corroborated by Gaston & Blackburn (1995) who found that large-bodied birds are at higher risk from extinction than smaller ones. Consequently, Emperor penguins, the 6th heaviest bird species in the world (del Hoyo et al., 1992; Marion & Maigret-Mondry, 1999), would be considered at risk of

extinction. Therefore, conservation practices for the Emperor Penguin need to be examined to determine whether they could be suitable in preserving the longevity of the species.

The response of a species to the climate varies and may shift as a response to global change factors (Lee et al., 2015), and as a result, it can be difficult to precisely plan conservation strategies. Understanding the direct threats associated with climate change (de Cha-zal & Rounsevell, 2009; Mantyka-pringle et al., 2012) and accurately projecting the ecological reactions of such threats (Jenouvrier et al., 2009) are amongst the biggest challenges facing the conservation of Emperor Penguins. Once these predictions are made and threats are fully understood, particular management strategies can be deployed depending on the circumstances of the species (Dawson et al., 2010). Currently, most work on Emperor Penguins highlights the issues that population of Emperor Penguins may face and has focussed on extrapolating current climate trends, however, only a few studies seem to address any conservation proposals for the species.

Understanding the natural ability of an individual to deal with changes in their environment is key to conservation efforts (Brooke, 2008). With some species more vulnerable to changes then others this may limit their ability to naturally adapt to climate change (Pacifici et al., 2015; Summers, et al., 2012). By observing past trends and historical context, the ability of a species to adapt to change can be observed (Hof, et al., 2011; Jump & Penuelas, 2005; Williams, et al., 2008), In addition to this, vulnerability assessments, i.e. assessing a species risk from climate change, helps to create a framework for the identification of a species vulnerability to climate change (Williams, et al., 2008) with the aim to aid the design of conservation strategies for specific species (Dawson, 2011).

One such example of a vulnerability assessment is seen in Dawson's (2011) paper; presenting a framework of three factors to assess the extent to which a species is threatened with decline:

- Exposure: Extent of climate change likely to be experienced by the species, depending on the magnitude and rate of climate change;
- Sensitivity: The degree to which the survival of the species is dependent on prevailing climate change, with more sensitive species showing greater responses to changes;
- Adaptive Capacity: The capacity of the spices to cope with climate change in situ without shifting to more suitable habitats.

Emperor penguins are at extreme risk of exposure to climate change (Trathan, et al., 2011; Gaston & Blackburn, 1995), they are sensitive to such changes (Barbraud & Weimerskirch, 2001; Jenouvrier, 2012) and are believed not to possess a natural adaptive capability to deal with this change without

moving habitats (Jenovrere, et al., 2009; Gearheart, et al., 2014; Cristofari, et al., 2016). As a result, the species is considered vulnerable within Dawson's vulnerability assessment.

The vulnerability of a species changes depending on how they adapt, with many species over the past decades adjusting their geographical ranges in ways consistent with relatively small climate changes (Parmesan, 2006; Walther et al., 2002), some undergoing major range restrictions and population declines (Thomas, et al., 2004; Jackson, 2000; Williams, et al., 2002). It is hard to assess whether Emperor penguins exercise this range adaptation due to the variation in colonies year on year, however, some evidence suggests the species does adapt (Davies, et al., 2006; Thomas, et al., 2001; Morin, et al., 2008; Fretwell & Trathan, 2019). Over the past 60 years, a colony on the Brunt ice shelf has moved to and from adjacent sheltered creek's, this due to the changing topography of the region (Fretwell & Trathan, 2019). Although this indicates that Emperor penguins naturally shift to more suitable habitats, it is key to understand that this behaviour is not seen universally across the species; thus it could be an anomaly. Dawson (2011) also suggests the possibility of microevolutionary changes within a population, however, this is difficult to quantify due to the lack of sufficient and reliable methods of detecting such events (Dawson, et al.,2011; Chenin, et al., 2010; Visser, 2008), especially within the Emperor penguin populous. It is postulated that many species can adjust to climate change in situ via phenotypic plasticity (Dawson, 2011; Visser, 2008; Baker, et al., 2004) and microevolution (Franks, et al., 2007; Phillimore, et al., 2010).

The possibility of microevolution, discussed by Franks (2007) & Phillimore (2010), is scientifically possible but realistically improbable over the short timescale pressed by recent climate trends. With the primary implication of climate change being the increase in temperature (Rathoure & Patel, 2020), the species has been observed to cope well with temperature regulation, even in the warmest months; reaching around +5°C (Vincent, 1998). Thus, the species micro-evolution is therefore more likely to be a response to the secondary implications of climate change, i.e. reduction in food availability and suitable breeding grounds (Barbraud & Weimerskirch, 2001). However, further evidence is needed to conclusively back this up.

Species with large range sizes tend to have large populations, thereby buffering against habitat loss (Dawson 2011) and fostering large genetic variability (Dawson, et al.,2010). However, although the range of Emperor penguins spans across the vast Antarctic peninsula, they tend to live in relatively small populations. Due to the remoteness of each colony (Fretwell & Trathan, 2009), the species may have developed genetic variability. Emperor penguins have been observed on the peninsula for the past 246 Years (Wienecke, 2009), and it is believed that the species itself evolved between 23 to 5 million years (Baker, et al., 2005). However, despite genetic variability generally developing over

time scales of up to 1 million years (Uyeda, et al., 2010), no genetic variability between the colonies has been documented, which may be due to the similarity of biotic and abiotic conditions experienced at each colony location (Fretwell, et al., 2012).

2.3.1 Current Conservation Strategies

There are currently few conservation efforts in place for Emperor penguins, which may be due to harsh and inaccessibility of the environment, which may hamper conservation efforts (Borborglu & Boersma, 2013; Snyder & Stonehouse, 2007). A notable exception is the Antarctic Specially Protected Areas (Borborglu & Boersma, 2013), an area of the peninsula protected by scientists and international bodies. However, as this initiative does not contain an active conservation strategy for Emperor Penguins, it has been labelled as inadequate by others (Shaw 2014).

Due to the species inquisitive nature (Thomas, 2014) they are vulnerable to human interaction. The extreme environment and remoteness of Emperor penguin colonies provides some natural protection from more common anthropogenic disturbances such as tourism (Landau & Splettstoesser, 2007). However, some evidence has suggested this natural barrier is not enough, with occasional instances of tourism and science both disturbing colonies (Burger & Gochfeld, 2007). In addition, as highlighted by Borborglu & Boersma (2013) under Article 3 of Annex II of the Protocol on Environmental Protection to the Antarctic Treaty, the killing of animals for research terms is allowed if they have been provided with a permit from the relevant national agency; potentially contributing to this vulnerability.

Food sources are of vital importance to the survival of the Emperor penguin (Pacoureau, et al., 2019; Weichller, et al., 2004; Wauters & Lens, 1995; Oro, et al.,1999; Fretwell, et al., 2014), as a result, organisation's such as the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), consider Emperor needs e.g. their food requirements, when setting out goals for ecosystem-based management (Younger, et al., 2017). This helps conserve all marine wildlife and their food sources, thus technically aiding in the conservation of Emperor Penguins; albeit not its main focus. Overall, there is a lack of adequate conservation methods currently in place specifically for the emperor penguin.

2.3.2 Future Conservation Strategies

There are a variety of different schemes that may be suitable for future conservation of the Emperor penguin (Borborglu & Boersma 2013). Firstly, schemes that aim to reduce the impact of future tourism by combatting the expected increase in tourism by the creation "International research and

tourist visitation protocols" (Borborglu & Boersma, 2013 p.30). Secondly, greater restrictions should be set to permit invasive research within the scientific community during vulnerable periods, e.g. chick-rearing, which can reduce the losses of eggs and young chicks (Borborglu & Boersma, 2013). Thirdly, academic research into the Emperor penguin should be is sustained, specifically that focusing on the global populous. Particularly, research monitoring Emperor penguin populations utilising high-quality census data by employing modern technology, would provide a better understanding of the species, whilst reducing human contact (Borborglu & Boersma, 2013). For example, Fretwell & Trathan, 2019 showed a three-year breeding failure of the Halley Island colony using satellite data. Although there are still practical difficulties around using sensing equipment, further advances in remote sensing will make remote observation of Emperor penguins much more achievable in the future. Finally, with the increasing number of nations carrying out research on the continent and ever-growing interest in Emperor penguins (Dudeney & Walton, 2012; Watts, 1992), all nations operating on Antarctica should strive to conduct research together in a safe and renewable manner.

Ultimately there is a lack of future conservation strategies in place, with their development proving costly and intensive (Hoffmann et al., 2010). While developing such strategies is key, further research into other elements of the species is just as important. With more analysis comes the greater ability to understand the species and processes effecting it (UNEP-WCMC, 2017); fundamentally improving our ability to mould conservation strategies to best suit the species (Simpfendorfer, et al., 2011).

2.4 Species Distribution Modelling

Species Distribution Model's (SDM) have become increasingly popular as of late(Yackulic, et al., 2013), with their unique ability to characterize trends in species occurrence and abundance (Pacific, et al., 2016) and inform a variety of ecological, biogeographical and conservation applications (Guillera-Arroita, et al., 2015 Miller, 2010; Zhang, et al., 2012). With the intricacies of distribution left unknown for many species, SDM's provide a powerful platform to further develop and fill gaps (Newbold, 2010); particularly beneficial for assessing the exposure of a species to climate change (Dawson, et al., 2011). Their ease of use and power in explaining modern distributions is valuable (Elith, et al., 2006), however, their ability to produce results assessing extinction risk, delineating suitable habitats and predicting ecological outcomes is still somewhat unproven (Botkin et al., 2007).

The type of SDM to best use is still debated. A mechanistic approach, not necessitating geographical occurrence data with high generality, is frequently utilised for SDM's (Kearny & Porter, 2009). However, Thomas (2004) highlights that employing a correlative SDM, estimating the potential distribution with a set of environmental predictors (Guisan & Zimmermann, 2000; Elith et al., 2006), to envisage a spatial distribution of a species is more effective and logical; substantiated by Kearney (2010) stating that their simplicity, flexibility and relative ease of use within freeware packages is advantageous. These highlighted benefits serve to justify a correlative SDM's use within this project.

Niche models are best suited to identifying the exposure to climate change (Warren, et al., 2010; Dawson, et al., 2011), they find it hard to assess and predict the actual change a species will experience due to their inability to interpret a species natural resilience to such change (Dawson, et al., 2011), with climate species interactions so complex and context-specific (Doak & Morris, 2010; Johnson et al., 2010; Bradshaw, et al.,2006; Ozgul et al., 2010). As a result, a human reflection upon the climate impacts will be needed to assess their fate under projected changes (Dawson, et al.,2011). Consequently, any models made with be queried with human consideration and post processing to ensure the best output, supplementing what a computer cannot comprehend with academic knowledge.

2.4.1 Previous SDM works

Abadi (2017) utilised a Bayesian integrated population model allowing the estimation of survival in young emperor Penguins. Although not an example of an SDM it reflects how models can and are extremely beneficial and provide significance to research. Corroborating this Barbraud & Weimerskirch (2011) utilised a model to research the drop in Emperor population in the 1970's, concluding that Surface See Temperature (SST)'s influence on colonies accounted for 89.9% of the yearly variation in population. A factor such as SST could be utilised as a variable in a species distribution model alongside other parameters suspected of affecting emperor distributions. Jenouvrier (2009) utilised a stochastic population model to project future emperor responses to changes in sea ice, predicting the effects of changes in environmental conditions on the population. However, this does not take into account any spatial scale's, something that SDM's commonly do (Elith & Leathwick, 2009). Similarly, Ainley et al (2010) looks at emperor population changes with a 2°C increase from pre-industrial levels, utilising a variety of different climate models.

Overall, there are a handful of works that carry out various types of population modelling on the species, but unfortunately, none specifically using species distribution models. With it suggested that

"species distribution models should be the next step to quantitatively project the penguin responses to climate change" (Ainley, et al., 2010 pp59), the apparent lack of such models fundamentally highlights a gap in the known literature that would be insightful if filled. Programme acquisition and data for such models is of abundance. A recent study by Fretwell (2012) detailing an up to date colony location and breeding population estimate that "can be used in future population models and will provide a baseline for long-term research" (Fretwell, et al., 2012 p.1). In addition, there is a huge array of environmental datasets that could contribute to a species distribution model.

2.4.2 SDM Packages

Species distribution modelling is entirely hosted within the domain of computerised technology, providing multiple platforms for the task. Programmes such as R, Biomapper, ModEco, SAM and Maxent are all used to create species distribution models, providing equally sound results (Hijmans & Elith, 2011; Vaclavic & Meentemeyer, 2009; Guo & Lie, 2010; Fourcade, et al., 2014). The choice of software used will depend on the data specific to this study. With total confidence in the absence data, all of the approaches would prove successful, however, the nature of this studies sampling data does not allow for such confidence, thus a presence-only approach is required. All of the proposed software can utilise presence only data, but Maxent is the most popular and effective (Yackulic, et al., 2012; Fitzpatrick, et al., 2013); specifically, utilising background points as a presence-background method which has proved to be justly robust in many comparison studies (Guillera-Arroita, et al., 2014).

Qiao, et al (2015) proposes the 'no free lunch' theorem, that not one single optimised approach will be able to prove the best under all situations. It was concluded that the type of tool required for niche modelling will vary depending on a huge array of variables, suggesting that any study including such a model should "test a suite of algorithms for predictive ability under the particular circumstances" (Qiao, et al., 2015 p.1126). Maxent does a good job of meeting this criterion, testing an array of different algorithmic approaches and variables for their predictive ability and allowing the selection of those with the highest predictive ability.

This no free lunch theorem (Qiao, et al., 2015) and the underlying importance of tailoring model development and delivery to a specific species (Sofaer, et al., 2019) should be taken into account when selecting a programme for species distribution modelling. All of the modelling programmes are unique and provide a blanket application of SDM aimed to produce good results among a huge array of species. But the theories from Qiao (2015) & Sofaer (2019) stress that none of the models will be able to produce a perfect outcome as they have not been designed with one species in mind. The perfect model would be one specifically designed for emperor penguins on Antarctica,

unfortunately, a model like this has yet to be created, thus the closest would be selecting a programme with high customisation within a user-friendly parameter; allowing for the adjustment of variables and parameters to best suit the species and study location. R has an almost unlimited amount of customisation (Hijmans & Elith, 2011), however, the learning curve of this high-level programming language is extremely steep (Naimi & Araujo, 2016) and to create a model of sufficient performance would take considerable time. Maxent, on the other hand, is easy to access, free, user friendly, tested against a huge array of species and is relatively customisable to allow for the adjustment of parameters to best suit the research topic (Fourcade, et al., 2014). This is reflected when looking to academic works, with Maxent seeming to be one of the most commonly used programmes within SDM, especially for beginners (Yackulic, et al., 2012). There is no denying that many academics believe it is a very valuable and effective tool (Elith, et al., 2006), but how does it excel and what flaws have to be considered for its employment within the project.

2.4.3 Review of Maxent

Maxent is based on the principle of Niche modelling, commonly used in distribution modelling (Barve, et al., 2011; Soberon, 2010; Townsend Peterson & Soberon, 2012). Utilising the maximum-entropy approach to modelling a species niche and distribution. Given a range of environmental gridded variables and occurrence values, it creates a probability of distribution whereby every cell has a predicted suitability of conditions for the study species, or as with this studies application of Maxent, a binary (1,0) predicted presence or absence value. Its user-friendly simplicity has allowed many academics from a broad range of backgrounds to utilise it (Elith, et al., 2010; Phillips & Dudik, 2008; Merow, et al., 2013); providing valuable and reliable results for their work (Kumar & Stohlgren, 2009; Khanum, et al., 2013; Galletti, et al., 2013). Maxents renown stems from a variety of reasons. Firstly, in combination with the programme being particularly good at closely matching quantities empirical data (Anttila & Magri, 2017), It uses only presence data; recognising that absence data are rarely available or reliable (Phillips et al. 2006; Elith et al. 2011; Phillips and Elith 2013), categorising all background values as absences during the modelling task (Renard et al. 2012; Arnold et al. 2014). Due to the sampling complexities of the study species, i.e. sampling being temporally and geographically dispersed, it is hard to definitively classify all absence as true absences; thus a presence only approach is favourable. Additionally model output, i.e. maximum likelihood estimate of the relative probability of presence, continuously allows for fine distinctions to be made between the levels of predicted probability in different areas; helping to create a presence-absence map and make more nuanced interpretation than presence-absence predictions (Phillips et al. 2006; Arnold et al. 2014). Maxent also uses a generative approach, utilising environmental data

from across the study area rather than a discriminative approach; beneficial when presence data is limited (Phillips and Elith 2013).

However, Maxent is not perfect. Various academic papers have noted that Maxent tends to overfit models (Phillips, 2017; Anderson & Gonzalez, 2011; Radosavljevic & Anderson, 2013; Anttila & Magri, 2017), this is of particular importance in this study due to the limited sample size of colonies. There are methods of mitigating such issues, the program can utilise a regularization multiplier that reduces overfitting by ensuring the empirical constraints are not followed too precisely (Merow, et al., 2013; Phillips and Dudík 2008) and penalizing the model in proportion to the magnitude of its coefficients (Tibshirani, 1996). It is also key to take into account the mitigation of sample selection bias, something that some 87% of academic papers utilising Maxent failed to do (Yackulic, et al., 2013). Producing an optimum model within Maxent can be difficult due to the plethora of model customisation features, with many academics still using default settings to run models (Morales, et al., 2017). As a result, the output of the model may not carry peak optimisation, this somewhat mitigated by the exploration and understanding of all variables. Nevertheless, many of these issues are not exclusively linked to Maxent but apply to a broad range of presence-only modelling techniques, this is a caveat that should be taken into consideration when reflecting upon the results. The results of the programme are astounding and still provide significant and reliable outputs (Phillips, 2017; Elith, et al., 2010), all of which far exceed the requirements of this report.

2.5 Conclusion

The literature reviewed has indicated that the species requires protection. Currently, only a handful of penguin population models have been created and proved useful for their intended purposes(Abadi, 2017; Barbraud & Weimerskirch, 2011; Jenouvrier, 2009); However, none specifically focus on SDM of Emperors. This highlights a gap in current literature that has been expressed as valuable if filled (Ainsley et al., 2010); a gap this dissertation aims to bridge. Ensuring the reliability of the outputs, a transparent and structured decision-making framework, as proposed by Guillera-Arroita (2015), will be carried out. The review makes it clear that the numerous advantages to a novice species distribution modeller (Fourcade, et al., 2014; Elith, et al., 2010) and limited drawbacks (Phillips & Dudik, 2008) make Maxent the most suited application for this study; Thus, it will be justifiably used.

3.0 Research Design and Methods

3.1 Introduction:

This chapter covers the methodology and research design used to model and predict current and future emperor penguin distributions. The initial section details the rationale behind the selected methods, discussing the advantages and constraints of the techniques utilised. Data handling techniques are then addressed and a pathway of events is presented, specifying exact methods and how they were interpreted to draw relevant conclusions.

3.2 Research Design:

Due to the specific research aims at hand secondary data is used throughout, taken from reputable online sources, databases and academic papers. With the project's heavy reliance on statistical inference, all of the data used is quantitative, with a few qualitative data sources employed for post-processing.

Programmes:

This section discusses the software utilised to achieve all of the studies objectives throughout the dissertation, justifying its use, advantages and disadvantages within the study.

- **ArcMap**

ArcMap, created by ESRI within the ArcGIS package, is an analytical programme facilitating the handling of geographical data (Shaner & Wrightsell, 2000). The package is well regarded amongst academic consensus to be one of the best geographic information systems (GIS) tools available (Wampler, et al., 2013; Barnes 2002; Jebur, et al., 2015). Bosting a huge array of robust and intuitive features encapsulated within a user-friendly interface, makes it intuitive and easy to use (Jobe, 2018). There are a few caveats to the software, fortunately, they will not pose any significant impact on the project and thus will not hinder its utilisation in achieving the studies objectives.

- **Maxent**

Of late many academics have ventured into Species Distribution modelling with the recent development of methods to analyse presence-only data (Yackulic, et al., 2013). The majority of this species distribution modelling utilises the principle of Niche modelling (Barve, et al., 2011; Soberon, 2010; Townsend Peterson & Soberon, 2012). One such programme is Maxent, using the maximum-entropy approach to modelling a species niche and distribution. Given a range of environmental gridded variables and occurrence values, it creates a probability of distribution whereby every cell has a predicted suitability of conditions for the study species, or as with this studies application of Maxent, a binary (1,0) predicted presence or absence value. Its user-friendly simplicity has allowed many academics from a broad range of backgrounds to utilise it; providing valuable and reliable results for their work (Kumar & Stohlgren, 2009; Khanum, et al., 2013; Galletti, et al., 2013).

However, Maxent is not perfect. Various academic papers have noted that Maxent tends to overfit models (Phillips, 2017; Anderson & Gonzalez, 2011; Radosavljevic & Anderson, 2013), this is of particular importance in this study due to the limited sample size of colonies. There are methods of mitigating such issues, the program can utilise a regularization multiplier that reduces overfitting by ensuring the empirical constraints are not followed too precisely (Merow, et al., 2013) and penalizing the model in proportion to the magnitude of its coefficients (Tibshirani, 1996). It is also key to take into account the mitigation of sample selection bias, something that some 87% of academic papers utilising Maxent failed to do (Yackulic, et al., 2013). Producing an optimum model within Maxent can be difficult due to the plethora of model customisation features, with many academics still using default settings to run models (Morales, et al., 2017). As a result, the output of the model may not carry peak optimisation, this somewhat mitigated by the exploration and understanding of all variables. Nevertheless, many of these issues are not exclusively linked to Maxent but apply to a broad range of presence-only modelling techniques, this is a caveat that should be taken into consideration when reflecting upon the results. The results of the programme are astounding and still provide significant and reliable outputs (Phillips, 2017; Elith, et al., 2010), all of which far and away exceed the requirements of this report.

Planned Methods:

The aim of this dissertation is to create a species distribution map of the current range of emperor Penguins (Binary Presence/Absence). Once created the model would then be used with future

environmental variables. Producing a set of scenario's projecting the potential range shift of emperor penguin colonies under these scenarios: Scenario 1, projected changes on the population in 2050 under RCP 4.5 assumptions (IPCC, 2018); Scenario 2, the predicted changes of a complete loss of sea ice.

Firstly, occurrence data for all emperor penguin colonies with coordinate data for GIS inference will be collected. The data for these occurrence points will be assimilated and referenced from a variety of academic sources, mainly from Fretwell's dataset (Fretwell, et al., 2009; Fretwell, et al., 2012); with conformation and updates from other academic studies. In addition, an extensive collection of high-resolution environmental variables, highlighted to effect penguin distributions from the literature review, will be collected and setup for use within Maxent.

With the data set up it will be entered into Maxent with the optimum model settings fixed. This will produce a distribution map of emperor penguins within the current environment observed on Antarctica. With the model set up, the future scenarios will be run through Maxent with their own individual set of variables reflecting the environment seen under each scenario. Once completed the outputted data will then be statistically analysed and put through ArcMap for visual inference, with the aims of seeing how much of a distribution change the model is predicting the species will experience under these future environmental scenarios.

3.3 Data:

The reliability of the results lies within the quality and dependability of the data. As a result, assuring the data is acquired from reputable sources and cross-checked is key. The two main informants of data are Fretwell (2009 & 2012) and WorldClim2.0 (Fick & Hijmans, 2017), providing colony occurrence data and current environmental data respectively. These are both extremely reputable sources referenced frequently in academic literature (Panagos, et al., 2017; Molyneux, et al., 2014; Trathan, et al., 2019).

Data acquisition under future scenarios becomes more problematic. To maintain a high level of accuracy the study continues to use fine spatially referenced data. Unfortunately, there are limited data sets available on a high enough spatial resolution, with many future data sets completely excluding the region of Antarctica entirely. As a result, much of the future data is inferred from well-educated assumptions from selected academic sources, notably IPCC's climate reports for much of the future projections. Due to the academically astute nature of these sources, it is with a high

degree of certainty that these inferences best represent the future scenarios, thus maintaining the accuracy and reliability within the results.

3.3.1 Data Handling:

This section covers each of the data frames and the techniques used to refine them to ensure the highest levels of reliability within the study. Achieving objective 1 with all of the data frames presented pictorially in Appendix A

Occurrence Data:

The occurrence data detailing the 45 known locations hosting emperor colonies were collected through various academic papers and studies. The most prominent was that of Fretwell (2009), utilising advanced satellite imagery to locate signs of emperor colonies through their faecal debris, this both clarifying the knowledge of existing colonies and also discovering new ones not located before. Alongside this other papers such as (Borborglu & Boersma, 2013) presented further colony locations, and allowed for the creation of a presence-only dataset reflecting emperor colonies globally (This seen as a table in appendix A-1 and as a map in figure 5). Due to the known and proven accuracy of this data not much data handling was needed, apart from assuring the coordinates were correct by cross-referencing against other studies and physically against a map. As a result, the sources were fully trusted and limited uncertainty within the dissertation.

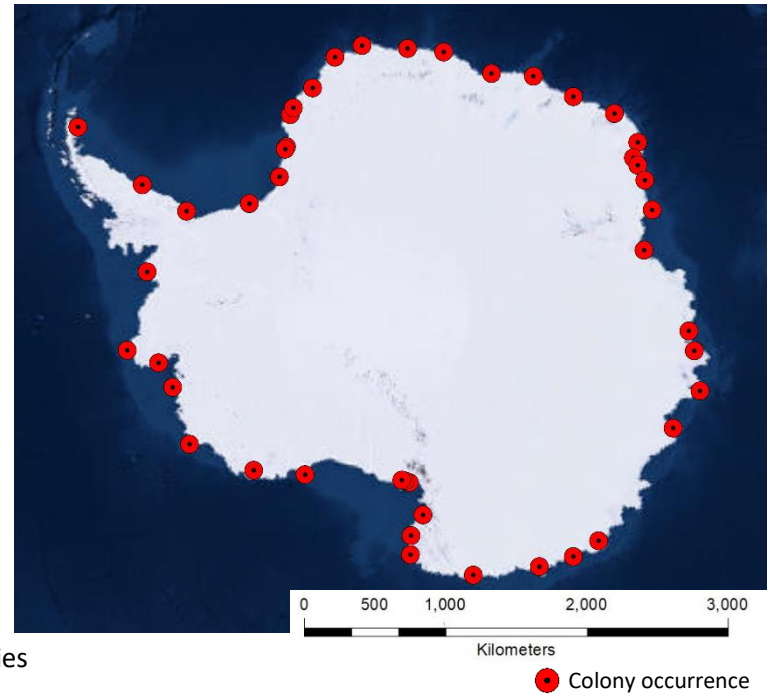


Figure 5: Occurrence map of all known emperor colonies on Antarctica

Data handling of the occurrence data came from assessing the location of the colonies against the environmental data on a spatial scale. One of the biggest problems encountered was that a large number of the colonies had coordinates that placed them outside of the data range, this not down to the inaccuracy of the data but the fact that many colonies breed on sea ice very close to land masses but not on the landmass itself. This is a problem due to the technicality of the study and the

setup for the model. All of the environmental data is captured and represented on the Antarctic landmass, resultantly any environmental data captured on sea ice is left out due to its variability year-round. Thus, when comparing the spatial range of the occurrence dataset to the environmental data (both which have to match up perfectly in Maxent) many of colonies lie outside of this range. If this issue was not rectified Maxent would not be able to compare the occurrence points to their associated environmental variables and thus the reliability of the results would dramatically drop as many occurrence values would not be sampled within the model. As a result, the colonies outside of the environmental data frame were moved to the closest landmasses cell. The distances moved varied from location to location but they were all under 1km, so if there were changes in their environmental variables, they would be minimal. Consequently, resolving the problem with a negligible effect on the results.

Environmental Variables

- **Current Environmental Variables**

The environmental data used for curating the model under the current environmental conditions were acquired from WorldClim (Fick & Hijmans, 2017). WorldClim 2.0 is a set of global climate layers (gridded climate data) with a spatial resolution of about 1 km^2 (Fick & Hijmans, 2017), providing data for wind speeds, average temperature, temperature variation and average precipitation. A few factors were taken into consideration. Firstly, WorldClim 2.0 resolution is 1km^2 (Fick & Hijmans, 2017) this potentially too coarse for similar studies on different species on a smaller spatial scale; where higher resolution data would provide more representative in areas of increased topological complexity (Ruiz-Labourdette, et al., 2011). However, for the study area of Antarctica the spatial resolution is less of a factor, this due to the sheer size of the area and the less dramatic variations in environmental conditions (BAS,2019; Schneider, et al., 2004). Hence frequent changes in the environmental data are not observed as they would be in areas of greater elevation variation (McCain & Christy, 2005). Thus this data, although hosting room for improvement still supports the achievement of the studies objectives. The data itself technically does not directly represent current environmental conditions. WorldClim's data frame uses a reference period from 1970-2000 (Fick & Hijmans, 2017), this some 20-50 years ago. As a result, it may not accurately represent the current environmental conditions being experienced by these colonies. However, this is but a caveat of the resource, with WorldClim 2.0 data widely considered to be a suitable source for model development; used within many academic works (Fick & Hijmans, 2017; Molyneux, et al., 2013). Thus, for a project such as this, the advantages of this dataset greatly outweigh the disadvantages.

As a free to use resource, providing sufficient spatial and temporal resolutions with high accountability and ease of use within ArcMap and Maxent. Many data frames holding the required environmental variables did not accommodate for Antarctica and had the region excluded from the data, whereas WorldClim 2.0 proved to be one of the only sources of data that retained the region of Antarctica.

The data handling of this information resulted in projecting coordinate systems and adjusting the file type. These were all done in ArcMap to allow for the data to be compatible with Maxent. Data was briefly crosschecked against current environmental conditions to see the variation this 20-50 year difference had. The changes were minimal, thus it was concluded that the data for current environmental variables were fit for use within the project.

Future Environmental Variables

The future data for the two scenarios were required to have the same spatial range to be entered into Maxent. Initially, it was planned to use WorldClim data but instead of the new 2.0 model, the older 1.4 model would be used, thus allowing for the selection of previous and future global scenarios from a range of RCP's. Unfortunately, WorldClim 1.4 as with many of the other data frames, failed to include Antarctica in the data's spatial resolution, thus other alternatives were located. Initially, it was planned to utilise a variety of other models producing future environmental projections, issues of compatibility and more importantly a lack of reliability within the sources resulted in the dispersal of this method. As a result, much of the data for future scenarios came from various sources through academic literature, mainly individual ensemble models with a high degree of reliability thus not huge amount of data handling had to be done (IPCC, 2018). The only thing required was converting the data from various sources to the same data frames as those used in the current environment ensuring their compatibility within Maxent's model.

3.4 Methods:

This section is a brief but detailed process of the major steps taken to acquire results for discussion with justification. Highlighting issues encountered along the way as well as other prominent decisions made to meet objectives 2 & 3.

All of the environmental variables had to be in the format of .asc (ASCII) with the same resolution and processing extent ($1km^2$ & WGS_1984). The information below details the process of setting up

the environmental variables for use in Maxent. First specifying the variables used for the current environmental conditions, then those used for future scenarios.

Some variables within the study were not directly inputted into Maxent due to impracticality or a lack of statistical value within the model. Thus some were utilised as post-processing variables for reflection after the results of the model had been produced.

3.4.1 Current Environment (Objective 2)

- **Air Temperatures**

Air temperature and sea surface temperature represent different mechanisms but their values are very closely correlated (Rueda, et al., 2009). Thus, the study used air temperature due to its easy integration within Maxent as opposed to sea surface temperature. There is more available data on land surface temperature on higher resolutions than sea surface temperature, especially within the study area of Antarctica. The use of land surface temperature as opposed to sea surface temperature has been used within academic works and still provides viable results (Trathan, et al., 2011).

- **Average Air Temperature**

  This variable was used in the study because it is well documented and referenced that penguins respond with relation to temperature (Croxall, et al., 2002; Jenouvrier, et al., 2009; Barbraud, et al., 2001; Alhatem & Saavedra, 2018; Barbraud & Weimerskirch 2001; Fretwell & Trathan, 2019; Ainley, et al., 2010), especially in such a fragile environment. The average yearly temperature data was accessed from WorldClim2.0, providing a gridded raster on a high 1km2 resolution covering all of the study area. This data was then inputted into ArcMap in the .tif file provided, clipped to the Antarctic study extent, converted to ASCII (Maxent's required input file format) and then projected to WGS_1984' coordinate system. A 'calculate statistics' was run through the data due to the values changing, this statistical calculation resolved this bug thus made the dataset ready for use within Maxent.

- **Temperature Variation**

  The temperature variation variable was chosen as a way of representing minimum and maximum temperatures at each cell, but also as a way of assessing how much temperature stability emperor colonies require; divulging If they choose locations that

have more consistent temperatures year-round or those that have greater differences between the min and max temperatures.

Again the data for this variable came from WorldClim2.0 but in the form of an average minimum and maximum temperature. With these two files, the temperature variation was then calculated using the 'raster calculator' tool, subtracting the minimum temperature values from the maximum values of each cell. With the underlying data created the process of setting the data up for Maxent, projecting to the correct coordinate system, clipping to the Antarctic study area and converting the data to .asc file; this setting up temperature variability for Maxent.

- **Wind Speed**

  It has been speculated that wind speed has a greater effect on penguin distribution than initially anticipated, being referenced as a cause of range shifts (Fach & Klinck, 2006) and a contributing factor to colonies changes in the past. It also seems to affect the food sources in some instances (Botsford, et al., 2003; Millot, 1979). As a result, it is justifiably included within this work.

  Average *yearly* wind speed data was not available from WorldClim2.0, however, data on the average *monthly* wind speed was. Thus this monthly data was downloaded from WorldClim and averaged across the 12 months to give a yearly figure across all cells in the study area; with values ranging from 0 to 19.9 m/s (up to 42 mph winds). The data was then run through all the processes to be set up and ready for use within Maxent.

- **Precipitation**

Not a huge amount is known about precipitations effect on emperor penguins, with occasional studies disputing its role. Some have referenced its effect and how it may have negative implications on the species as levels rise (Ainley, et al., 2010), and others suggest its requirement in emperor lifecycles (Kooyman, 1993). Thus its inclusion within the study is justified, with the finished model able to provide statistical evidence to further detail its impact.

The average annual precipitation was collected from the WorldClim 2.0 data set, with the process for preparation following previous variables; data clipping, projection of coordinate systems and conversion from .tif to .asc via the 'Raster to ASCII' tool in ArcMap.

- **Sea Ice Extent**

Foraging distances for emperor penguins are constantly discussed in academic papers (Massom, et al.,2009; Fretwell & Trathan, 2019), with their importance seemingly high for the survival of individual adults and chicks. It is highlighted by some such as Massom (2009) that increased sea ice extent is detrimental to breeding success, whereas others suggest that less sea ice can also prove detrimental (Younger, et al., 2015), thus it is necessary to incorporate this into the model to observe its statistical impact. As a result, a maximum and minimum 'distance from open water' variable was created, being the closest distance from each cell of land to water, this variable changes with the sea ice extent so in some ways is an indicator of the amount of sea ice extent in the region. It would be expected that emperor colonies favour regions that have less sea ice extent and thus less distance to travel to acquire food.

Looking at the breeding timescale (Figure 1) the months of greatest (September) and least sea ice extent (December) were selected and a shapefile of the ice extent was downloaded. GIS processing begun on these two layers converting them from line to raster files. With these raster's set up a 'Euclidean distance' was used to calculate the distance from the edge of the raster (ice extent) to each cell within the study area under the minimum and maximum ice extent, thus giving a value for the distance (m) that penguins would have to travel to reach the sea and forage to food sources. As with all the other variables this was then converted and projected to allow for its use within Maxent.

Slope (Post Processing)

The slope of the area does affect where penguins breed (Fretwell, et al., 2014). It is known that they commonly breed on areas of flat land avoiding steeper regions (Williams, 1995) after Maxent had been run it was planned to put the output raster through 'raster calculator' and classifying any areas where the slope is more than 2 degrees as unsuitable for penguin colonies, suggested to be unsuitable for colony life.

To do this a 1km DEM of Antarctica was acquired from reference elevation model of Antarctica (REMA) (Howat, et al., 2019), a high resolution, time-stamped digital surface model of Antarctica. This was then converted to the same coordinate system and cell size of the other environmental

variables being used within the study. From there the slope of the region was calculated within ArcMap and all cells with values over 2° were classified as 0, with any under 2° being classified as 1. Then a raster calculator was run multiplying all of the slope values with those of the predicted probability from Maxent, thus all areas with slopes higher than 2° would show no probability as they would be multiplied by 0.

Not only does this variable give a good indicator of areas emperors would not colonise, but it also gives valuable information for conservation and relocation efforts. From initial analysis and academic literature, emperor penguin colonies are situated close to an area of geographical shelter. Discussed in literature this shelter is a natural way to mitigate the effects of strong wind speeds and harsh winter storms on the colony (Kooyman, 1993). Thus the product of this report could provide areas of relocation highlighting regions of shelter.

- **Food sources (Post Processing)**

The abundance of food is a large factor in assessing how successful a colony will be (Pacoureau, et al., 2019), if there is no food available in the area then the colony would not be able to survive. This study has attempted to somewhat reflect upon the food sources emperor penguins consume and assimilate any trends associated with them. To do this the main sources of food were highlighted, these being: Antarctic Silverfish, Krill and Glacial & Hooked Squid (Kooyman & Cherel, 1998; Flores, et al., 2012); These being the majority of the species that emperors forage for. Data from GBIF was downloaded providing occurrence data for each of these individual prey species. With the data downloaded their extent was once again clipped to the study area and accumulated all of their point values into Arc map for post-processing. The reason behind this was that incorporating food sources into Maxent proved increasingly difficult, especially with the Data from GBIF that was unreliable and riddled with frequent discrepancies. One of the largest issues apparent with the data was that there was an extreme observation bias. The data were curated from observations of these species, but these sightings came from shipping and fishing routes, as a result, many of the data sets were sampled in a line, with a ship travelling from A-B (Appendix A-9), instead of a dedicated sampling mission scanning all of the surrounding ocean. This presence only observation bias greatly affecting the validity of the results. Overall the food data itself could not be trusted enough to incorporate it within the Maxent model and thus was used just as a reflective tool for post-processing.

3.4.2 Future Environment (Objective 3)

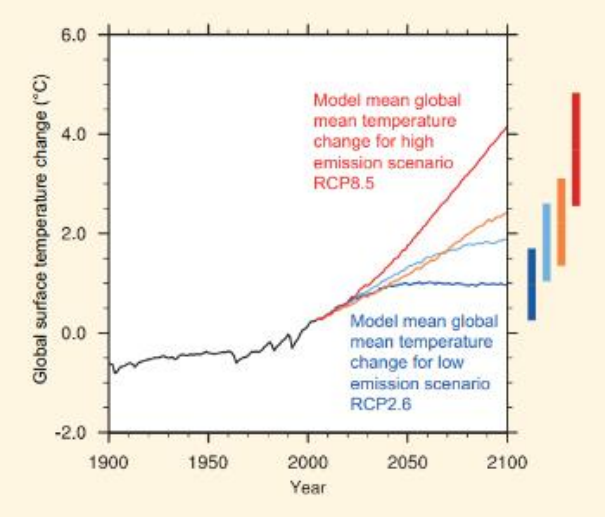
With the current environmental variables set up to be used in Maxent, data acquisition and setup for future scenarios was required. Unlike the current environmental model, It was decided to split the future into two separate scenarios. Scenario 1 (S1) presents the predicted environment in the Antarctic in 2050 under RCP 4.5, utilising ensemble models from various sources and best assumptions of 2050 climates referred from academic literature. This anticipated to be one of the most likely scenarios, and one that is referenced frequently in many studies's on future climates (Chou, et al., 2014; Wang, et al., 2014; Kim, et al., 2015; Lee); thus, justified its choice within the study. Scenario 2 (S2) simulates the environment with a complete loss of all Antarctic sea ice, leaving just the landmass of Antarctica for colonies to breed on. This selected due to the frequent suggestion in many academic studies (Jenouvrier, et al., 2014; Jenouvrier, et al., 2009; Fretwell, et al., 2014) that a complete loss of sea ice will have devastating impacts on the species, thus it would be interesting to see how the study model interprets the conditions.

Scenario 1

Originally it was planned to acquire results from several environmental models that predicted the conditions in 2050 under RCP 4.5 on Antarctica. Unfortunately, there was a severe lack of available data for the region meeting the studies quality specifications, with those including Antarctica having extremely poor spatial resolutions and various other data issues, thus making the data extremely hard to manipulate within ArcMap. As a result, referring from academic literature was carried forward as the best course of action, with well-educated estimations within studies suggested being manually depicted within the project. The biggest downside to this being that it would be near impossible to accurately reflect local changes in the climate across Antarctica, which are observed in real life (BAS,2019; Schneider, et al., 2004). As a result, much if not all of the assumptions made were generalisations that were applied to the entirety of the continent.

- **Land Surface Temperatures**

To calculate the land surface temperatures in 2050 under RCP 4.5, a best assumption of the environment was drawn from the IPCC's WG1's Report (IPCC, 2018), in this report, it was concluded that in 2050 the average global temperatures will have increased by around 1.5°C (IPCC,2018). A raster calculator was run on the current environment land surface temperature data set, adding 1.5°C to all of the values. The advantage of this method is that the data frames will remain correctly set up with no impact on the spatial resolution, thus ready to be run in Maxent; however, it does not consider local temperature variation.



IPCC WG1 Temperature pathways (IPCC,2018)

Temperature Variation

As for projections of temperature variations into the future, it was concluded that a robust increase in warm and decrease in cold temperature extremes would be observed at the end of the 21st century (IPCC, 2018), with the magnitude of the changes increasing with anthropogenic forcing (IPCC,2018). With these projected changes causing an increase in the warmest temps by 2.1° and a decrease in the coldest temps by 2.5° under RCP 4.5 (IPCC, 2018). A raster calculator was run on the minimum and maximum temperatures in the current environment with these IPCC values, then subtracted from one and other to give an estimation of the temperature variation in the year 2050. This followed by processing to make the data compatible and ready for use within Maxent.

- **Wind Speed**

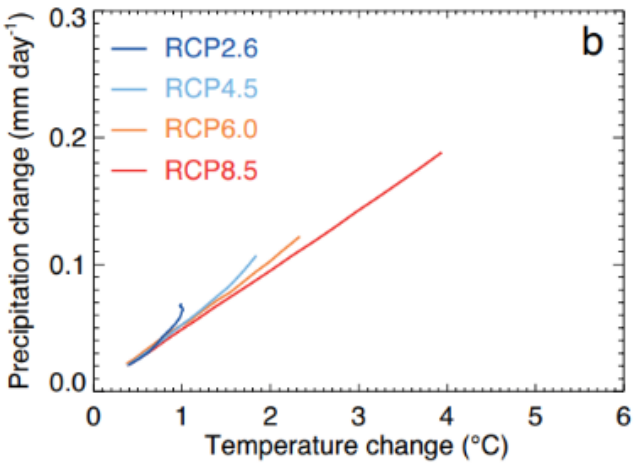
There is little to no literature of the future changes of wind speed on the antarctic peninsula, and what seems to be absolutely no data available for consumer use. As a result, a future layer was not able to be applied under RCP 4.5, and thus alternative methods referring from the academic literature was used. The only piece of work completed on wind speeds on the peninsula comes from Bintanja, et al., (2014), this an assessment of "The future of Antarctica's surface winds simulated by

a high-resolution global climate model: 2. Drivers of 21st-century changes". In this paper it was concluded that the average wind speed In the future (2094-2098) reduced by 0.2 m/s as generally surface wind speeds over the Antarctic mainland exhibit a small decrease (Bintanja, et al., 2014), by this assumption the value was halved to represent a figure for around 2050, resulting in a reduction of 0.1m/s.

Raster calculator was then employed to subtract this 0.1m/s from the current wind speed values to give one for 2050. How accurate these assumptions are is left up to the interpretation of the study and will ultimately only be proved looking to the future. But at the moment it is the most educated assumption possible for this region within the context of the literature.

- **Precipitation**

There is little data on a high enough resolution of precipitation on Antarctica to use within this study. As a result, the IPCC WG1's pathway's (IPCC, 2018) was used to assess the predicted change in precipitation. This report suggests that under RCP 4.5 a precipitation increase of 0.8mm per day for a temperature increase of 1.5° would be observed (IPCC, 2018), also reinforced by Ainley et al., (2010) with his models predicting a 25-30% increase with 2°C warming. This was multiplied to give a yearly increase (292mm annually) in precipitation. Added to the precipitation raster of the current environment, it gave results ready for use within Maxent that best assimilate the precipitation levels in 2050.



- **Sea Ice Extent**

Lastly, the maximum and minimum sea ice extent were acquired. Once again there is not much data on future sea ice extent, but fortunately, academic works by Parkinson & Cavalieri (2014) reported a net sea ice extent increase of 1.2 - 1.8% per decade (0.13/0.20km^2) during 1979-2012. This was extrapolated to 2050 and added to increase all the sea ice in the extent by this percentage per decade. Unfortunately, there are flaws with this method. The most important being that if increased

by the set percentage it would not take into account areas around the peninsula that might whiteness a reduction in extent. It is known that some areas grow whilst others decline but still resulting in a positive net change (Yuan & Martinson, 2000). Thus when changing the data it would only be able to increase all areas of SIE to accommodate for this % change when in fact in some areas may decrease and others may increase. Unfortunately, there is no other feasible way of doing this accurately within the time scale. This study by Parkinson & Cavalieri (2014) seems to go against the grain to assume that every 10 years sea ice extent in the region of Antarctica would increase in volume by 1.5%, especially with an increase in temperature of 1.5° at this time. The IPCC WG1 (AR5) states that Antarctic sea ice covers are projected to shrink in the 21st century under all SRES scenarios, with a large range of model responses (IPCC, 2018; Meehl et al., 2007). The CMIP5 multi-model mean projects a decrease in sea ice extent that ranges from 16% for RCP2.6 to 67% for RCP8.5 in February and from 8% for RCP2.6 to 30% for RCP8.5 in September for 2081–2100 compared to 1986–2005 (IPCC, 2018). As a result, it is both more reputable and logical to use the IPCC's conclusion as they utilised models to predict the future as opposed to assuming past trends will continue, thus Februarys figure for December was used with the average of the RCP's 2.6 and 8.5 to best replicate an RCP 4.5 scenario; It should be noted that the averaging of RCP's is unconventional and is not normally carried out within climate impact assessment's. The values produced were for 2100, thus they were halved to give a more representative value for 2050.

September RCP 4.5 = Decrease of 9.5% SIE December RCP 4.5 = Decrease of 20.75% SIE

These were then deducted from maximum and minimum sea ice extent values in the current scenario and processed to be ready for use within Maxent. With all of the variables set up and ready for use in scenario 1, the process of setting up data for scenario 2 begun.

Scenario 2

Scenario 2 was designed to see how much of an impact the model predicts changes in sea ice extent will have, as it is commonly referenced throughout academia to have an impact (Fretwell, et al., 2012; Gearheart, et al., 2014; Putz, 1995; Borborglu & Boersma, 2013). As a result, this scenario assumes that all of the sea ice around Antarctica vanished maintaining the current environmental conditions. Naturally maintaining these other environmental conditions would be unrealistic, as it would be expected to see them also change with a reduction in sea ice extent. However, the climate under this scenario is disputed thus any attempt to predict the other environmental variables would be fraught with inaccuracy.

To create this data none of the environmental variables were changed from the current environmental conditions apart from minimum and maximum sea ice extent, whereby these were both set to 0 on all cells to simulate the loss of sea ice.

3.4.3 Maxent Setup

The setup of species distribution models can have a rather large impact on their ability to carry out the task (Guillera-Arroita, et al., 2015; Styfert, et al., 2013). The setup itself is heavily dictated by the species biology, study goals and data limitations (Meron, et al., 2013), and thus there are several key decisions to be made when setting up (Merow, et al., 2013; Guillera-Arroita, et al., 2015). Figure 6 presents the settings screens as they were used in the project. A major thing to address is the number of background points to use within the model. The number of background points used can have effects on the models output in many study areas (Phillips, et al., 2017b), with areas of extreme

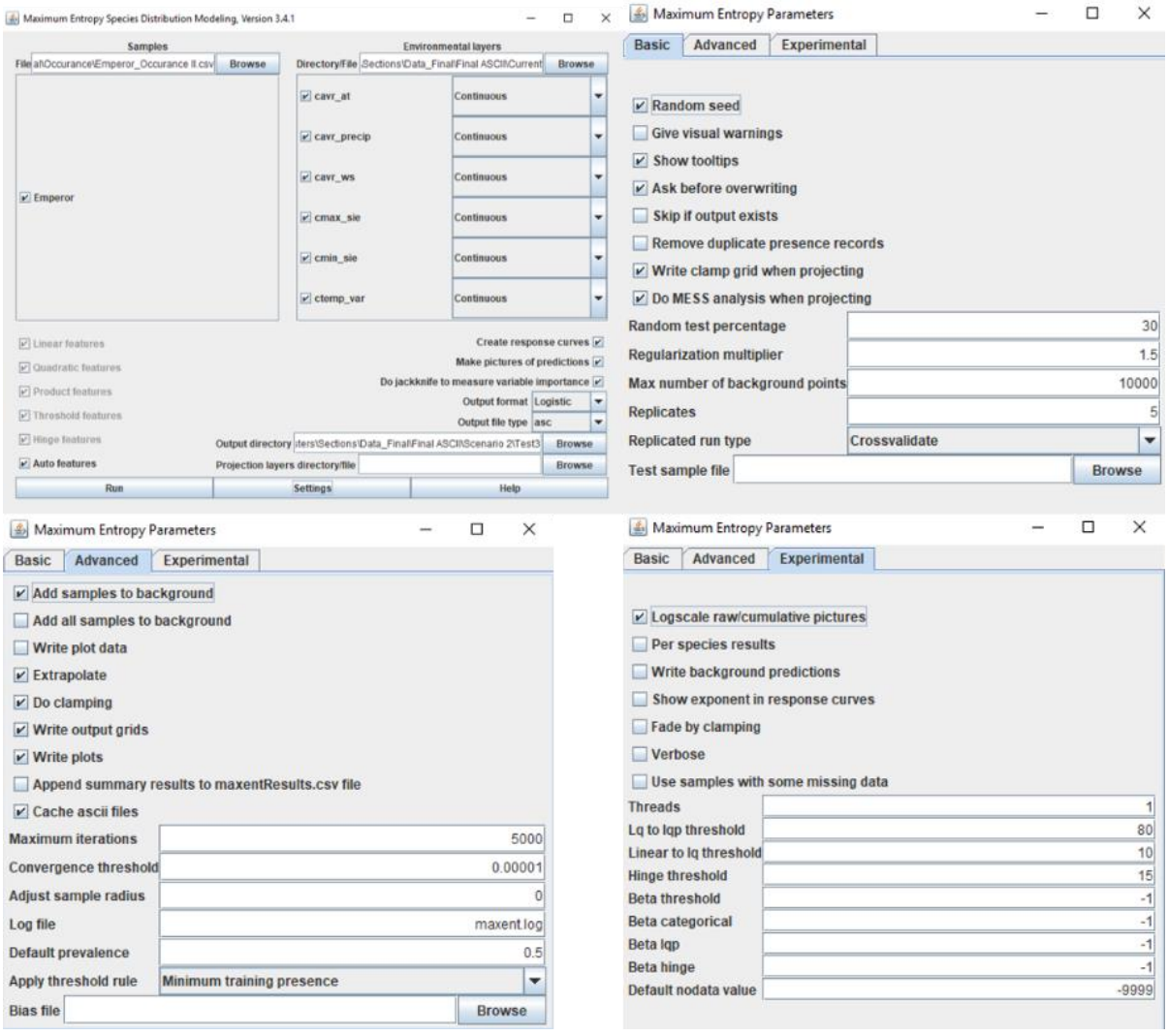


Figure 6: Maxent setup used for the creation of the model

environmental variation over a smaller area (mountain ecosystem) requiring an increased number of background points to fully interpret the environment (BCCVL, 2019). However due to the vast expanse of Antarctica as a study landscape and the lack of extreme variation in environmental variables it reduces the importance of background points, thus the default value was utilised.

Feature classes also have an impact. It was decided to leave this setting on auto to allow the model to judge for itself the best fit. Maxent deciding how complex the model will be based on the amount of presences (Phillips & Dudík, 2008), Maxent's optimisation was carried out with roughly 250 species with varying ranges, so the auto features has been optimised with a large number of species making it highly trustworthy.

There is much discussion in academia as to what output is the most advantageous, with some such as Meron (2013) suggesting a RAW output due to no reliance on post processing assumptions, where as other prefer to use the logistic, as highlighted by Yackulic, et al., (2012). This study used logistic, a modification of RAW, attempting to normalise across all the RAW probability values for its compatibility with the statistical interpretation to be used. The random seed is usually selected to subset 30% of the presence points as testing data after the models are run and for smaller test runs, however the crossvalidation setting was used to test the model instead. This especially useful with small sample sizes as it uses multiple replicates utilising different presences to train the model and a different set to test the model (Farkas, et al., 2007). This is well known as a good way of dealing with low sample sizes but not so effective on those with larger values (Philips, 2017), hence its use within this project due to the inherently low occurrences of colonies in comparison to the larger number of occurrences expected to be seen in other SDM's.

The maximum iterations of the model was set to 5000, with a convergence threshold at 0.00001. When the iterations become very similar the model is stopped assuming It is found the best fit, thus stopping at either 5000 runs or when the difference between the outputs gets to within 0.00001; saving on computing power and time whilst staying accurate and effective.

When setting up a Maxent model the issue of overfitting must be taken into consideration. It is constantly referenced as one of the flaws of Maxent (Phillips, 2017; Anderson & Gonzalez, 2011; Radosavljevic & Anderson, 2013) but the tool 'regulisation multiplier' is a way of mitigating these overfitting effects (Radosavljevic & Anderson, 2013). The best regulation multiplier value is still debated, some believe to achieve an optimum model complexity a regulation multiplier higher than default is used (Radosavljevic & Anderson, 2013) but others suggest performance decreases as the regularization multiplier was moved from default setting (Radosavljevic & Anderson, 2013).

Conclusively it is recommended that the multiplier is set to between the default (1) and 2, as a result the study was set to 1.5 to mitigate these overfitting issues.

The threshold rule is a setting used for the output. The minimum training presence was selected so when the model is run its predicted range keeps all of the occurrences within the presence section as it is know for sure that these emperor occurrence points are true and colonies are located in these positions.

The setting discussed represent the main adjustments made making the model perform the best within this study area and species. They are all the best assumption concluded from academic papers so they should provide well justified and informed results.

The interpretation of the results produced by the model can have a profound impact on the overall consensus of its representability. With the model run, the natural output was logistic, producing a value for each cell ranging from 0 – 1. This value gives a probability of presence within a cell, thus a cell with a value of 0.89 has a far higher probability of hosting emperor life as opposed to a cell of 0.12. However, as stated by academics such as Yackulic, et al., (2012), it does not prove useful to interpret the values with their specific probability units. As a result, it is suggested and referenced to interpret these results as presence or absence (Aarts, et al., 2011; Jimenez-Valverde & Lobo, 2007). Consequently, a threshold value was required, delineating the logistic output a cell would need to be above to be predicted as present. This threshold value was derived from Maxent's interpretation of the current environment and colonies. From here the results were put into ArcMap to be presented as seen in figure 12. Some post-processing was carried out to include reference to slope, putting the output file through a raster calculator with the slope layer deducting areas greater than 2°, thus ready for results interpretation.

3.5 Conclusion

Overall, the methods used in this project, although not optimal, have been justly selected with reference to reputable sources; thus should provide sufficient results to an acceptable degree of accuracy. The limitations of the methods should be reflected upon when interpreting results. Specifically, many projections failed to incorporate regional and local variation in the conditions as predicted to occur by the IPCC (2018). In addition, much of the information was derived from literature as opposed to accredited climate models. With more time and resources, a more accurate and reflective model could be produced.

4.0 Results & Discussion

This section discusses observations and trends seen within the results of the project, achieving objective 2 & 3 and providing supporting evidence for statements underlined in the literature review and methods sections. In addition, it will attempt to describe more prominent trends and propose their cause with the reinforcement of academic literature. Further to this, it will delve into the main discussion points of the dissertation, highlighting limitations or areas of improvement.

4.1 Current Environmental (Objective 2)

The next section details the results of the first Maxent model created to achieve objective 2, specifically utilising previously collected values of current environmental variables. This will allow for an assessment of the model's effectiveness at predicting the current environment, seeing how well it can predict areas where penguins are currently situated before moving on to predict future scenarios.

4.1.1 Model performance

Seen in figure 7 is the receiver operating characteristics (ROC) for the current environmental conditions in the first run of the model. This presents the ACU, a common metric used to assess the predictive ability of the model (Glover-Kapfer, 2015). The AUC normally uses presence and absence assessment data to evaluate a model's ability to effectively predict where a species is present and where it is absent. When absence data is not available the AUC measures whether model predictions are better than random (Phillips et al. 2006). These AUC scores range from 0 to 1, 1 indicating that the model predicts presences perfectly, and 0.5 indicating that the model predictions are equivalent to random guesses (Elith, et al., 2006). Looking at figure 7 the AUC score for the model is 0.973, with a standard deviation across the 5 models averaging 0.016. A standard deviation this small suggests that the 5 models run to test

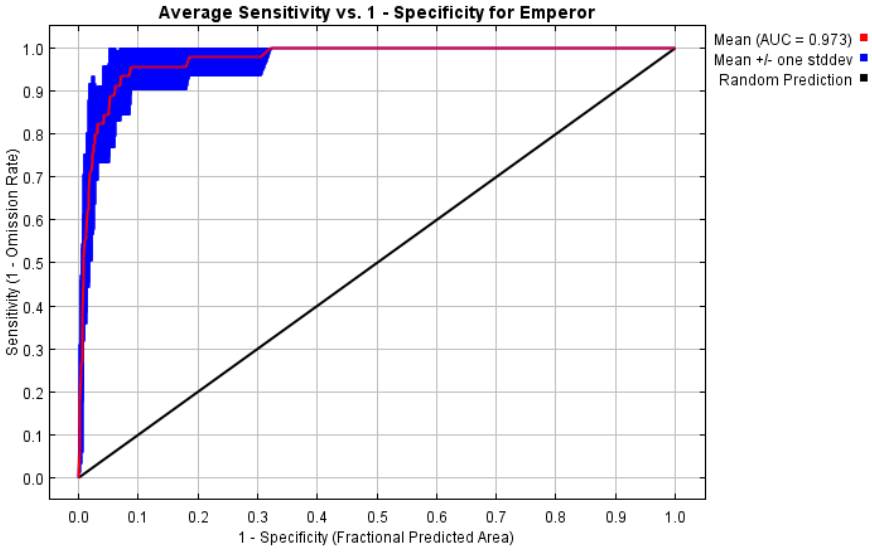


Figure 7: ROC of model under current environmental conditions

and train the ensemble all predicted similar results with only a tiny deviation between the minimum and maximums, thus increasing the perceived accuracy and reliability of the model. The general rule of thumb for an AUC, highlighted by Araujo (2005), is that a score over 0.8 is considered good, and those above 0.9 are considered very good. As a result, this AUC score of 0.973 is very good and thus the analytics are suggesting that the model has a very good predictive ability and therefore should be trusted. There have been criticisms raised by Lobo (2008) and Jimenez-Valverde (2012) of using an AUC as the solitary statistic for evaluating the suitability of these models, with its tendency to ignore the predicted probability of values as well as the goodness of fit of the model (Lobo, et al., 2008), making it an arguably misleading measure of performance. But to date, it remains the most common and reliable means for measuring model performance, hence its continued use throughout this project.

Variable	Percent contribution	Permutation importance
cavr_at	86.5	96.1
ctemp_var	5.9	2.9
cavr_ws	3.2	0.6
cavr_precip	3.1	0.1
cmin_sie	1.2	0.2
cmax_sie	0.1	0

Figure 8: Table of variable contributions for the current environmental conditions

4.1.2 Model Percentage Contribution

Many trends seen in the model can be somewhat explained by analysing the statistics in Maxent, these giving a potential insight into how it is creating the output. Looking at the percentage contribution column on the table (figure 8) the average air temperature (cavr_at) has the greatest contribution to the model's output. A contribution as high as this raises concerns regarding the models' performance (Phillips, 2017), potentially degrading its effectiveness as it heavily relies upon air temperature to dictate how suitable an area is for emperor penguins, with a more even weighting across the board being more common amongst other species. Emperor penguins are not like most species however, with a vast array of academics commenting on how increasing temperatures are known to have a profound effect on the species

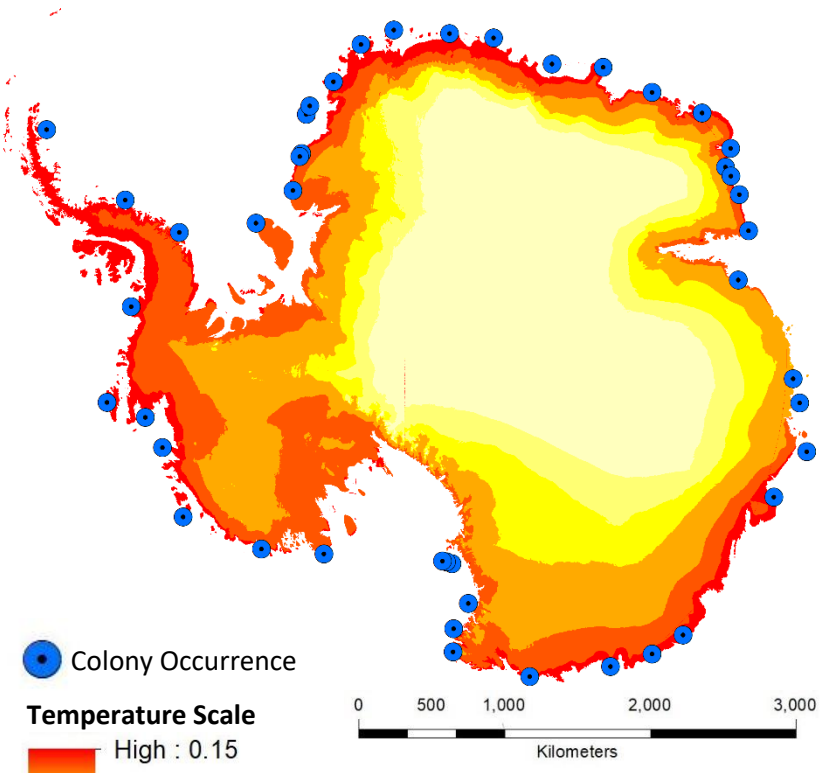


Figure 9: Temperature map with emperor colony occurrence

(Croxall, et al., 2002; Jenouvrier, et al., 2009; Barbraud, et al., 2001; Alhatem & Saavedra, 2018; Barbraud & Weimerskirch 2001; Fretwell & Trathan, 2019; Ainley, et al., 2010); Thus it is possible this high contribution does carry relevance. As highlighted by academics, increasing temperatures do not seem to directly affect the species, but have an indirect impact by affecting other processes penguins rely upon; such as its impact on food sources and sea ice extent.

Referring back to figure 8, the percentage contribution of other variables such as (cmin,cmax_sie & cavr_ws) lie relatively low in comparison to cavr_at. Realistically however these variables (min and max sea ice extent & wind speed) have a far greater contribution, and one that has been commented on by numerous academics (Barbraud & Weimerskirch 2001; Barbraud et al., 2011; Fretwell & Trathan, 2019; Trathan, et al., 2011; Cheung, 2008; Huang, et al., 2016; Jenouvrier, et al., 2009; Ainley, et al., 2010), so it is interesting to see that the model is not reaffirming this. It is possible this is due to multicollinearity, whereby variables following similar trends can be predicted by other variables (cavr_at) with a substantial degree of accuracy (Farrar & Glauber, 1967) this leading to their true impact being negated (Glover-Kapfer, 2015). However, this seems unlikely as their response curves (as seen in figures 10 & 11) portray vastly differing trends. It is more likely that this high contribution of air temperature and low contribution of other variables is a coincidental correlation. Maxent suggested that the biggest causation of emperor distribution is average air temperature, but they may just share a correlation. Looking to figure 9, all of the colonies are located on the coast of Antarctica, coincidently these coastal temperatures are comparatively the highest across the continent, mainly due to their proximity to warm water currents (thermohaline circulation) and lower latitude's increasing the ambient temperature (Screen, 2014). As a result, Maxent is correlating this trend statistically which then results in the model believing the average air temperature is the biggest driver for colony location, with warmer temperatures increasing the probability of presence. This backed up by the fact that the coldest regions of Antarctica further inland have no colony occurrence, further solidifying the models' assumption that higher temperatures equate to higher presence probability. However, reflecting upon this trend it becomes more realistic to suggest that penguins may not be on the coast solely because it is warmer, but because it is closer to their food sources. It is yet to be conclusively unproven but emperor penguins may, in fact, be able to adequately survive 5-10° degrees further south experiencing much colder weather if they had easy access to food sources. Although it is not proven that they can or cannot live in harsher conditions for the duration of the breeding season it is commonly referenced that they can survive in temperatures below -50°(C&F) during severe antarctic winters (Gilbert, et al., 2006; Gilbert, et al., 2007; Kirkwood & Robertson, 1997: Richter, et al., 2018), so it would not be unfeasible to assume they would still be able to thrive if the average temperature dropped 5-10°C,

below that of the models predicted colony niche. Ultimately the model is suggesting that average air temperature (cavr_at) is the biggest player in dictating emperor presence due to the location of current colonies matching that of higher observed temperatures, but realistically this is not the case; with reflection upon the results suggesting this temperature trend is a correlation not in fact a causation. If true this could prove misleading, as this reliance on air temperature by the model in predicting presence may end up negating the arguably more prominent and well-understood effect on the species, with its locality to foraging sites & food sources or optimum location for shelter (Trathan, et al., 2011; Huang, et al., 2016), all being a more logical suggestion for why the colonies are located on the coast, but one that obviously shows less of a statistical correlation thus is not highlighted by Maxent.

It may seem tempting to discount variables from the percentage contribution table (Figure 8) with low contributions, but because all variables influence model predictions to some degree, doing so would be a mistake. Particularly because their influence on model predictions may vary depending on environmental conditions. For example, if extrapolating model results to a new area where the variability of some environmental variables is different than where the model was developed, the relative influence of the variables may shift. Furthermore, although variables may not feature prominently in model predictions, that does not mean they are not critically important. Rather it could mean they are needed by the species in small amounts and that the accessibility of these variables does not vary throughout the study area (Glover-Kapfer, 2015). On top of this, there is already a limited amount fo environmental variables selected for use within this model, there are other variables that would be useful but due to complexity and a lack of available data, they were not included. Thus to remove more variables due to a seemingly low variable contribution would further degrade the effectiveness and ability for the model to best represent the environment.

Ultimately the results here have shown that the cause for the distribution is without a doubt a conglomeration of variables that all work together to dictate the habitable range for emperor penguins. But more prominently that the models' suggestion of variables contribution only shows correlation, not causation. With the average air temperature, although undoubtedly having an effect on the species, not having a direct effect as emperors have been seen to negate temperature in various cold weather scenarios.

4.1.3 Individual Response Curve Analysis

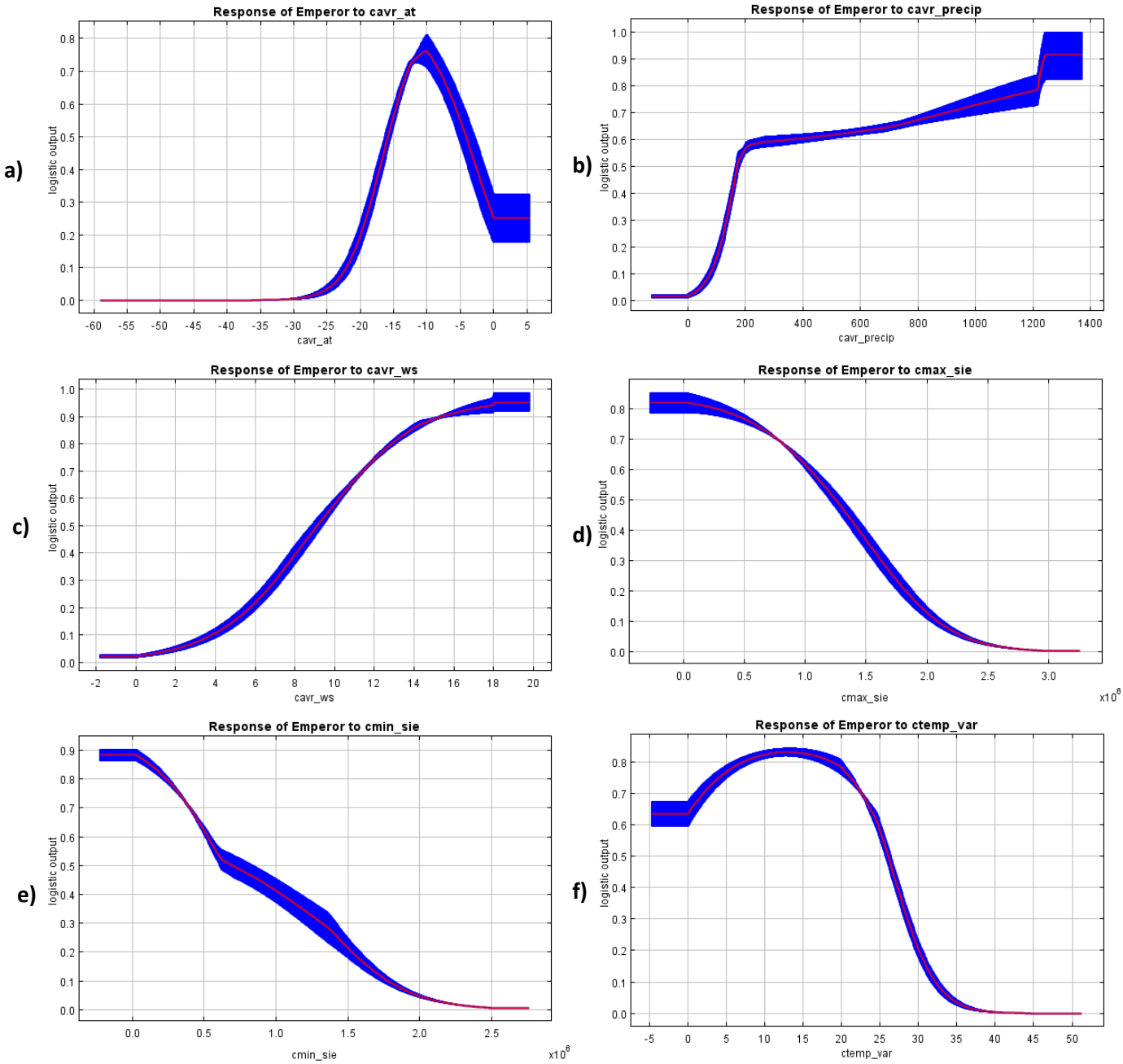


Figure 10: Response curves for all of the environmental variables used in the project within Maxent. Environmental variables run individually as the only variable in the SDM

The response curves display how each environmental variable influences the suitability of the environment. Looking at the environmental conditions alongside their percentage contributions, a better understanding of what the model is predicting and how the variable impacts the model can be gained. Figure 10 presents the response curves for each of the environmental variable if they were run individually as the only variable used in the model. Figure 10a shows the response curve

for average air temperature. The red line running throughout represents the average of all the 5 models put together, with the blue area representing the mean ± 1 standard deviation. With this in mind, it is apparent that all of the five model runs are predicting similar trends with little variation within the results. The response curve is plotted with 0.0 logistic output till around -30°C, at this point it begins to exponentially increase till it peaks at around 0.75 (-10°C) and falls to plateau at 0.25 (0°C). The area under this curve symbolises the models suggested optimum temperature range for the species, -30°C - 0°C. The temperatures at the colony locations correlate strongly with this assumption, with the minimum and maximum temperatures being -5°C and -30°C. The peak of this graph (highest logistical output) lies around -10°C, thus the model predicts this as the perfect temperature for emperor colonies. Interestingly however the data flat lines at 0°C; This could be attributed to the input data, with a lack of higher temperatures with known absences, potentially highlighting a flaw within the modelling process. Figure 10b presents average precipitation. With precipitation increasing, exponential growth is observed as the levels of precipitation pass 100mm/year levelling off at 200mm/year with a 0.6 logistic output. From here then the response curve slowly climbs till 1200mm/year and finished with a logistic output of around 0.9. This generally shows that as precipitation levels increase emperor penguins have a higher probability of presence. Precipitation has been discussed in academic literature to have an effect on the species, with Ainley (2010) stating it has a bearing on the well-being of Antarctic penguin populations. It is not a forefront proponent of the distribution but as highlighted within figure 8 (variable contribution table) and (Ainley, et al., 2010) It does seem to play a role. That being said the trend seen within this model may not be an accurate depiction of real processes. As with air temperature, it is doubtful that precipitation causes the distribution but just has a natural correlation. It is commonly referenced that the coastal areas have far higher precipitation accumulation due to higher temperatures thus moisture (Bromwich, et al., 2011; Delaygue, et al., 2003; Frezzotti, et al., 2004) compared to those of the drier interior; thus the model suggests a requirement for precipitation when realistically emperor's would probably survive perfectly without, but coincidently there are higher levels of precipitation on the coast where the colonies lie.

Figure 10c shows average wind speed in correlation with emperor presence. Starting at 0 a smooth increase in logistic output to 20m/s is observed; plateauing at 0.95. This high logistic output suggests wind speed has a large impact in colony locations. Corroborated by (Fretwell & Trathan, 2019) suggesting it must play a role in the distribution of this species. How much of an impact and whether that impact is direct or indirect is still unclear. It is speculated that wind speed has an indirect effect on the species as it is known that areas of higher surrounding wind speeds cause an increase in upwelling (Rueda-Roa & Muller-Karger, 2013; Morrison, et al, 2015; Anilkumar, et al., 2010) and

areas of upwelling are known to be major sources of food for penguins (Crawford, 2007), affirmed to have affected the distribution of sea birds (Weichller, et al., 2004). Thus as alluded by this response curve, wind speeds could play a more vital role in the distribution of emperor penguins than is commonly referenced, and therefore more academic work is needed to expand our knowledge on this intricate process.

Figure 10d shows the response curve of maximum sea ice extent. Here much of what academics suggest is further backed up statistically. As maximum sea ice extent increases, the probability of emperor presence decreased. As the distance penguins have to travel to get food for themselves and their chicks increases (Maximum sea ice extent) the probability of presence decreases. Penguins themselves have been known to travel huge distances, but to maintain the livelihood and mortality of a chick this is not preferred, as increased sea ice extent results in further to travel, thus more time a chick would go without food. Consequently, this means there is a higher chance of chick starvation, decreasing the breeding success of a colony and ultimately reducing their population. As the maximum walking speed for emperor penguins is 1.7mph (Nuzzolo, 2002), it does not take a huge amount of increased area in sea ice to have large effects on the travelling time. Over the duration of fertilisation and incubation males fast for roughly 115 days (Kooyman, et al., 2018) thus an increase in travel time would assumedly have negative effects on the fasting individual as they would have to travel further and expend more energy without food.

Minimum SIE shows very much the same thing but with a different trend (Figure 10e). The theory described above stands for this variable, but the trend seems to adjust its rate of change throughout the increase in minimum sea ice. This potentially due to the wider range of variables at minimum sea ice, with some areas having a substantial amount of sea ice and others having none.

Temperature variation's response curve (Figure 10f) suggests that with no variation emperor penguin colonies thrive. This corroborated by Goldsmish & Sladen (1961) stating that the consistency of temperature causes fewer survival issues. However, as the variation increases, the logistic output also increases, levelling off at around 12.5°C of variation between the hottest and coldest temperatures and then slowly then rapidly dropping to 0 within 20° from this optimum temperature. This is due to all colonies experiencing some form of temperature variation, thus the model believes some variation is needed when it may not be. The severe drop in probability presence is likely a result of a low frequency of colonies with large temperature variations. It is known that emperors can survive extreme anomalies in variations such as winter storms, and with their physiological setup allowing them to survive extreme temperatures it may prove that temperature variability has an insignificant impact on the species.

Collectively these response curves reinforce assumptions and academic literature explaining the reasons for emperor colony occurrence with reference to individual environmental variables. However, an accurate model does not assess each of the variables individually but assimilates all to see how they interact and affect the species collectively.

4.1.4 Collective Response Curve Analysis

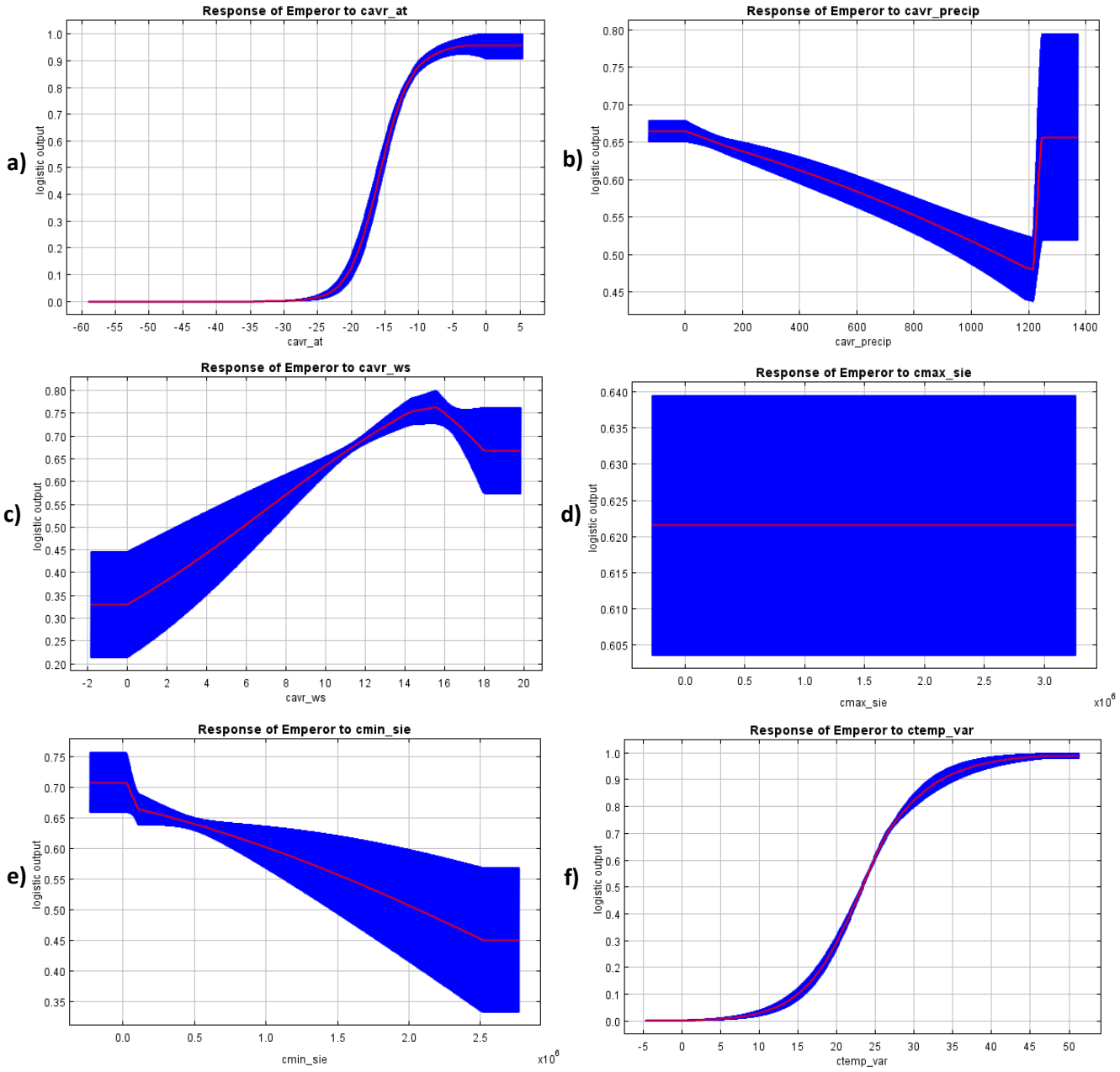


Figure 11: Response curves for all of the environmental variables used in the project within Maxent. Environmental variables run together within the SDM

Figure 11 presents response curves for all the environmental variables run through Maxent collectively within the same model. Before inferring from these results, it is key to understand that the curves can be hard to interpret if variables are strongly correlated. The model can potentially depend on correlations in ways that are not apparent within the response curves, only showing negligible effects of changes in one variable, when in fact it may take advantage of groups of variables changing in unison (Phillips, 2017).

Figure 11a presents average air temperature impact amongst all of the other variables. Comparing this to (Figure 10a) there are drastic differences. Firstly, the overall trends vary, with the model showing an exponential increase in the logistic output at around -25°C levelling off at 0.95LO at -5°C, this a change from figure 10a as this drop is not seen in its logistic output after a set temperature but a plateau at higher temperatures. This could suggest uncertainty in the model's ability to project to higher temperatures as a result of this response curve ending with such a high logistic output. With more absence background points of higher temperatures (lower latitudes), it may not display such a trend, as the model would have a reference for the species upper-temperature boundary. This may be due to all the variables being used within the same model, potentially interacting with one another in a unique way unapparent within the response curve graph. Ultimately there is little literature describing this occurrence, thus further testing would be needed to resolve the query.

Figure 11b shows average precipitation within the combined variable model. The figure predicts a relatively high logistic output of 0.65 at 0mm/year, then as the rainfall increases this logistic output decreases slowly to 0.45, at this point it then rapidly jumps back up to 0.65 whereby the 5 models show varying logistic output results with some predicting 0.8 and others only showing an increase to 0.52. This trend of a sudden jump just after 1200 mm/year is replicated in figure 10b, so it makes sense to assume most of the colonies precipitation levels fall around the point of 1200 mm/year. However, the highest logistic output of this variable is not conclusive, with a level of 0.65 at the start and the end. Thus the maximum logistic output for precipitation is not impactful on the overall model, backed up by its additionally small 3.1% percentage contribution in figure 8.

Figure 11c displays the combined model's response to average wind speed. The graph presents an increase in probability as wind increase, corroborating the idea that wind speed may have a more intriguing relationship with distribution than highlighted. As the average wind speed reaches 15m/s a drop in the logistic output from 0.75 to 0.67 is witnessed. This would suggest that the optimum wind conditions suggested by Maxent for emperor penguins lie between 10ms/-1 to 18ms/-1.

Figure 11d displays the response curve for the maximum sea ice extent. The curve stays consistently at 0.622, potentially indicating the model's dependency on correlations that are not evident within this curve (Phillips, 2017).

Figure 11e displays the response curve for the minimum sea ice extent. A reduction in logistic output as the minimum sea ice extent increases is observed, more specifically a minor drop from 0.7 logistic output to just over 0.65, then as presented in the graph there is a gradual decrease reaching a minimum logistic output of 0.45. The degree to which this reduction changes varies throughout the 5 models. The area in blue increases in size as the sea ice extent increases, thus the accuracy and certainty of this result towards the upper end of the spectrum comes into question. This trend is somewhat expected as all of the colonies are seen on the coast, thus individuals have less distance to cover in order to forage for food. Statistically, the model is assuming that penguins favour areas with less sea ice extent. This may be true in some instances but the intricacies of optimum sea ice Figure 11f varies from its individual counterpart, with Figure 10f depicting temperature variation increases causing a reduction in the logistical output of the model. However, when combined with all variables figure 11f suggests that as the temperature variation increase so does the logistical output and thus the probability of presence for emperor penguins. It is expected that penguins strive for temperature stability for a more comfortable lifestyle, whereas the model suggests emperors prefer a niche whereby the minimum and maximum temperatures are varied more drastically. It is unclear as to why the model is presenting this trend, with the percentage contribution table (figure 8) showing its small 5.9% contribution to the overall model, thus somewhat reinforcing the idea that the variability of the temperature has less of an impact on the species and only comes into play at extreme variation.

Overall these response curves have presented individual model responses to the environmental variables, highlighting how both independently and dependently the probability of presence changes as environmental conditions are adjusted. It is also highlighted some prominent trends to be discussed in further detail in the main discussion section.

4.1.5 Visual Interpretation

The first Maxent model (Figure 12) was run using current climate environmental conditions, to accurately predict the presence of current colonies. This providing information (from Maxent) as to what variables affect the distribution, how they affect it and assessing any trends the model is presenting in their current distribution.

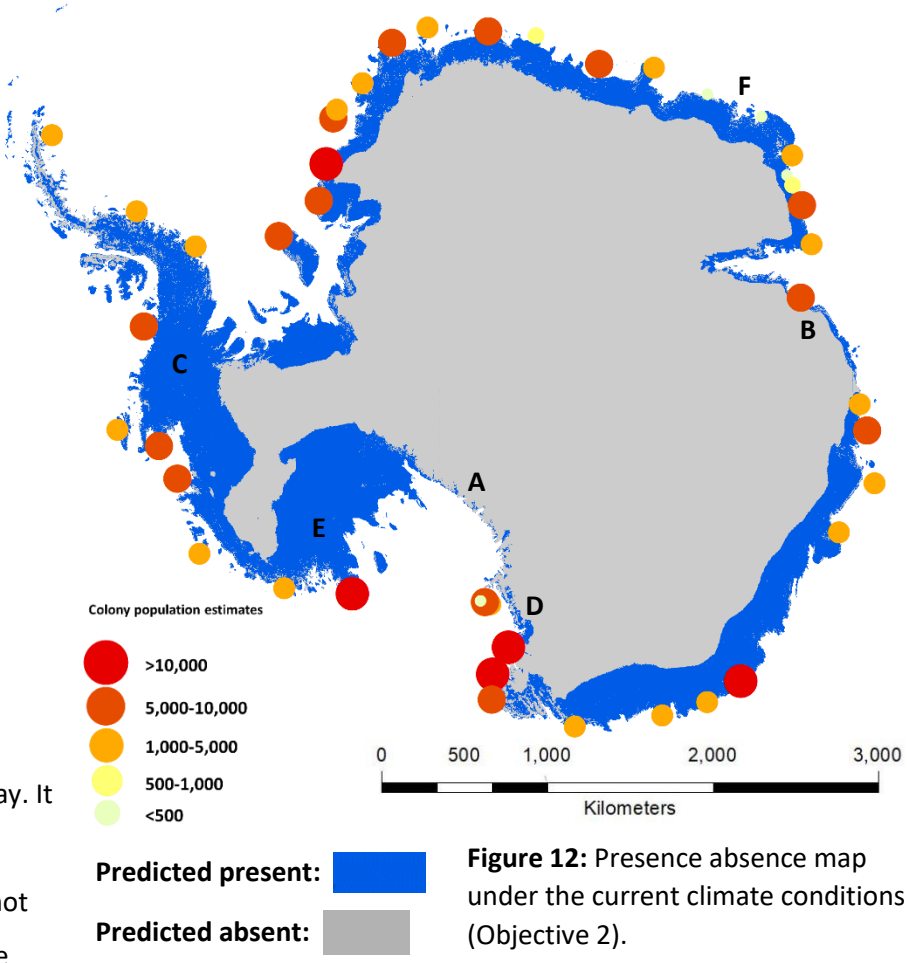


Figure 12: Presence absence map under the current climate conditions (Objective 2).

Figure 12 presents the ensemble model of the current environment run through five iterations in Maxent. This variant of the model correctly predicts the presence of all emperor colonies as they stand today. It can be seen that the locations that emperor colonies are found at are not the only areas that they could reside within. All the area in blue (exclusively situated along the coast) are locations whereby the environmental variables fall within the species environmental niche (defined by the model) and thus could support an emperor colony. Reflecting upon the general trends the model is presenting it can be seen that it is predicting areas along the coast to have the highest chance of occurrence thus is classifying these areas as presence. This corresponds with the actual locations of the colonies, with all of those observed in the real world today falling within areas of presence. Looking at the general distribution and frequency of the colonies there does not seem to be too many observable trends, all of the colonies are situated along the coast but with regards to the frequency and their distance apart it seems random. One would expect to see that areas along the coast that are home to a large number of colonies would have more presence conditions surrounding them, but this does not seem to be the case, with areas such as **D** showing extremely limited presence predictions but with 6 colonies referenced to be

present in this general area. In contrast observing area **E** it can be seen that there is an abundance of the surrounding area predicted as suitable for presence but only 2 colonies in the vicinity. This could potentially allude to the model not accurately assessing the variables affect the species distribution. Besides this, there is a relatively consistent spread of colonies reasonably evenly distributed around the peninsula regardless of how much of the surrounding area the model is predicting as presence.

It was concluded that larger colonies (those with greater populations) would be located in and around large areas of predicted presence, but this does not seem to be the case. In location **F**, for example, are two of the smallest emperor colonies with populations of under 500 individuals (Fretwell, et al., 2012) thus suggesting that perhaps it is less favourable to live here, however, the model is suggesting that there is a large area of predicted presence buffer around these colonies that could host life. In contrast, some of the biggest colonies with populations up to and greater than 10,000 (Fretwell, et al., 2012) are located around point **D,** which has a limited area of predicted presence in its vicinity. This raises questions as to whether or not the environmental variables inputted into the model are best representing the distribution/population, or if there are other variables not included in the model that are having a bigger impact on the species. One such example of a variable not referenced within the model is that of food stocks, something that could have a far greater impact of the size of the colony potentially explaining the unusual trends seen with area **F** & **D**. A greater abundance of food results in the increased prosperity of a population (Wauters & Lens, 1995; Oro, et al.,1999; Fretwell, et al., 2014). Unfortunately, the data acquisition for such a variable would be extremely hard to acquire and incorporate significantly within Maxent, thus further research and development is suggested to further improve on modelling this species.

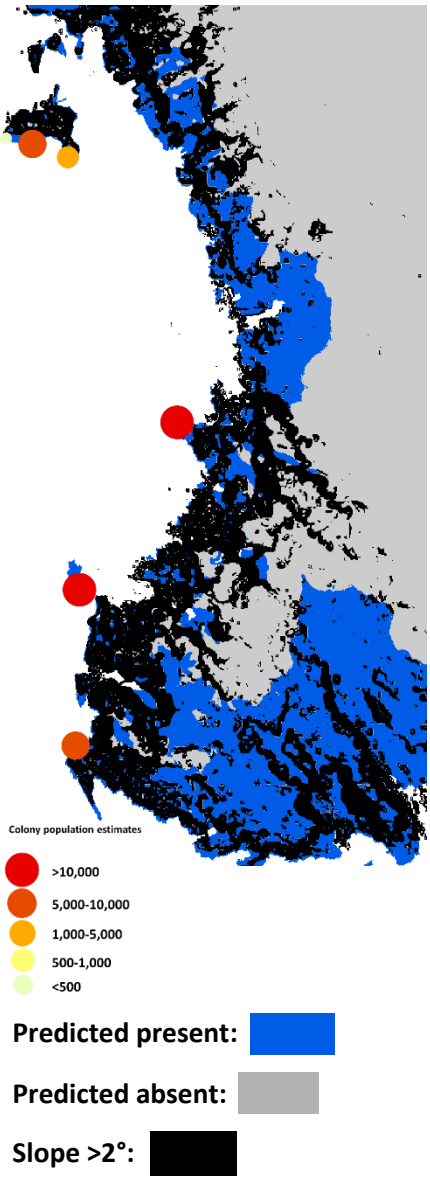


Figure 13: Areas of slope greater than 2° on the Borchgrevink coast (Black)

Interestingly there is a large amount of variation from coast to coast, with locations such as (**A** & **B**) having an extremely low area of presence, compared to a location such as **C** and its surrounding area, whereby the model is predicting an abundance of area with favourable environmental conditions for emperor penguin colonies. Such regional differences are naturally to attributed to the variations in environmental conditions across Antarctica (BAS,2019; Schneider, et al.,

2004) highlighted by a plethora of studies to be influenced by the Southern Annular Mode and El Nino-Southern Oscillation (Bromwich, et al., 2003; Ribera and Mann, 2003; Gillett and Thompson, 2003; Kwok and Comiso, 2002; Thompson and Solomon, 2002). This regional climate is predicted to have more noticeable effects on Antarctica looking to the future (Vaughan, et al.,2003) and as such these trends highlighted by the model may become exaggerated, with some areas being uninhabitable whilst others thrive. Yet another reason work such as this should be carried out and conservation efforts for the species should be considered.

Looking at all of the locations where emperor penguin colonies are found it is seen that they are nearly all situated in positions next to an area of slope higher than 2° (Figure 13, a map of the whole continent can be found in Appendix B-1), with many if not all located close to steep ridges. Kooyman (1993) states that one of the most important physical characteristics for a breeding habitat is shelter from the wind, exactly what the model is presenting and corroborating. Many emperor colonies situate themselves next to cliffs and ice shelves on land that are used as shields from harsher winds. This becomes invaluable information when discussing further conservation and relocation efforts.

Due to the performance of this model and its ability to accurately and reliably predict all of the locations for current emperor penguin occurrence, it is considered a proficient optimum model and was carried forward as the base model to reflect upon when discussing future scenarios. Unfortunately, a flaw with Maxent is that it cannot run a model with a range of different environmental scenarios, the programme only allows the model to be run with one future scenario. This means that to produce future projections for the other scenarios the model will have to be run multiple times with the same settings to represent a different scenario each time. Naturally, this will cause minor variability between each model run as it will not provide the exact same variable contributions, AUC for example. Maintaining the settings of the base model (current environmental conditions) will mitigate this error and drastically reduce the possible fluctuations in the models' analysis.

4.2 Future Environment (Objective 3)

The next section details observations of scenarios 1/2, providing explanations and academic evidence for witnessed trends, ultimately achieving objective 3. It is hypothesised that with an increase of 1.5°C there will be an observed decrease in the projected niche.

4.2.1 Scenario 1

Model Performance and Attributes

Maxents projection onto the future conditions seen in scenario 1 resulted in an AUC of 0.971 and a standard deviation of 0.020; maintaining the respectable predictive ability and reliability of the base model. The model's percentage variable contributions similarly remain largely the same as that of the current environment's.

Visual Interpretation

Scenario 1 was the first of three scenarios designed to test the model against future environments. Heavily based upon the IPCC's RCP 4.5 (IPCC, 2014; IPCC, 2018) for the year 2050. Under this scenario it is expected that global temperatures will increase by roughly 1.5°C having impacts on the environmental variables, but is also the global limit set by the Paris agreement (2016) that highlighted by Jenouvrier, et al., (2019) gives the species the best chance for survival. Figure 14 presents the results of this scenario, with all areas in purple highlighting predicted colony presence. Interestingly it seems the results of this model go against much of current academic literature and the proposed hypothesis, with more total area of Antarctica being predicted as habitable for the species. This contradicts many academics who have suggested that increases in temperature as a result of climate change could potentially prove devastating (Barbraud & Weimerskirch , 2001; Jenouvrier, et al., 2009; Jenouvrier, et al., 2012; Jenouvrier, et al., 2014), with 50% of emperor colonies predicted to decrease in size or disappear as a result of a 2°C increase (Ainley, et al., 2010). The overall change from the current environmental conditions does not seem to be too large, with areas along most of the coastline showing a slightly greater area of predicted presence. Interestingly however it seems area A will experience the biggest change, with much of the region surrounding becoming available for colony

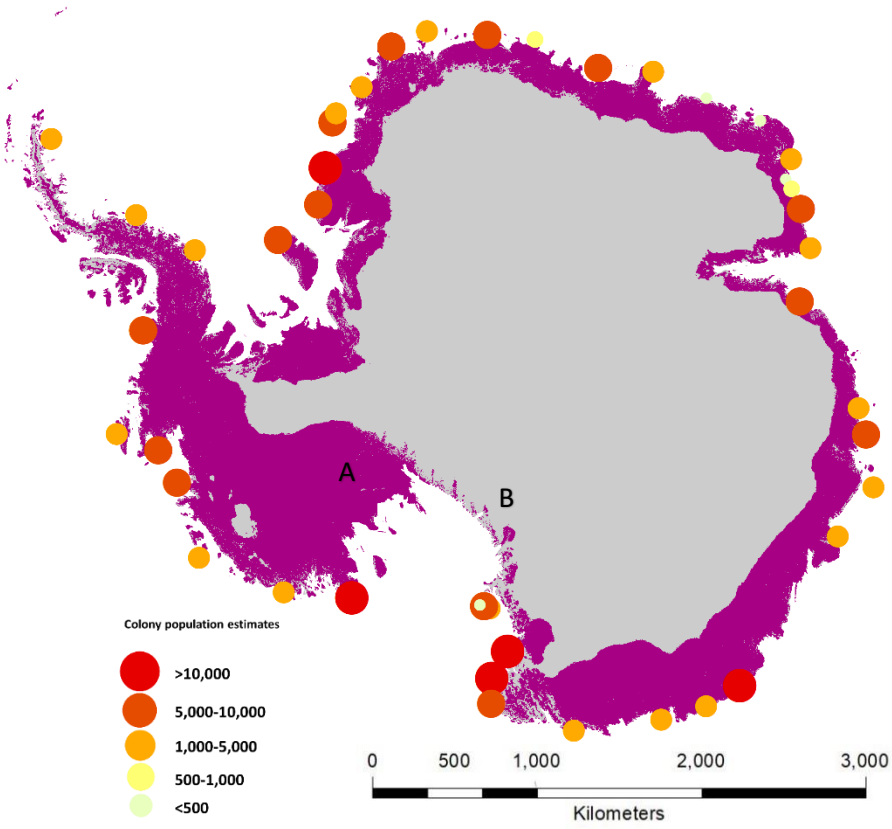


Figure 14: Presence absence map for Scenario 1 (Objective 3)

presence compared to the current environment (1.5°). The cause for this shift can be attributed to the temperature values at A in the current environment laying just outside that of the environmental niche, so as there is an increase of 1.5°C this region is then shifted to within the environmental niche. Overall there does not seem to be too large of a change seen in scenario 1 compared to the current environment, with just a small increase in the predicted area of presence across all of Antarctica. The uniformity in this increase is partially due to the data setup, with the process of simply adding 1.5 to all of the cells to acquire a 2050 value. The change itself, however, is down to the fact that the model is heavily relying on the average temperature to dictate where penguin colony presence is. With Maxent assimilating higher temperatures with more preferred environments, it is seen that as climate change progresses and temperatures increase more of the previously colder locations on inland Antarctica would fall within the temperature niche of emperor penguins. This trend poses intrigue as it could be accurate. If the climate of Antarctica became warmer as a result of climate change then extreme negative temperatures would not be as impactful and the living conditions would be more comfortable, with the addition of colonies being able to breed further inland due to this environmental niche shift presented in figure 14. However, the model does not take into consideration other non-numerical factors that were not incorporated within it. With average temperatures increasing by 1.5°C sea ice would classically be expected to see a reduction (Lie, et al., 2004), this is somewhat incorporated within the model, however, the impact this would have on food availability for emperor penguins is not. As temperatures increase Krill and other food stocks who consider under ice as an important habitat (Brierley, et al., 2002; Marschall, 1988) will be directly impacted, causing a probable reduction in populations (Nicol, et al., 2007). Water quality could also become unsuitable for the food stocks with increased ocean acidification attributed to warming (Doney, et al., 2009). Overall this shows an inherent flaw within this model and critically impedes on its ability to be transposed to real-world scenarios. Negating the implications on foods, the model does do a good job in predicting areas that penguins could reside within if only referencing their environmental niche. It could also have applications within conservation as it potentially highlights that the most fragile and important variable in dictating emperor distribution is their food source.

Predicting a change in distribution such as this is beneficial but is based on many physiological and dispersal assumptions (Jenouvrier, et al., 2019). Can emperor penguins survive in a climate 1.5°C above what they experience now? Would they be too warm and overheat? As it stands there has been no academic work in recent history on the physiological limits of emperor penguins, especially in regards to their maximum temperature and its effect on their livelihood. But Peck, et al., (2009) states that Antarctic marine species were observed to survive temperature changes of 8-17°C with a

temperature increase of 1°C per day (with varying effects on the rate of change) but its relevance on emperor penguins is undecided. Naturally to carry out an experiment concluding the maximum temperature of the species would be inhumane as it would be putting the lives of emperors at risk, so it is hard to definitively say whether the species would be able to survive in predicted future conditions. The only reference is that of Maxent, assessed running hundreds of test across lots of different species, including plants (Wilson, et al., 2009; Yang, et al., 2013; West, et al., 2016) its default bounds either side of the current occurrence is set up and tested reliably, thus for this project it was assumed that they fall within this and the model is predicting correctly. There is uncertainty within this method as emperor penguins could be an anomaly and may not fit the trend due to their unique lifestyle and environment. But It can be believed that the physiology of the emperor would be able to sustain life in an area with an average temperature increase of 1.5° in its current environment. They have survived previous increases but only further research would be able to affirm this. If the species struggled physiologically with living in conditions of 1.5° above current conditions, then the model does a fantastic job of highlighting areas of environmental buffer inland they could simply move to maintain their current temperatures.

Area B has experienced little to no change in its predicted presence or absence from the current environment. This may be down to the heavy weighting of temperature, and this area is further inland with a higher latitude and elevation, even with an increase of 1.5° its values do not fall within the projected environmental niche of the species. The region is also an area of mountainous terrain, so even if it fell within the environmental niche of the species the model would suggest it was unsuitable due to the slope being too high for a suitable rookery. It could, however, prove to be a useful area as this terrain would provide shelter for colonies, known to prove beneficial for the species (Kooyman, 1993).

Why is the model predicting this future 2050 environment will be more beneficial for emperor's? As seen in figure 15, the percentage contribution of the model running scenario 1 is very similar to that of the current environment model, with this cavr_at having the highest contribution, solidifying

Variable	Percent contribution	Permutation importance
cavr_at	89	96.6
ctemp_var	5.4	2.2
cavr_precip	2.8	0.2
cavr_ws	1.9	0.7
cmin_sie	0.5	0.2
cmax_sie	0.3	0

Figure 15: Percentage contribution table for Scenario 1 (Objective 3)

previous statements of the models heavily reliability on average temperature when calculating the probability of presence for emperor's.

Figure 10 & 11 presents the response curves of each of the variables within the Maxent model for scenario 1, with the probability on the y-axis and variable range on the x-axis. Focusing on the curve that best represents scenario 1, (figure 16) in coordination with figure 15 (percentage contribution table) shows just how much of an impact this average temperature is having. With an increase of 1.5°C seemingly small, if locations on Antarctica are on the edge of Maxent's predicted environmental niche, then as seen in the graph a change in temperature of 1.5°C could cause an increase in this logistical output of between 0.1-0.2, this along with figure 15's average air temperature percentage contribution of 89% explaining just why there is such a prominent increase of the area of predicted presence.

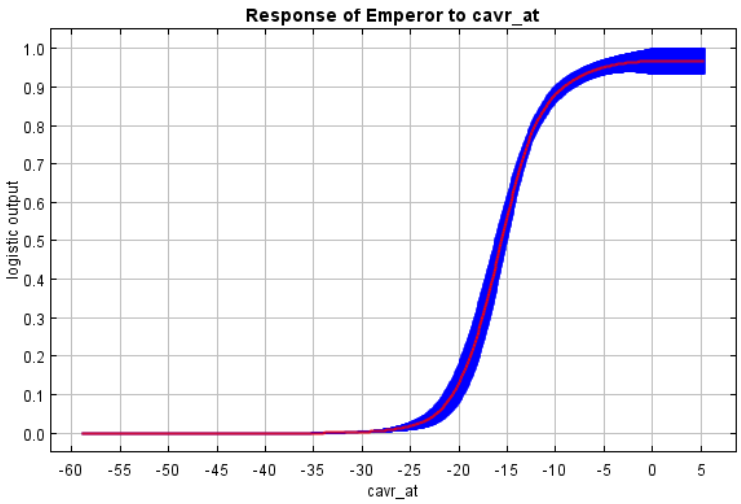


Figure 16: Response curve of average air temperature

Ultimately scenario 1 demonstrated that the model is presenting an increase of 1.5°C, expected to be seen in 2050 under RCP4.5, causing a relatively moderate increase of emperors environmental niche. This goes against much of academic literature but can be attributed to the models heavy weighting on the average temperature in predicting the distribution. It is also key to understand that the model has not incorporated all of the variables that impact the species due to constraints, and the inclusion of some such as food source availability would potentially have prominent effects aligning the results with that of current literature. On top of this, it must also be understood that the model is predicting change in the environmental niche of the species, and is not predicting the actual change emperor penguins will experience. Thus if reflecting upon the results with this in mind it seems a probable and realistic assumption.

4.2.2 Scenario 2

It is hypothesised that scenario 2 will display a reduction in the presented area of presence, due to the known relationship between reductions in sea ice and emperor populations.

Model Performance and Attributes

The performance of the model run to simulate scenario 2 yet again upholds the high standards of the model's predictive ability so far, with an AUC of 0.972 and a standard deviation of 0.015; with this low standard deviation suggesting reliability within the models and its mean. The model's variable percentage contributions remain largely the same as the model run for the current environmental variables.

Visual Interpretation

Scenario 2 was designed as a more extreme environmental scenario, with a multitude of sources suggesting that with a loss of sea ice penguins would see negative consequences (Ainley, et al., 2010; Barbraud & Weimerskirch , 2001; Jenouvrier, et al., 2009; Jenouvrier, et al., 2012; Jenouvrier, et al., 2014). As a result, this scenario assesses the situation of emperor penguin presence if there was a complete loss of sea ice, seeing if the model follows trends or had any resemblance to these academic assumptions. Whether or not Antarctica will experience a total loss is up for debate, with many academics alluding to the devastating impacts this warming will have on ice (Barbraud & Weimerskirch 2001; Barbraud et al., 2011; Turner, et al., 2017; Forcada & Trathan, 2009) and others such as Smith et al (2012) proposing how current ozone recovery may substantially mitigate Antarctic ice loss, alleviating concern on the matter. Figure 17 presents the visual results of the Maxent model run will all the environmental variables identical to the current day but with sea ice extent values reduced to depict a complete loss of sea ice.

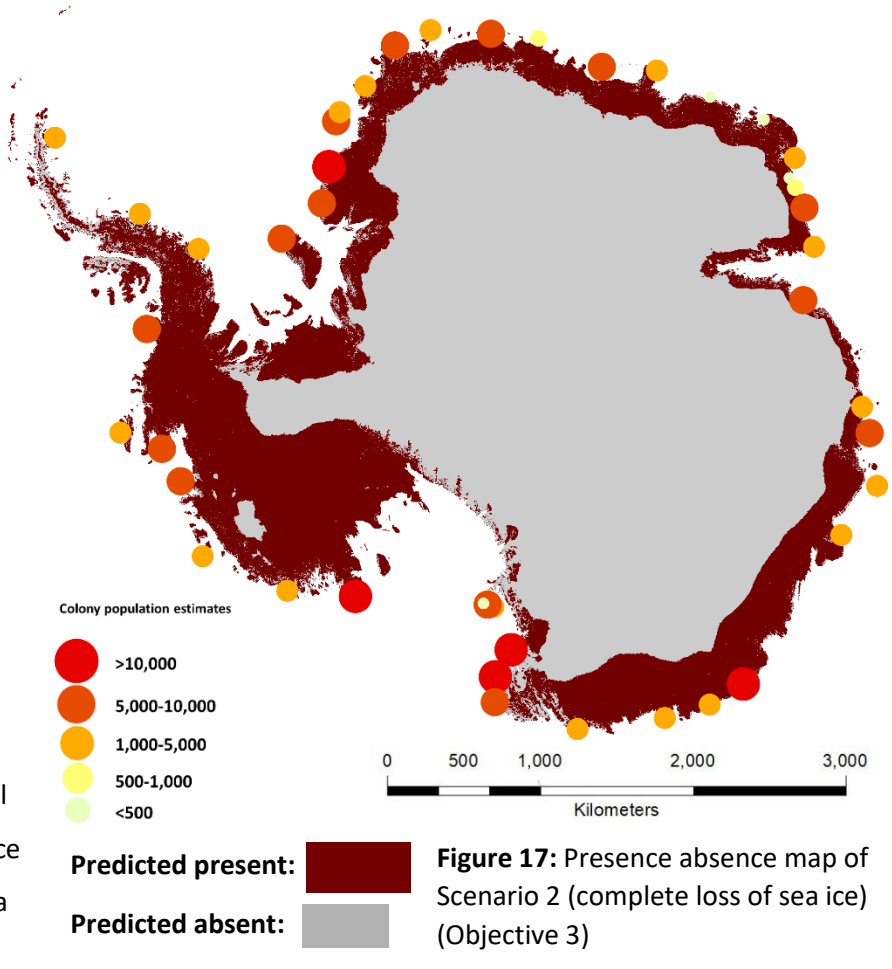


Figure 17: Presence absence map of Scenario 2 (complete loss of sea ice) (Objective 3)

As seen in figure 17 Maxent's conclusion for a scenario with no sea ice somewhat matches the results seen in scenario 1 (2050 predictions), this goes against much of academic knowledge as it would be expected to see areas with predicted presence shrink as opposed to expand, resulting in the rejection of the proposed hypothesis. It would be expected and has been commented that living conditions for emperor penguins would drastically reduce with a complete loss of sea ice; with 44/46 colonies situated on the sea ice (Fretwell, et al., 2012) and their main sources of food relying upon sea ice for survival (Atkinson, et al., 2004; Nicol, 2006)

The difference between scenario 1 and 3 are minimal. The western coast of Antarctica has an almost identical predicted niche as that of scenario 1. Interestingly moving around to the east and specifically the south coast it can be seen that the effects of no sea ice are far less than those of the 2050 scenario 1 assumption. This potentially due to the fact that there was already less sea ice on this south coast, thus a total loss is less drastic.

Overall however Maxent is not suggesting a substantial change. Looking to figure 8 & 15 it is seen that the total overall contribution of maximum and minimum sea ice extent is not that large, and looking at figure 18 it is seen that within the model and when run individually the general model consensus is that as sea ice extent increases the probability for penguin presence reduces. This makes sense within the context of the model and the parameters it was given, as all of the colony presences are along the coast, coincidently having the shortest distance to the edge of the sea ice. As a result, the model would assimilate these statistics and assume that as the distance from sea ice increase (moving inland where there are no colonies), then the probability for a colony would decrease. However, reflecting upon the real-world situation and those the model cannot take into account, changes the outlook of the

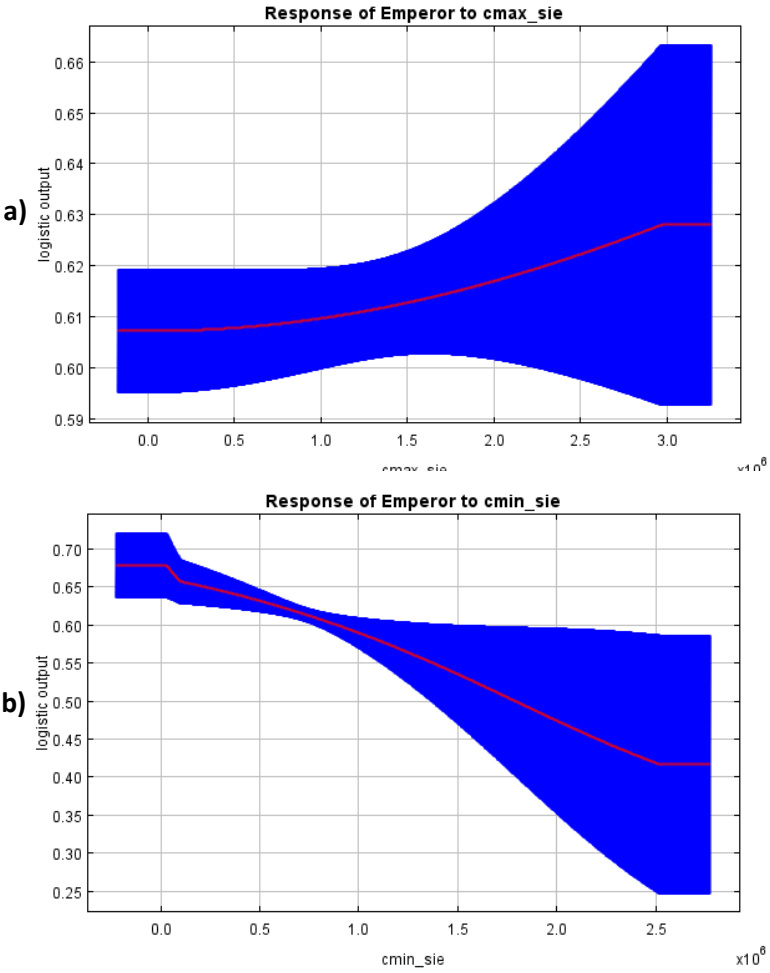


Figure 18: Response curves of minimum and maximum sea ice extent

results. To some extent, the model is correct in stating that as the distance from the colony location to open water increases then the likelihood of a colony is reduced, due to the long distances penguins need to travel causing increased chick and individual mortality (Gross, 2005). However, there is a finite balancing act in place, with increased distances to the edge of the ice can have a range of negative effects, but as does a reduction in the distance. Ultimately the impact of a complete loss of sea ice is not well documented, with uncertainty as to the exact effect of the situation. It may be found that the model is predicting correctly and a lack of sea ice provides beneficial to the population as their food sources may against all assumptions be able to thrive, but this is up to future studies and research to determine its exact effects.

Why is the Maxent suggesting this trend? Looking in greater detail at the impacts of the variables in figure 18, these representing a more detailed view of the effect min and max sea ice extent has on the model as a whole. In (figure 18a, maximum sea ice extent) as the maximum sea ice increases there is a slightly larger predicted probability with an increase of 0.02 on the logistic output, with much-disputed variation between the 5 model's as highlighted by the standard deviation (blue), somewhat following confliction in academic works. In comparison, it is seen that figure 18b (minimum SIE) shows a rapid drop of 0.25 logistic output as the extent of the sea ice increases. This suggesting that penguins prefer it when the maximum distance of the ice in winter is greater and in summer when the ice has less of an extent. During the harsher winter months, penguins want to travel less distance, and in summer it would not matter as much due to the more mundane conditions. Interestingly September (the time of greatest sea ice extent) is the point that the chicks require the most energy and thus both parents go to forage, whereas during December (the month of lowest sea ice extent) Chicks have started to fledge and the majority have abandoned the colony (Borborglu & Boersma, 2013). Perhaps emperors need to adapt their breeding cycle to best represent these ice extent patterns, especially with climate change's predicted impact on shifting the breakup, build-up and duration of sea ice extent (Scambos, et al., 2000; Maris, et al., 2015).

The degree of change seen in figure 18 from the reduction in sea ice is not large. Looking at figure 8 & 15 this is reflected by the minimal effect the minimum and maximum SIE has on the model as a whole. Looking again at Figure 10 it can be seen that both the min and max SIE were run independently in their own model. In this model, the effects that the variable has on the overall predictive ability are greater, with the individual models suggesting that as the SIE increases the probability of presence is greatly reduced, with both having a probability of 0 as the distance gets to two-thirds of the size on the graph (figure 10). But with all of the variables inputted together this impact on the model is then reduced, due to statistically the correlation of SIE and colony

occurrence being far less than that of the land surface temperature, dwarfing the impact that SIE has on the overall as the model believes it to be insignificant.

This minimal change highlights issues within species distribution modelling on a species that relies so heavily on feeding grounds impacted by an array of variables, and one that cannot be directly represented within the model. The output suggested complete sea ice loss would cause a slight increase in the area of predicted penguin presence. Statistically, this makes sense, with the general trend analysed by the model being that as the maximum distance from the colony to the sea reduces the probability increases. Assessing this via post-processing and from a human standpoint, however, provides evidence to the contrary. Ultimately the percentage contribution of SIE was decided by the model be to extremely low (around 0.3-0.5%) as a result of the overwhelming contribution of average temperature, thus the model does not present a large change in their predicted niche even with a complete loss of ice.

Upon reflection to the future of current colonies observed on Antarctica, this model predicts that with a loss of all sea ice there will be no need for conservation or relocation efforts. But this does not take into account food availability being affected by this ice loss, thus the results would vary drastically if they did. The model is not able to comprehend all of the implications a loss of sea ice would have as it is not represented statistically. It is known that if sea ice drastically reduced it would have severe impacts on the species as a result of food availability issues (Atkinson, et al., 2004; Nicol, 2006). This highlights the importance of post-processing reflection if there is no capability to create an intricate model reflecting every interaction the species experiences.

4.3 Main Discussion Points

Ultimately the results of this model and scenarios suggest that emperor penguins on Antarctica are not under threat from future climate change. The modelling undertaken proposes that future climate conditions, mainly rises in global temperature, will be beneficial for the species. As previously commented on this goes against the main trend of the literature, with the vast majority of

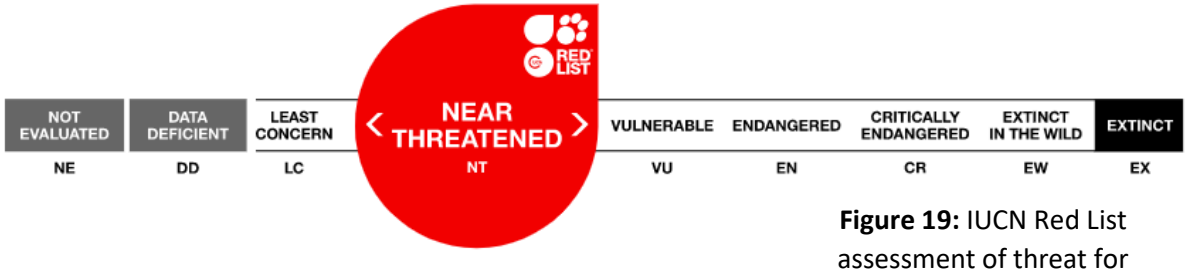


Figure 19: IUCN Red List assessment of threat for emperor Penguins (IUCN, 2018)

studies suggesting the opposite to what these results are suggesting. The only indication that emperors are not at threat comes from the IUCN red list, which labels them as “near threatened” (BirdLife, 2018) (Figure 19) at the healthier end of the spectrum, and Walther (2005) suggesting they may benefit from climate change. However, the modelling undertaken needs to be assessed from a critical standpoint and as such would suggest that the results displayed in this project, which suggest emperor penguins will thrive as a result of climate change, are not taken as a straightforward conclusion. The following points will highlight the most prominent areas of discussion highlighted from the project.

4.3.1 Distribution Trends

One of the aims of this project was to further develop the academic understanding of the distribution of emperor penguins. A basic method of carrying this out is via visual inspection. This form of post-processing provides a human explanation to the distributions without statistical analysis, which can on occasion negate less obvious trends that do not present themselves within the statistics. Figure 12 geo-plots the current environment model, presenting the distribution of colonies around the peninsula. Unlike many other species, there does not seem to be any obvious reason for this distribution. Excluding the fact that they are all on the coast for food, shelter and potentially temperature, there lateral spacing seems random. It could be expected with the support of academic literature that the locality and expanse of ice cover would potentially elucidate this distribution due to its clear benefits and the species reliance (Barber-Meyer, et al., 2007; Barbraud & Weimerskirch 2001). However, this does not seem to be the case. Some areas with lots of ice have colonies and other locations with minimal ice have lots of colonies. Location E In figure 12 is an area with minimal colonies with lots of stable surrounding sea ice. With vast distances to travel to reach open water along with a latitudinal and elevation caused temperature of -35°C (significantly lower than others), this does not make for a beneficial site for an emperor colony. This example and many others point to the idea that temperature is an explanation for their spatial distribution. In addition, a lack of a trend along coastal colonies could be attributed to limited temperature variation. Maxent conclusively agrees with this deduction as shown by the percentage variable table, assumptions can be made based on statistics but to accurately affirm this would be almost impossible. Testing this would require a forced reduction in the temperature of a section of the coast where emperors reside, if witnessed drastic decreases in population and the colony not returning then it could affirm this assumption.

Temperature dictating distribution is also referenced within scenario 1 (2050) (figure 14). Here the average temperature is increased by 1.5°C, as a result (and along with a few other variables all of which have smaller contributions) the model is predicting an increase to the liveable area seen on Antarctica. This is logical as temperatures increase in regions on Antarctica too cold to host life now fit within the 'liveable band' of the species niche.

Alongside temperature's intricate interaction with species distribution, there were several other variables that posed interesting trends raising questions with regards to their exact impact on the species.

4.3.2 Sea Ice Extent

Sea ice extent has been a focal point for much of academic literature with regards to the species, being discussed frequently during this thesis. As a result, it has become apparent that this extent is a delicate and intricate balancing act that should be assessed with extreme care in relation to the distribution of emperor penguins. The general scientific consensus seems to be that higher levels of sea ice extent are more beneficial for emperor's (Fretwell, et al., 2012; Gearheart, et al., 2014; Putz, 1995). With its known benefits of hosting more food (Atkinson, et al., 2004; Nicol, 2006), and with more ice generally comes more favourable environmental conditions. However, at a certain point, more sea ice becomes detrimental, with increased travelling times increasing individual and chick mortality (Massom, et al., 2009; Gross, 2005), with historical data proving maximum glacial conditions are detrimental to populations (Younger, et al., 2015). Thus in reflection sometimes lower levels of sea ice extent are more beneficial as they reduce travelling time for individuals foraging (Massom, et al.,2009). But at the same time, the extreme reduction in sea ice causes more food issues, as demonstrated by the Halley Bay collapse in 2016 whereby the loss of sea ice caused the colony not to return till feeding conditions improved (Fretwell & Trathan, 2019). It is key to strive to further understand this intricate process to define the optimum sea ice extent for emperors balancing all of the implications highlighted.

4.3.3 Wind Speed

Results within this thesis alluded to wind speeds having a more prominent impact on penguin distribution that is commonly referenced. There are no studies that specifically focus on the impacts of wind speeds on the species, and few that reference it. This seems interesting as figure 20 presents a general trend that increased wind speeds have a positive effect on emperor penguins. As a result, wind speeds may have a larger effect than initially anticipated, and one that may have been overlooked by academics.

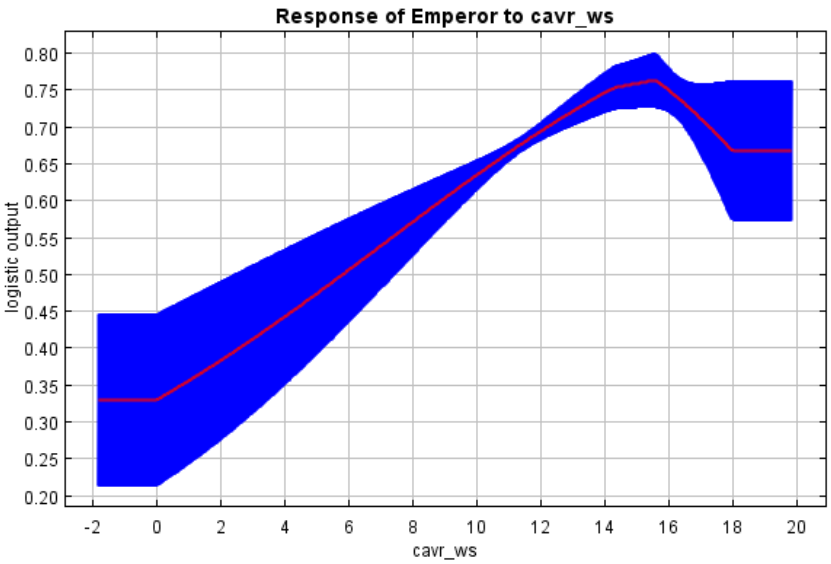


Figure 20: Wind speed response curve

The most probable explanation for this trend within the model is that of the wind's interaction with emperors foraging sites. As highlighted by Botsford (2003) and Millot (1979) increased wind speeds induce more upwelling within the ocean emperors forage within, as a result, this upwelling promotes increased biological productivity within the area, thus, in turn, more food is available for the species. It has also been commented by Kooyman (1993) that penguins require fresh snow accumulation, something that increased wind speeds allow for with its transportation abilities. Intriguingly there have been a few studies that suggest otherwise. McCafferty (2013) highlights how emperor flipper and feet temperatures were dependant on wind speeds, with increased speeds making it more uncomfortable for them. Not only this but both McCaffery (2013) and Maho (1976) commented on how heat loss it mitigated at lower wind speeds, with their naturally ridged plumage allowing for a reduced impact on heat loss up to 5m/s, thus higher wind speeds result in decreases in body temperature.

The location of colonies also suggests emperor's favour lower speeds. It is referenced continuously throughout Kooyman's (1993) paper that penguins seek shelter from this wind, pursuing colony locations behind ridges, ice shelves and other topographical features (Kooyman, 1993), not only this but he comments on how increased wind speeds also result in higher chick mortality, as stronger winds can result in the abandonment of eggs and chicks when the thermoregulatory needs of adults take priority. More devastating however is the apparent effect on wind speeds on colony collapse. It was speculated in the past that strong winds may cause ice break up, potential causing the

destruction of a colony (Kooyman, 1993), and in 2016 this was proven, whereby an entire colony collapsed as a result of increased wind speeds eroding away underlying sea ice, causing the loss of up to 25,000 individuals (Fretwell & Trathan, 2019). Somewhat contradicting this is Ainley et al (2010)'s deduction, whereby higher wind speeds result in increased sea ice extent, with decreasing speeds resulting in less ice extent. Ultimately consensus seems conflicted, with much of academic knowledge suggesting the adverse effects of wind speeds on emperors but the statistics within this model and a few studies suggesting otherwise. This may again prove to be a trend that lies within the flaws of statistical assumptions, but it is clear that there is a definitive gap in the knowledge. Consequently, this study has shown more work in both the form of statistical analysis, developing further models to represent wind's, and independent works focusing on and detailing the impacts of wind speeds on the species. This further corroborating Kooymans (1993)'s statement that "the best surface conditions for penguin are ones with lower winds" or potentially detailing a far more intricate and fragile interconnect between wind speeds and colony occurrence system.

All of these variables have proven to have fundamental interactions with the species; Interactions that are crucial to representing the emperor's distributions. But even with these prominent variables, there are factors not included within this project (for previously highlighted reasons) that could drastically improve on the predictive ability and accuracy of the model.

4.3.4 Excluded Variables

Food sources, a variable that would be hard to manipulate and input into the model, but if done adequately representing food availability, abundance and location, would uncover further trends on the species distribution. It is referenced that food sources, specifically prey abundance, is one of the biggest drivers of top predator populations (Pacoureau, et al., 2019), and from the results of this project, it is logical to assume they would have an extremely influential impact on its outcome if incorporated. To adequately include food within this model would take extreme effort if maintaining the aim of achieving a realistic reflection of the distribution. To calculate food sources of the current environment, data would need to be acquired on all of the individual food species (silverfish, krill and squid) (Cherel & Kooyman, 1998; La Mesa & Eastman, 2011; Ponganis, et al.,2000), their current distribution and quantity. One of the most challenging aspects is accurately representing the distribution of the prey itself, with such a vast array of area and depth for sampling, this data would prove to be difficult to acquire, especially if trying to mitigate presence only issues (Ward, et al., 2009). The real difficulty comes when projecting this food to the future for use within the final

emperor SDM. With emperor food sources being inherently linked to multiple other variables such as temperatures (La Mesa & Eastman, 2011), wind speeds (Fach & Klinck, 2006) and predator competition (Bernard, et al., 2017), a SDM would have to be created just for the food species to accurately predict its future range and population before inputting the results into an emperor SDM. Ultimately proving to be a challenge. This difficulty may well be the reason for the gap in academic knowledge of this type of study. This work has fundamentally highlighted that to adequately produce an advanced more representative SDM on emperor penguins, extensive data on their food sources must be collected and become readily available for interpretation; further highlighting the intrinsic interconnection of the marine food web.

There is the possibility that ice thickness and health could be included in future SDM's, with its ability to represent potential areas of avoidance and its effect seen on the species attributing to the Halley Bay colony collapse in 2016 (Fretwell & Trathan, 2019). Data for this variable has of late become more readily available with some such as (Stutterly, et al., 2019; Liu, et al., 2018) utilising advanced technology such as high-resolution radar to acquire such data.

A variable representing predators would also be interesting and something that has not been reflected upon within this project. It is commented on by Williams (1995) that they have an impact on the population, all be it a small one. As with food sources, it is hard to accurately represent and acquire, but it could suggest areas to avoid or potentially provide reasons for current distributions.

If included within the model these variables would prove extremely beneficial and allow for a better representation of the overall environment, but also other living factors not commonly included within SDM's. As it stands, however, the data is not readily available and is extremely hard to interpret into the model. As a result, the variables used within this model represent the most feasible and reliable to acquire the optimum model. But there should be efforts to acquire the suggested data to improve our understanding of the species with its utilisation within SDM's.

4.3.5 Correlation vs Causation

One of the largest issues that lie within the model and one that caused the biggest impact on the overall results is that of the Maxents interpretation of the statistics. Highlighted by Austin (2002), Sinclair (2010) and much of the scientific community is that a strong correlation does not necessarily imply causation. Within this project, Maxent suggests average air temperature as the biggest contributor to emperor penguin distribution by an overwhelming margin (figure 8). There is no doubt the two variables are related, however that does not mean one causes the other, with a

greater likelihood that they are both related to a third factor. The issue is that extrapolating correlation to causation is riddled with assumptions (Zar, 1996; Czech, et al., 1997). It is widely known that environmental data can be connected to many ecological phenomena. Robust correlations may allow environmental data to predict species occurrences, even if the climate minimal relation to the species' distribution (Lozier et al. 2009). Consider a species with a once vast distribution but now limited to a solitary island as a result of predation. This species' distribution is not limited by climate; however, environmental variables may be able to precisely predict its distribution within a model, along with the latitude and longitude. Consequently, the true impact of the current environment in the distribution of the species remains unknown. This is occurring within this project but with reference to temperature variables. As seen in figures 8 the model is suggesting that average air temperature has a percentage contribution of upwards of 80%, firstly environmental variables with such a large contribution are generally seen as misleading and should be interpreted with caution (Phillips, 2017), but again that might not necessarily be the trend as Antarctica is such a unique environment contradicting many environmental assumptions. It is not certain that the model is understanding the actual causation of this distribution, but just assimilating a strong correlation. As seen, all of the penguin colonies are situated on the coast figure 5, alongside this, the average temperature on the coast is also the highest (Appendix A-3), the model assimilates this trend which strongly suggests that the higher the temperature the more likely for colony presence as a result of its strong positive correlation, but this may not be entirely the cause for their distribution with correlation not implying causation. There is no doubt temperature plays a part in impacting their distribution, but it must be researched more to truly understand the real causation of this trend.

Penguins are known to survive at temperatures both above and below that of their average colony temperature, this proves to some extent that they can survive in temperatures outside of Maxent' suggested niche. As a result, if temperatures on the coast independently dropped or increased there would not be a marked change in the distribution of emperors as the model results are suggesting. Therefore, the temperature has a correlation, but is not the causation for the species distribution; unlike the models believes. What is the real causation for this distribution and why is Maxent being tricked into thinking its temperature? The reason for penguin's coastal distribution as this study has shown is down to a number of variables working in unison, but those with the biggest impact are arguably factors affiliated with food, factors such as distance from food sources and shelter from landforms are more likely direct explanations for this coastal distribution (Robertson, et al., 2014; Barbraud and Weimerskirch, 2001; Willing, 1958), all ultimately making their quality of life easier. But this is not being reflected in Maxent's results as it is not picking up any other statistical trends

and the fact that food data is not included in the model. Further highlighting the requirement for human post-processing, with the models' inability to reflect upon other processes outside of the statistics that humans can infer from.

Ultimately the issue seen here could suggest that at a certain point species distribution models may infect be data dredging, misusing statistical analysis in the aims of finding patterns in the data that suggest statistically significant when in fact there is no real underlying effect (Smith & Ebrahim, 2002), somewhat seen in temperature within this project; ultimately impacting the reliability of results and the modelling technique itself. This being said it does not mean that finding this correlation is without value, it is still a vital move in finding the real cause of the causation. It is highly likely that the land surface temperature may actually be a secondary variable that impacts the species, one that dictates the trends and distributions of other primary variables that in turn dictate penguin distributions. It is hard at the moment to reliably test this theory with the extent to which changes in air temperature affect food availability being somewhat unclear (Robertson, et al., 2014). If this is the case with temperature directly impacting prey populations, then as it stands this temperature variable may be the best way of reflecting upon food availability whilst the exact data for food sources is not readily available. Nonetheless, with continued research and development within these study areas more will be explained.

4.3.6 Emperor Dispersal

The results of this model although providing insight as to where colonies could migrate to, rely heavily on the species natural dispersal ability. The study has highlighted that the niche for emperor penguins will shift under future climatic conditions, but it is uncertain if emperor penguins obtain the ability to naturally follow this niche shift into the future. Some academics such as Gearheart et al (2014) and Cristofari et al (2016) have suggested they obtain the ability to migrate, whereas other disagree suggesting that they may lack the ability to do so (Jenovrere, et al., 2009). Unfortunately, all of these academic works are based on numerous assumptions as they are all trying to predict the future, thus there is no real way of telling whether the spices will be able to migrate. Endeavouring to better understand their dispersal ability should be key, but there is only so much to gain, this aptly summarised by Jenouvrier, et al., (2019), who suggests that the dispersal ability of emperors has less of a capacity to safeguard the species future than global climate policy. Conclusive evidence will only come when observing their future trends in the hopes they do hold the ability to migrate. On top of this, shifts to their future niche may not follow as projected by the model. Unforeseen

events could occur that cause a divergence in the niche's future change or the climate may not change as anticipated, thus they may not need to migrate.

As highlighted the most reliable way of testing these migration assumptions and ultimately the reliability of this model is by looking to the future, utilising technology and observations with the aims of proving or disproving the results.

4.3.7 Proving Results

The results of any model with the outlook to predict the future, are always going to be left in the balance. With no real way to at the time assess how accurate the results are apart from a general assessment of their realism. Even though this is the case there should be efforts to prove and disprove the results. The tracking of colonies and individuals would be the most applicable method of proving the results, with tags or micro ships relaying GPS information to a centralised hub. Not only would this help prove the projects conclusion's by tracking penguin locations into the future, but it would also prove extremely beneficial and insightful for further projects into emperor penguins; providing key tracking data for foraging, diving depths, migration distances, et cetera. As it stands there have been a handful of studies tracking individuals via satellites (Ancel 1992, Fretwell & Trathan, 2009; Wienecke, et al., 2010; Juventin, et al., 1994) and none tracking with GPS's for ethical and practical reasons (Meiners, 2019). It was observed that with GPS trackers there was a reduced return rate and survivability of birds in king penguin populations (Froget, et al., 1998), this could potentially be the case for emperors thus the development of smaller less disruptive GPS trackers would need to be investigated. Studies utilising satellite trackers proved beneficial but only conducted experiments on a handful of individuals, not enough to prove conclusive overall population trends. Legally it can be done as highlighted by Article 3 of Annex II of the Protocol on Environmental Protection to the Antarctic Treaty (Borborglu & Boersma, 2013), but the only foreseeable issue with this would be logistically tagging as many of the population as possible across all known colonies whilst mitigating health risks to the populations.

Alongside this, the development and use of advanced RPAS (Remotely Piloted Aircraft System's) would be extremely beneficial, as seen with the Royal Air Force's new Protector it can fly for an extended duration in adverse weather conditions (Bourne & Thompson-Watts, 2018), a civilianised variant of this, collecting multispectral imaging data on the colonies and surrounding environmental variables would prove favourable. It would provide more data for emperor penguins but also prove extensively useful for a huge array of other remote sensing tasks in many study areas of Antarctica. This in conglomeration with further development of satellite technology would prove beneficial.

Steps have been taken to track populations via satellites (Ancel 1992, Fretwell & Trathan, 2009; Wienecke, et al., 2010; Juventin, et al., 1994) and other Antarctic species (Andrews,et al., 2008), so it is proven to work, but a more dedicated and flexible platform would provide more advantageous.

Monitoring these penguins to the future whilst disproving or proving the results of this project would develop a further understanding of the species physiological, also potentially emphasising their natural ability to disperse or adapt to upcoming adverse changes due to climate change. This is still something relatively unknown and really should strive to fully understand before completing and reflecting upon projects projecting the future of the species.

4.3.8 Antarctica

Unfortunately, This species distribution model fails to encapsulate the well-known fragility and vulnerability of the environment itself, with all of these predicted changes incorporated within Maxent it cannot take into account many known implications climate change will have on the landscape itself. The results provide a depiction of the species niche looking to the future, with reflection upon the likelihood of them filling this niche. But only briefly reflected upon is the quality of the environment under these future scenarios. How will Antarctica itself change as a result of these environmental adjustments? What will the quality of life be like for the environment on this undoubtedly changed continent? All aspects that should be considered when discussing conservation techniques for the species.

4.3.9 Reality of Species Distribution Modelling

Species distribution models present the distribution at the current environment, but when used to predict future environments do not predict the species distribution at all, but present their niche under new environmental conditions. Species distribution models utilise the environmental variables given to create various bands whereby the species is currently seen, a niche. This niche is then projected onto environments giving an idea of where the species could be distributed by highlighting areas that have similar environmental values as that of the species current niche. As seen from all scenarios, the species niche was detailed and refined within the ‘current environmental variables section’; It was then applied to each scenario presenting a shift in the position and range of the current niche to fit in the future environment. What it is unable to do however is accurately predict where the actual future distribution would lie. This can somewhat be attributed on part by the lack of data available to give to the model (physiology, food sources, dispersal ability), as a species distribution model is only as good and can only extrapolate from the data given to it, thus in part this

is the curators fault, but also due to SDM's lack of ability to do so. Although correlative SDMs have been applied successfully in evaluating the impacts of future climate change (Fois et al. 2016) and classifying appropriate conservation zones (Kaky and Gilbert 2016), they are known to have issues with extrapolation, especially to future scenarios (Fitzpatrick and Hargrove 2009, Elith et al. 2010, Veloz et al. 2012, Urban et al. 2013, Maguire et al. 2015, Urban 2015). This is especially prominent within this project as it was highlighted how SDM studies projecting species into the future should be interpreted. They should not be assessed as a projection of a species into the future, but as a projection of a niche into the future, reflecting upon the species ability to meet the proposed niche change and the probability of them meeting it. There are far too many assumptions made within species distribution modelling of emperor penguins that are unable to be justified, thus the reliability of any study suggesting an exact future distribution should be questioned. Until the technology and data is available to back up these assumptions the aim should be to create realistic and logical proposals of future niche's and assess the species ability to meet this niche independently.

Within the confines of this project Maxent produced feasible results within the limitations of the environmental variables that were given. Reliability however is detracted as the species is not dictated by just environmental variables. Biotic variables such as food sources and their physiological constraints, would have drastically altered the results of the model. However, at the current moment in time it is hard if not impossible to incorporate some of these variables into a basic SDM to provide beneficial results.

Currently the most advantageous method of modelling distributions of emperors is still SDM's. They give a good rough estimation of their future niche, not pinpointing exactly where a species will be but highlighting all the areas where it could reside, thus the area that it will reside is more than likely going to lie within this projected environmental niche. Even with the inherent flaws with data, technology and understanding the species, distribution models are still the best course of action for future projections and it is key the results are adequately interpreted as there true meaning can be hard to interpret and if not done correctly can be misleading.

4.3.10 Filling the Academic Gap

The work carried out in this report, although basic in comparison to other SDM projects, is a stepping stone to filling an important gap in the literature. There has been no species distribution model studies on emperor penguins and little to none carried out on any other penguin species. This may be due to the lack of technology and data available to make sufficient assessments in the past,

but as of late technology and data has got to the point whereby it is possible to make such a model. The work in this project does exactly that, utilising new methods and data to attempt to make a species distribution model for emperor penguins. The work highlights that while the technology and data is available, it is not quite at the stage whereby it can be used to make concise conclusions, but only as a basic proof of concept. That being said this work has given a vital insight into the future for emperor penguins and their niche, and has emphasised the development of this work to creating a more intricate and representative model to predict the future dynamics of the species.

4.4 Limitations

4.4.1 Climate Models

A fundamental limitation of this study is the lack of certainty for the climactic models used. The model used is reputable, however, it is common practice for impact assessments to use an ensemble of multiple climate models; better representing a scenario and decreasing model uncertainty. This is not practised in this study, thus should be taken into consideration when assessing the results.

4.4.2 Flaws with Maxent

The programme is a fantastic tool for species distribution modelling, noted as being extremely advantageous for multiple species studies (Fourcade, et al., 2014; Wilson, et al., 2009; West, et al., 20016; Yang, et al., 2013). However, for a species as unique as emperor penguins and the environment they live on, the parameters behind the scenes do not reflect well on the species. Emperor penguins are such different animals to those of the average animal kingdom, and as a result, it is seen that they do not respond the same as those used to test the modelling programme. Maxent used a plethora of species to test and ensure its ability to produce valid results, which is fantastic; but none were penguins. This becomes a limitation to the study as the environment they live within and the species itself is so far from those of the species utilised within the creation of Maxent, thus the assumptions the models makes may not be accurately followed with this species. The temperature buffer, for instance, some species may be able to live a set amount of °C outside of their current environmental niche; The Alaskan wood frog is an example of this, surviving extreme temperatures of -15°C outside of their normal 0°C minimum (Larson, et al., 2014), and Maxent averages this across all of those used for testing. But emperor penguins may not be able to survive in the conditions suggested by Maxent's average. Consequently, building an SDM from the ground up based upon the principles of Maxent, but curating for the specific application to emperor penguins and the environment they live in, as suggested by Qiao (2015) & Sofaer (2019), with construction

taking into account as much knowledge and physiological variables of the species as possible, potentially incorporating various other SDM's for their food sources to best represent this. Ultimately better reflecting emperor's and producing more specialised results.

4.4.3 Understanding the Study Species

To create an effective SDM it is strived to know with 100% certainly what causes their distribution for the most accurate reflection of the species and environment. This is something that is not fully understood for emperors and needs to be addressed before following through with more SDM work. Through the academic literature, there is a reasonable understanding of an array of variables that influence this distribution, however, no experiments have been done to derive the importance of them, leaving it to statistical models to decide the importance based on various assumptions. As displayed by this report there is an extremely complex and intricate system of variables that dictate emperor populations, all impacting one and other in various elaborate ways. Dumping all of these into a SDM (as shown in the results) can prove problematic as they miss represent the distribution trends. Thus work needs to be done to fully understand what the causes of this distribution are before progressing with furthermore advanced SDM's. Once this underlying understanding is constructed the next concern becomes the acquisition of all of the data, attempting to accurately represent these variables within a species distribution model.

4.4.4 Data Issues

Acquiring high resolution, accurate and academically reliable projections of future climatic conditions under set scenarios proves challenging for the region of Antarctica. Originally individual climate models predicting future temperature changes, precipitation changes et cetera, were used within the extrapolation phase of the modelling, however, they proved to hold little benefit due to their extremely low resolution and constant lack of Antarctica data. As a result, assumptions of future climates based upon academic literature were used. This proved beneficial, however in striving to curate an accurate and well-represented model for the future this technique would prove detrimental and reduce the local accuracy of the model. Many academic papers and reports suggest overall increases in temperature globally or regionally; average temperature for example from the IPCC report suggesting a global 1.5°C increase in 2050 under RCP 4.5. This specifically relates to the scenario planned to project, however it does not accurately depict the intricate nature of the temperature system in the region. It is expected to see some areas of Antarctica increase in temperature at a slower rate, some faster and others fall, constituting variability across the continent (King, 1994; Ahmed, et al., 2013). If this was incorporated it would have allowed a more

localised and accurate projection of future environments, permitting the individual analysis of all colony locations assessing if any specific region would experience more severe impacts than others. Future sea ice extent projections also suffered from this issue, with projections of a net decrease of 1.8% (Parkinson & Cavalieri, 2012), but more realistically local variability of this sea ice extent within the region would be experienced (Cavalieri & Parkinson, 2008; Jay Zwally, et al., 1983; Stammerjohn, et al., 2008). This would be specifically prominent for conservation strategies as it can focus on colonies who are facing more of a habitat threat than others. Consequently, this is something that would have to be addressed with the further development of high-resolution climate models specific to Antarctica. As it stands there is a limited amount of open-source climate data is available, and those that are host extremely coarse resolutions.

Antarctica is a naturally harsh environment and one that does not frequently allow for the capture of these variables (Fretwell & Trathan, 2009). As a result, the scientific community should endeavour to develop new methods of acquiring such high-resolution environmental data across a temporal scale, proving advantageous for analysis. The development of aviation recognisance platforms to aid in the collection of environmental data, seen in the RAF's Protector platform (Bourne & Thompson-Watts, 2018),) could provide environmental data if retrofitted. In addition, the drive to monitor individuals via micro GPS technology would provide an abundance of data with steps taken to develop specific GPS trackers for birds (Bouten, et al., 2012) that may mitigate the know issues. Tracking at least 50% of the colony across all colonies, although logistically hard, would prove to be tremendously valuable; allowing the assessment of foraging paths, migration, general trend assimilation and much more. The further development of satellites within the application of SDM's would also be beneficial, allowing the further tracking of colonies and location year on year as demonstrated by Fretwell et al (2012). If all of these current limitations within the data were lifted it would make the creation of SDM's much easier and thus benefitting the species in a multitude of ways.

There is a need for biotic data on the species. As it stands there is little to no information on emperor penguin physiology, detailing minimum and maximum temperatures or dispersal abilities. Research into this study area would greatly develop our understanding of the species, and within the application of species distribution modelling would enable the development of furthermore reflective models and a more up to date reflection upon current model predictions.

4.4.5 Niche vs Reality

Another potential limitation to this study and ultimately all SDM's alike is its ability to predict future distributions. As highlighted, when projecting to the future correlative SDM's such as this only present the transformation of the niche within a new environment; thus technically not presenting the spices future distribution. Due to the inability of the model to infer the physiological and dispersal abilities of the species it cannot accurately predict where a species will be in the future.

The output of maxent, showing an increased area of suitability is to be expected. Without all possible variables accounted for, the model cannot construct a realistic depiction of the niche. More importantly, the lack of incorporated biotic interactions drastically limits the output and its representability. The model predicts a basic outline of the fundamental niche, a set of conditions allowing an organism to survive in the absence of biotic interactions (Kearney & Porter, 2004), but with this lack of biotic inference, it fails to accurately predict this realised niche; a subsection of the fundamental niche incorporating biotic interactions (Miller, 2010). Therefore the correlative model cannot fully represent the species niche unless further abiotic and biotic data can be incorporated. However, this projected fundamental niche is an estimation of the range possible for the distribution of the species, and looking to the future the actual range of the species will more likely than not fall within this projected niche; Therefore, it still poses value. Unfortunately, the inability for these models to have their predictive ability practically tested (other than waiting to see if the species disperses as the projected), poses as a limitation to all SDM studies.

4.4.6 Human Reflection

Model's have a fundamental inability to take into consideration and infer logic from processes outside of the statistical realm. This is an inherent flaw with all species distribution models & data inputted, and will only improve with time. This inability for the model to assimilate processes from the outside world causes it to miss key interactions not reflected in statistics, drawing the results further away from the most realistic scenario possible. What is commonly referenced and suggested is the use of post-processing to mitigate this impact, Inferring trends from non-statistical variables by utilising the human brain, with our ability to reflect and draw conclusions from external values that potentially paint a more reflective picture of the real-world scenario. The examples highlighted within the study shows how the interaction between food sources, physiology, sea ice, temperatures are almost impossible to accurately represent in SDM's due to their complexity. Thus further

development of tactics of incorporating these within future models is required. The issue of lacking physiological and dispersal reference within the species can somewhat be mitigated by the creation of a standalone mechanistic SDM for the species, but the underlying limitation of having to look past the statistics for more realised trends will always be a limitation of SDM's as statistical analysis can miss portray intricate environmental processes, prominently seen with air temperature within this project.

4.5 Advantages

4.5.1 The Niche

Alongside these limitations, there were several other benefits to the study and the results. Firstly, taking into consideration the data limitations the overall results of the model do a good job at modelling the species niche, specifically whilst projecting to the future. With the set of environmental variables given to the model (those highlighted by the academic literature to have been fundamental in projecting their distribution), the model produces logical and realistic niche shift results, with the suggestion of expansion inland. It is hard to tell whether this niche will be followed into the future but to be a realistic and logical assumption and one expected to become the abiotic niche of the species, with the food limitations creating the biotic niche.

4.5.2 Proof of Concept

One of the most beneficial attributes of this study is its step in filling an academic gap. At the moment, potentially due to some of the limitations and difficulties highlighted within this study, there has been no work done to model emperor penguins via SDM's into the future. As a result, this study has attempted to bridge this gap. It has proven that creating an SDM of emperor penguins is possible but also highlighted the fact that whilst it is, much more work needs to be done in multiple areas to refine the process and produce an academically and scientifically viable result with a heightened degree of accuracy and representability. It can be seen as a proof of concept and one to be developed further in striving to fully understand and conserve the species of emperor penguins.

4.6 What Does the Future Hold for Emperor Penguins?

So, what does the future fold for emperor penguins? Taking the results of this project at face value it can be concluded that the future seems to be advantageous for the species, with the planned changes in the global climate proving beneficial to the distribution of emperor penguins. With increasing temperatures in the region supposedly causing an increase in the area predicted to be

suitable for emperor penguin presence. Alongside this, the reduction of sea ice also causes an increase in the proposed area suitable for emperor penguin colonies. Realistically, however, is this the case? From an academic standpoint, the conclusions deduced from the result of this project completely contradict assumptions and observations made by academics and go against the grain of much climate change and conservation efforts. Therefore, these results should not simply be taken at 'face value', with complex relationships displayed not always being made apparent when briefly summarising the results, and can tell a different story when analysed more specifically. The results of this project portray emperor penguins niche and project the change in this niche. Reviewing the results from this standpoint however proves to depict a different picture and one that does not contradict academic works.

The results depict the fundamental niche, but as food stocks come into play this abiotic niche and biotic niche diverge, with the biotic niche (not portrayed within this project) restricting the species to the coast due to food availability. But the abiotic niche (that where they can physically live without effects of biotic interactions) expands as a result of climate change into the future.

Reviewing the results from a standpoint of how emperor penguins will respond to future climates, not how their niche responds; these results seem completely illogical. Consequently, they should be viewed as they have been curated, projecting the environmental niche of the species, not their actual future distribution. It is possible to assess the likelihood of the species following this projected niche. Referring to this niche it is seen that the area they are predicted to reside within increases with the heavy influence of temperature into the future, this presents their abiotic niche. However, incorporating many other external aspects (food sources, predation, etc) their biotic niche drastically differs from the abiotic one presented within the results. Reflecting on these changes predicted to diverge the abiotic and biotic niche it can be seen that increased temperatures cause a decrease in sea ice extent, initiating a decrease in food availability (Huang, et al., 2016; Robertson, et al., 2014). This would have a huge impact and one to be researched further. This limitation of a food source for the species is the main driver of this biotic niche. Even though the species would be able to move inland to maintain the optimum environmental conditions, the optimum foraging conditions would stay on the coast. They would be more inclined to refuse migration increasing changes of food acquisition, with a projected decrease in abundance of food (Robertson, et al., 2014; Huang, et al., 2016). As a result, the distribution of emperors would stay in their current locations whilst their abiotic niche progressively retreats inland. As temperatures are predicted to continue rising (IPCC, 2014 & 2018) a reduction in sea ice will likely occur, food availability will at this point become extremely scares due to the removal of sea ice and coastal temperatures will become too harsh for

survival (Figure 18). This forcing migration to cooler temperatures inland as presented by the abiotic niche. Whether or not emperors have the natural dispersal ability is up for dispute (Forcada & Trathan, 2009; Trathan, et al., 2019) but assuming they will the ultimate challenge for the species living in this abiotic niche inland would be obtaining food. If food was still available in the now warmer open water, then they would have to traverse the harsher ice melted landscape. At this point, the quality of life for emperor looks poor, although maintaining optimum conditions residing within their niche they would have extremely limited access to food, thus human conservation efforts would be required. The land they live on and their niche remains in good condition with plenty of higher latitude land to retreat to maintaining this niche for potentially hundreds of years to come, however food sources are the Achilles heel of emperor's and thus will ultimately result in their demise. As a result, to maintain emperor populations humans would need to find a way of conserving their food sources and presenting this to them in an easy to reach and undisturbed way, a challenge to combat in the far future if conditions worsened to this extent. Conclusively the biggest threat to emperor penguins is still climate change, but not as a direct threat. They will be able to follow their abiotic niche to mitigate the apparent effects of it, however, the changing climate will undoubtedly impact the food sources, resulting in a population and distribution reductions. This ultimately presenting how climate change will affect emperor penguins indirectly, and why it is essential to strive to mitigate these impacts with the adaptation of the global climate policy (Jenouvrier, et al., 2019)

4.6.1 Food Stocks

As highlighted continuously throughout this work there is extreme underlying importance on the emperor's food stocks in dictating their distribution. As a result, understanding and modelling the future projections of the emperor's food stocks are just as much if not a more influential factor than other variables. So what actually happens to the food sources under future environments?

There are many speculations as to what will happen, will stock slowly decline (Trathan, et al., 2019), will they migrate from their habitat (Jenovrere, et al., 2009), or will they even thrive under different conditions? Focusing specifically on Antarctic Krill, one of the main supplements in emperor diets (Trathan, et al., 2019; Cherel & Kooyman, 1998; La Mesa & Eastman, 2011; Ponganis, et al.,2000) there are numerous predictions regarding their future. Krill themselves are one of the most abundant animal species on the planet (Nicol & Klages, 1997), and as a result, it would take an extreme extinction event to completely wipe them out. Thus it is more likely to see a slow decline in populations. Being in the diet of 10 other species across Antarctica, a reduction in their population

would result in increased competition for emperor penguins. Krill feed off of the underside of the sea ice, so as temperatures increase and sea ice retreats krill populations would suffer, as seen previously with declines in Antarctic krill biomass as a result of a reduction of the pack ice (Gross, 2005). The intrinsic relationship between this species of Krill and ice is seen throughout their lifespan. In the early stages of their development, Krill seem to need the pack ice to have a reasonable chance of survival. This pack ice provides natural structures used to evade predators. In years of reduced pack ice, the krill tend to suffer reductions in populations compared to the increase seen in Salps (Atkinson, et al., 2004), a floating feeder that also grazes on plankton; This could prove to be an alternative food source for emperors. Increased warming also causes ocean acidification, impacting Krill stocks as a result of increased carbon dioxide (Antarctic Climate and Ecosystem Cooperative Research Centre, 2008). Krill is very susceptible to increased CO2 levels as it is shown that increased carbon dioxide can interrupt the growth of eggs and prevent juvenile krill from hatching, this would lead to future extensive reductions in krill hatching success (Kawaguchi, et al., 2011; Kawaguchi, et al., 2013). There are other effects of rising temperatures on krill but much remains unclear, that being said academics worry that it could considerably impact their distribution, abundance and survival (Rowbotham, 2008; Orr, et al., 2005). The impact of humans also has implications on Antarctic Krill, with fisheries in the region removing 100,000 tonnes per year from the ocean (CCAMLR, 2009). Ultimately all of these have impacts of the populations of krill, and as climate change progresses this worsens, inevitably effecting emperor populations. The exact trends of krill and other food sources are not extensively documented. It is understood as highlighted that they will face a decrease in populations, but the extent and their range shifts are still disputed. These gaps in knowledge play a curtail role in further understanding the impacts of the future climate change on emperor penguins, thus more work is required.

4.6.2 Conservation

Ultimately the biggest challenge facing the future is conservation. It is key to strive to mitigate the loss of this beautiful species in every and any way possible. SDM's as shown in this work does possess conservation abilities. Firstly, presenting the species niche and possible range as seen through all of the scenarios, all suggesting if temperatures increased more beneficial conservation sites for the species would be further inland. On top of this, the academic literature and model itself suggests that the species require shelter for colonies, mitigating extreme weather conditions. This seen demonstrated by colonies locations being next to steep slopes in the statistics (Figure 13) and pictorial demonstrations such as figure 21, representing exactly this. All of these factors allow for the consideration of relocation sites within the niche's presented in the results. Ultimately if referencing their abiotic niche as presented by the results, emperor penguins are not in need of conservation, with increased temperatures proving beneficial. Realistically however the species will not follow this abiotic niche but a biotic one with the limitation of food availability. As a result, at the current moment in time the species is surviving adequately, but as these temperatures increase and effects on food stocks begin to occur then the species will require proactive conservation efforts. Thus, work should be completed assessing management and conservation strategies for the species with specific regard to the maintenance of their primary food sources. With possible stockpiling of food, finding suitable replacements or setting up infrastructure allowing humans to feed the species. From a global climate policy standpoint It is suggested by Jenouvrier, et al., (2019) to strive to limit global temperature increase by 1.5°C as set out by the Paris Agreement, thus giving the species a fighting chance for survival. Ultimately all endeavours in academic work surrounding emperor penguins aid in their conservation through the development of knowledge, thus the continued drive to fully understand the species and all of its interactions should be sustained.



Figure 21: Picture of Cape Crozier emperor colonies residing next to areas of shelter (Meiners, 2019)

5.0 Conclusion

This dissertation aimed to further advance the academic understanding of the distribution of emperor penguins. It has highlighted how food sources play an undoubtedly vital part of this distribution and emphasised the potential effects of both wind speed and sea ice extent on the species. More specifically the project completed its goal in creating a species distribution model to predict range changes in future climate scenarios, with all associated results suggesting the environmental abiotic (fundamental) niche of the emperor would increase in size as a result of future climate change; This a logical assumption based upon the numerous limitations within the study. However, reflection upon the biotic niche with the inclusion of other limiting variables (food sources), showed these models changed. The constraint on food availability due to climate change presented a biotic niche, but unlike the abiotic one, it did not grow due to the species inherent need for abundant food sources. It was therefore concluded that the threat of climate change would benefit the abiotic niche of the species, proposing the expansion of the distribution's abiotic features, but climate change's effect on the food sources emperors feed on would limit the biotic niche. Thus realistically projected changes to the climate would prove to have negative effects on the species distribution and population. It is key to note that this drastic variability in interpretation highlights uncertainty within the study's results. This uncertainty lies within the limitations of the study, with its lack of biotic variables, deficiency of ensemble climate models, the limitations of Maxent and the absence of high-resolution data for future climate scenarios; it can only provide a basic depiction of the fundamental niche of the species. It should be understood that the results of this study are not fully representative of the Emperor penguin, only providing limited insight into its future.

One of the most prominent conclusions raised by this project was the lack of content in certain areas of the species. Firstly, there is a need for high quality spatial and temporal data to be used within an SDM. High-resolution climate data projecting future scenarios for different environmental variables on Antarctica is not readily available. There is also a lack of physiological data on emperor penguins, beneficial for inferring to their dispersal and migration ability. Further to this, a more extensive data collection of emperor food sources would prove beneficial; potentially the creation of SDM's for these food species to highlight their individual range shifts under future climates. Lastly, a way to prove or disprove similar studies is required. Tracking of individual emperors, although proven to be logistically difficult, would prove advantageous as a way of verifying trends predicted by this and other SDM's.

Fundamentally this study shines a light on new understandings of emperor penguins and the act of modelling their species distribution; taking steps to bridge the academic gap. One of the most prevalent realisations is that although species distribution modelling of this penguin is possible (as proven for the first time by this study), the results created are not accurate enough to definitively represent future environments and draw categorical conclusions from. This, mainly a result of the limitations of the study, but also an absence of available data, technology and methods to produce an accurate and representative SDM for the species at this current moment in time. With further development in the highlighted areas and advances in the understanding of all aspects of the species, distribution modelling will become effortless and provide much more conclusive results.

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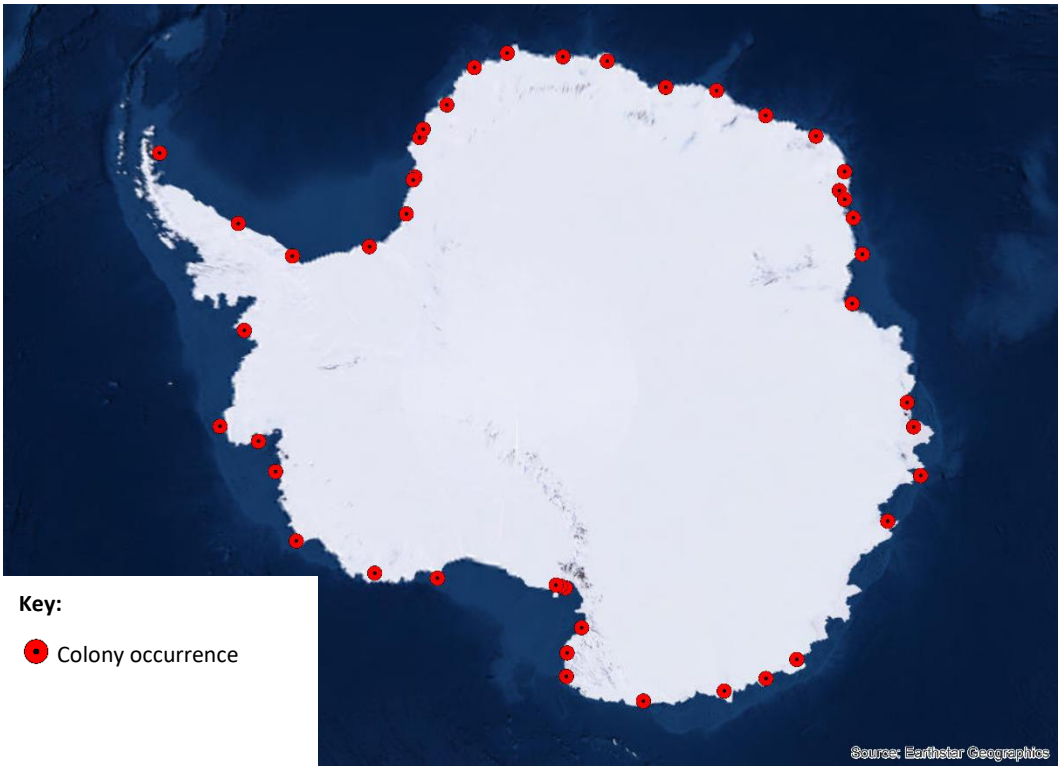
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7.0 Appendix

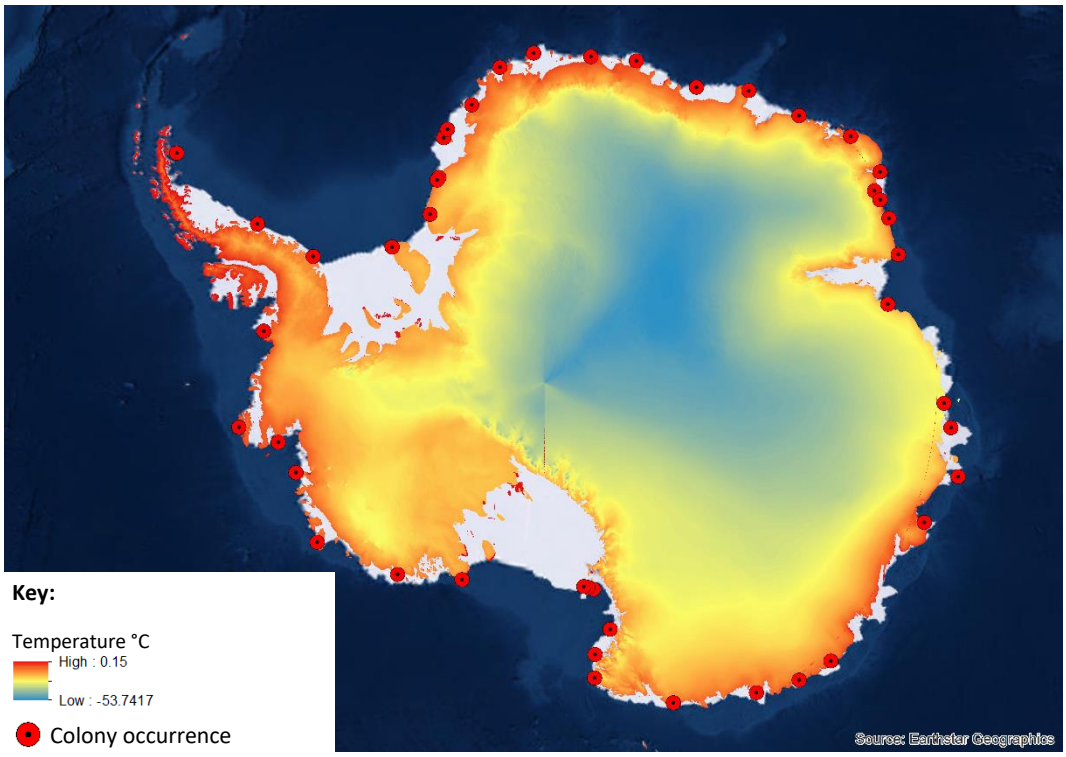
A-1 Emperor colony occurrence with population estimations and associated average air temperature

Colony	Long	Lat	Avr Temp (°C)	Population Estimation
Colony 1	-157.70	-77.15	-16.9	11438
Colony 2	-143.13	-75.54	-14.9	1550
Colony 3	-125.62	-73.51	-13.0	2989
Colony 4	-110.27	-74.37	-10.6	9457
Colony 5	-102.87	-73.89	-9.1	5732
Colony 6	-98.44	-71.81	-10.0	3568
Colony 7	-79.32	-73.16	-9.5	6061
Colony 8	-60.83	-74.37	-15.0	4018
Colony 9	-60.49	-70.61	-10.0	1620
Colony 10	-57.44	-64.52	-6.2	2164
Colony 11	-47.68	-77.82	-19.1	8242
Colony 12	-33.60	-77.77	-20.0	6498
Colony 13	-26.66	-76.11	-14.5	2597
Colony 14	-27.41	-76.21	-14.8	22510
Colony 15	-21.92	-74.07	-13.7	5455
Colony 16	-20.53	-73.68	-13.3	2305
Colony 17	-14.38	-72.72	-14.1	4013
Colony 18	-7.89	-70.85	-11.1	9657
Colony 19	-1.83	-70.18	-10.1	3193
Colony 20	7.92	-70.21	-11.1	1368
Colony 21	15.60	-69.93	-11.3	821
Colony 22	26.70	-70.12	-13.9	6870
Colony 23	34.36	-68.76	-13.1	4652
Colony 24	43.00	-68.10	-12.1	146
Colony 25	50.55	-66.78	-13.1	88
Colony 26	57.27	-66.65	-12.6	3283
Colony 27	59.28	-67.49	-13.0	213
Colony 28	60.86	-67.48	-13.1	519
Colony 29	63.97	-67.53	-11.6	7855
Colony 30	69.67	-67.88	-17.2	3465
Colony 31	76.84	-69.29	-20.5	6831
Colony 32	93.00	-66.56	-32.1	3247
Colony 33	96.46	-66.07	-27.4	6471
Colony 34	103.07	-65.17	-15.9	1609
Colony 35	110.59	-66.25	-8.8	1000
Colony 36	134.80	-66.37	-12.2	12476
Colony 37	140.03	-66.78	-12.7	2456
Colony 38	146.21	-67.65	-12.3	4781
Colony 39	158.49	-69.35	-12.7	1745
Colony 40	165.40	-74.64	-15.8	11808
Colony 41	166.97	-77.19	-18.3	1641
Colony 42	168.28	-77.38	-19.4	7561
Colony 43	169.31	-77.47	-18.7	303
Colony 44	169.67	-73.36	-16.6	25298
Colony 45	170.59	-71.99	-15.3	9505

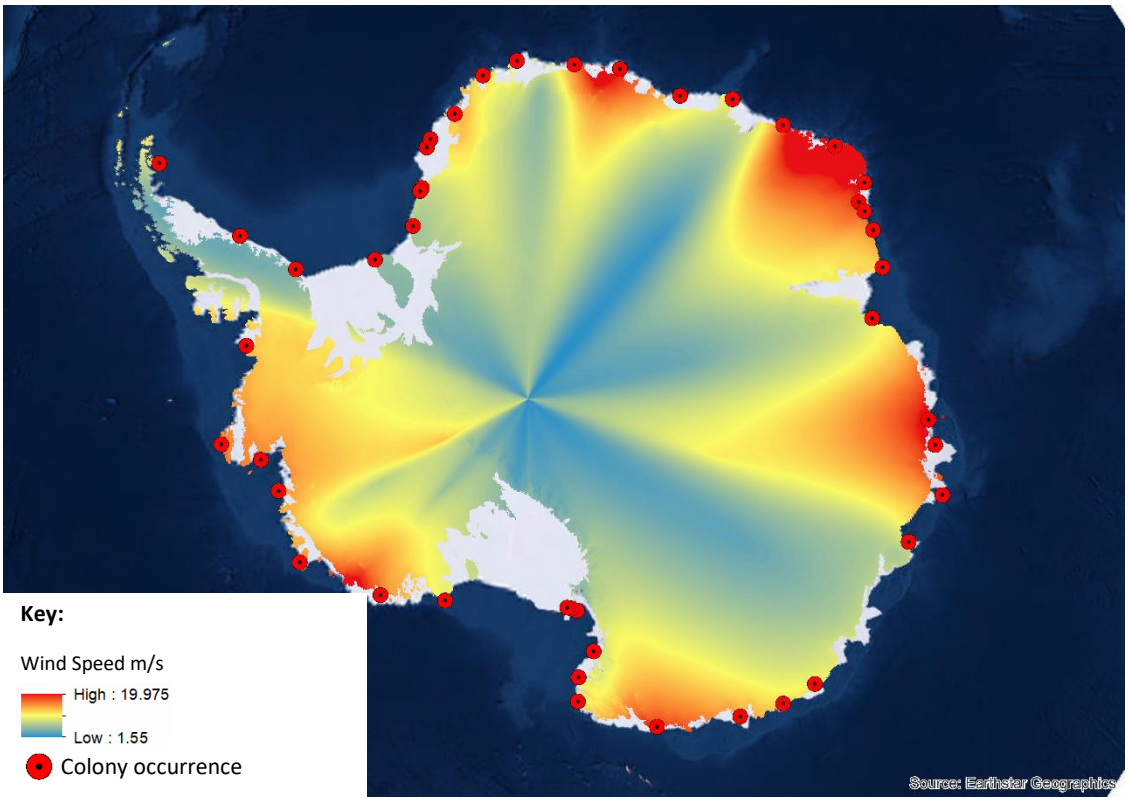
A-2 Map of emperor colony occurance extrapolated from Appendix A-1



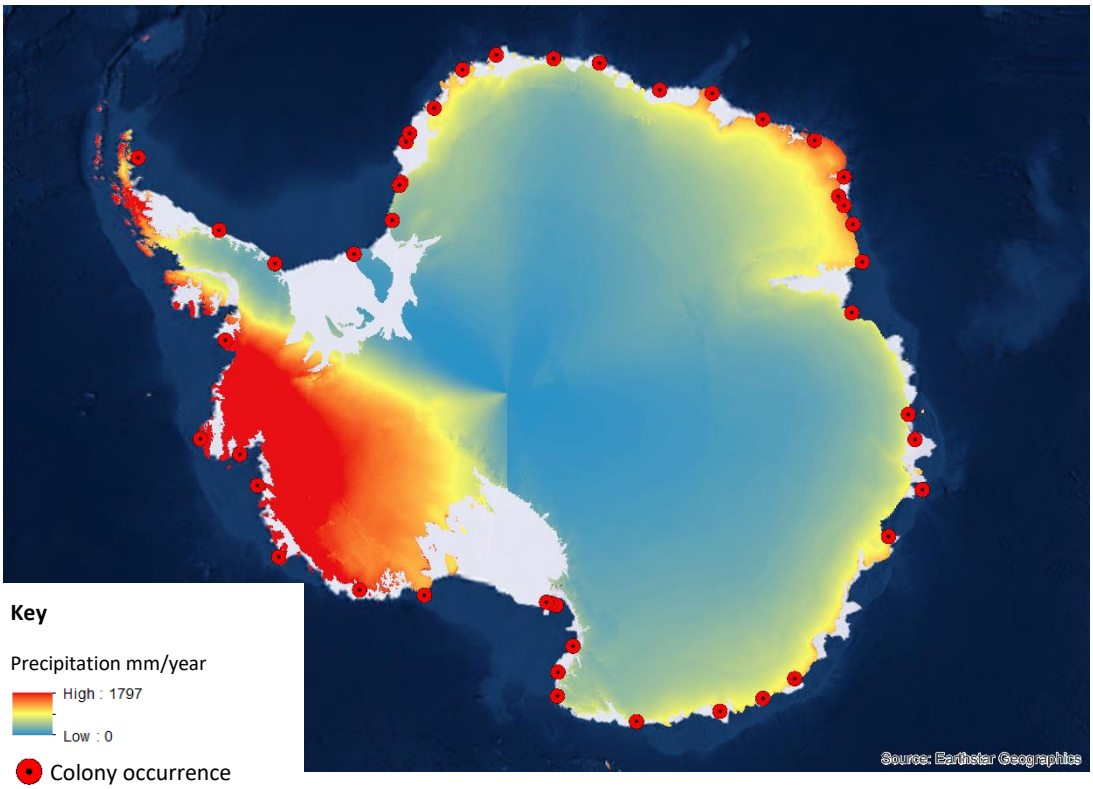
A-3 Map of average air temperature across Antarctica



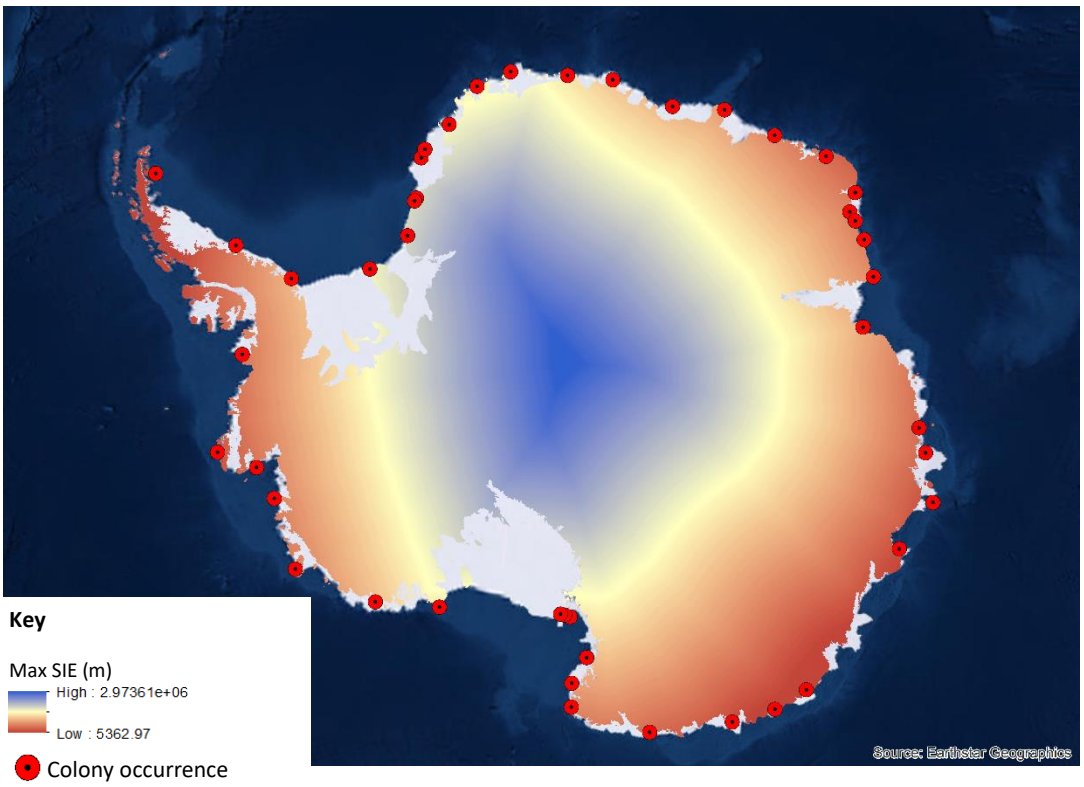
A-4 Map of average wind speed across antarctica



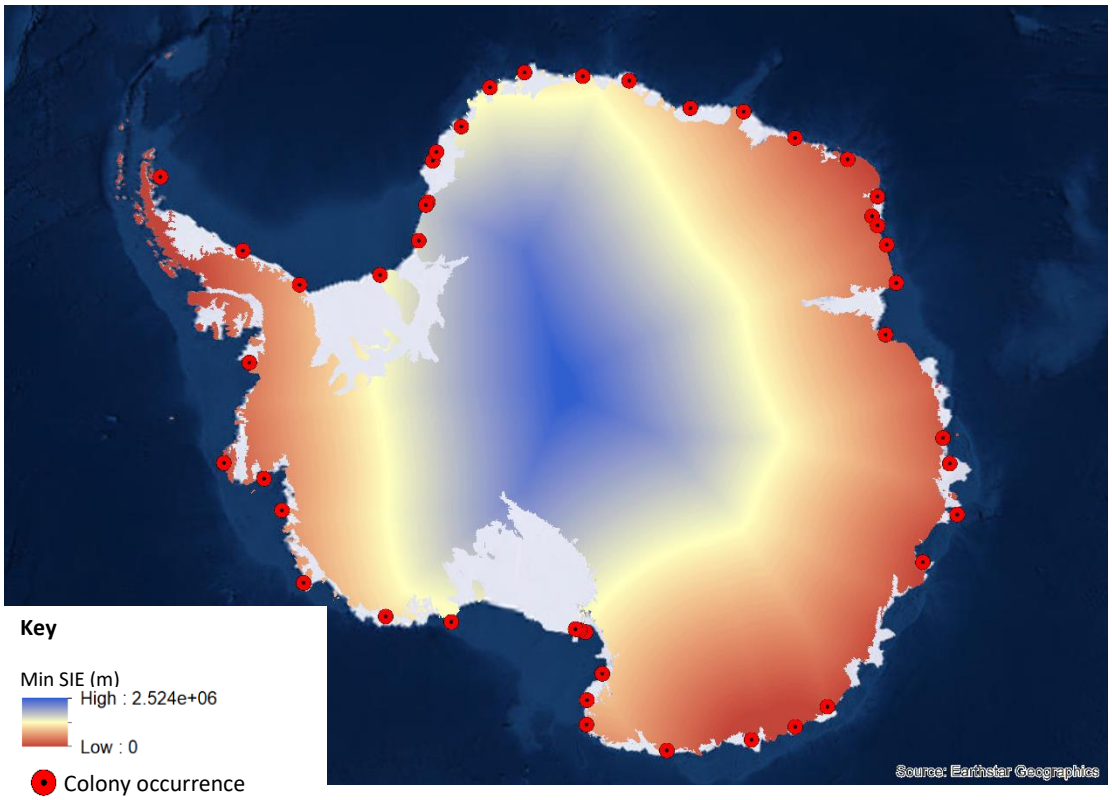
A-5 Map of average precipitation across antarctica



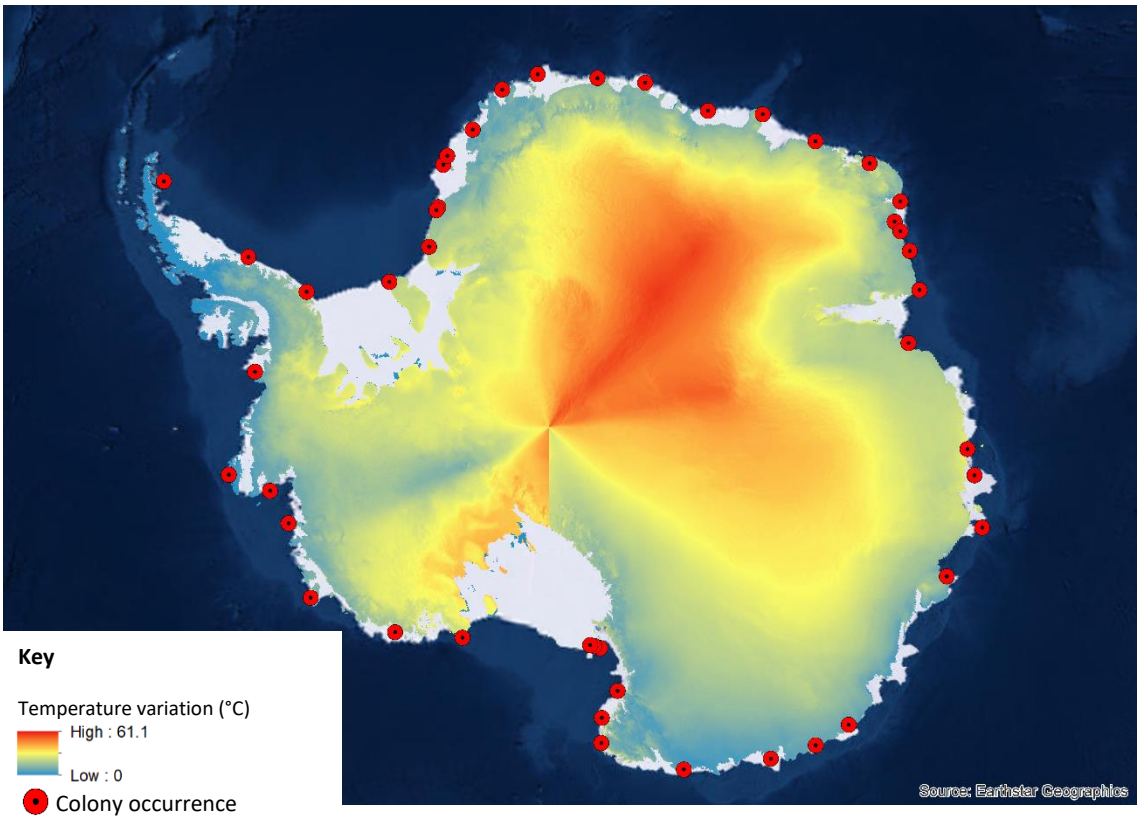
A-6 Maximum sea ice extent



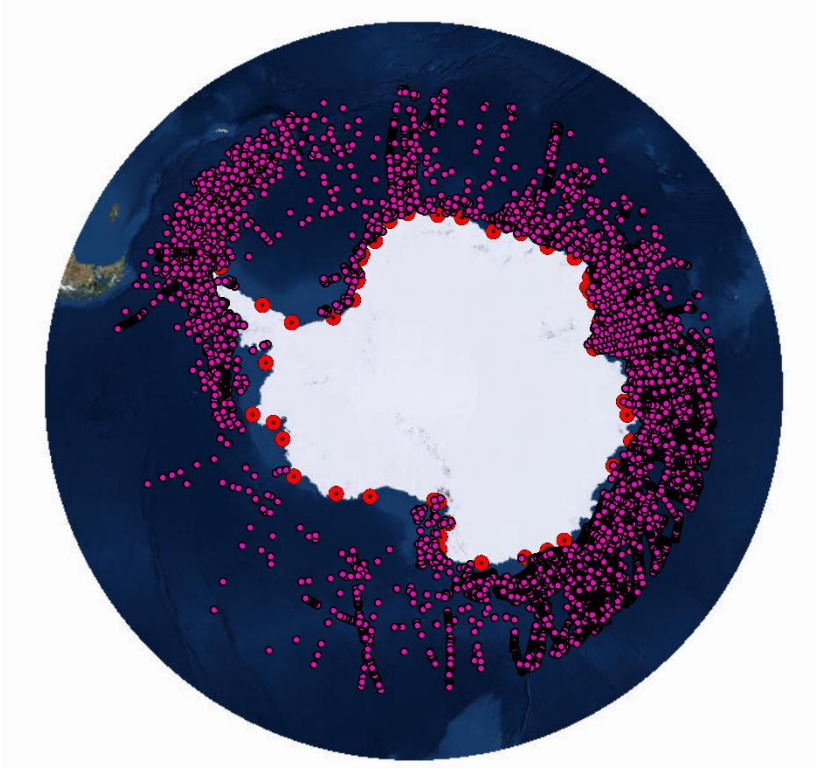
A-7 Minimum sea ice extent



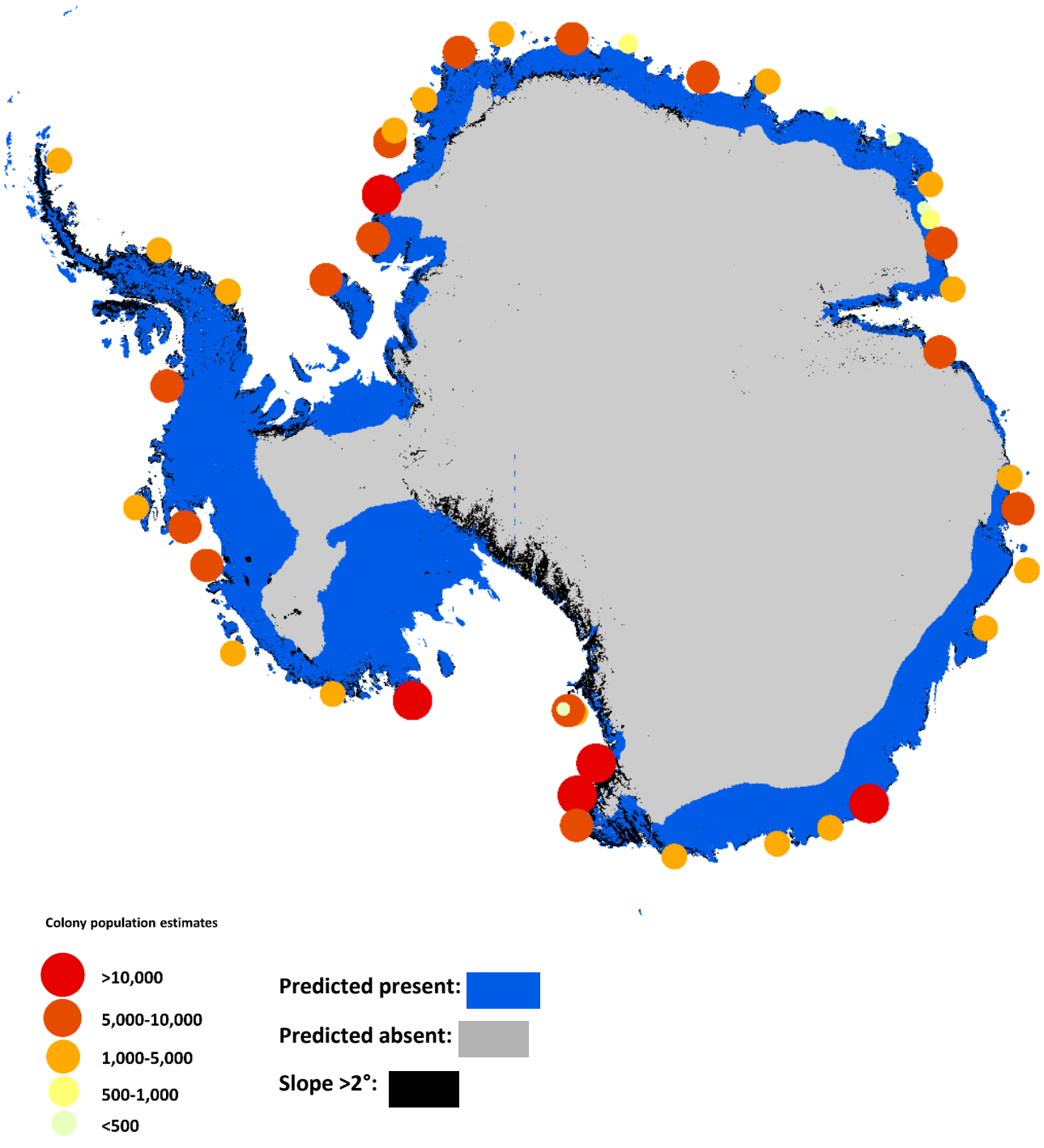
A-8 Temperature variation



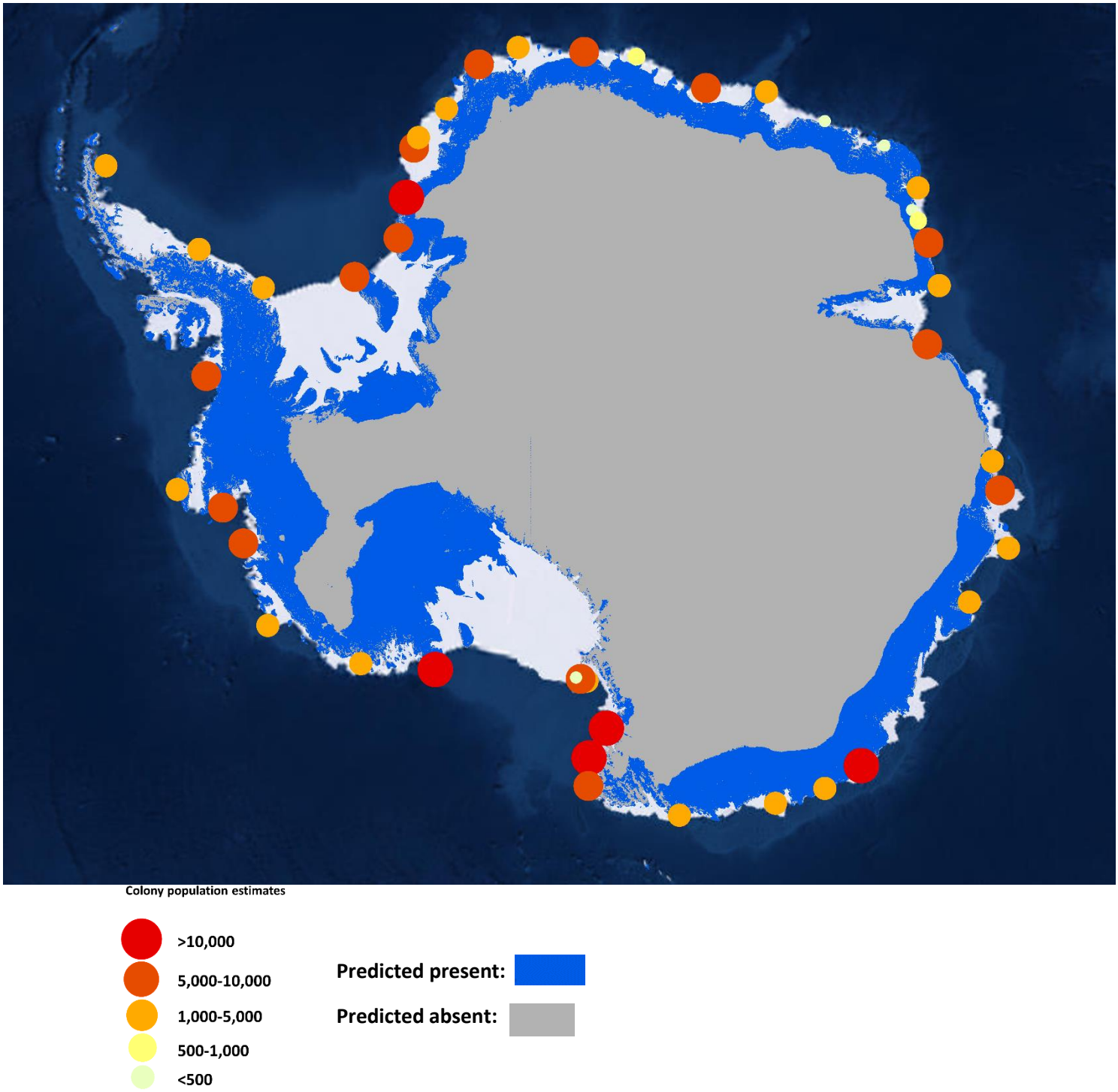
A-9 Krill occurances surrounding Antarctica



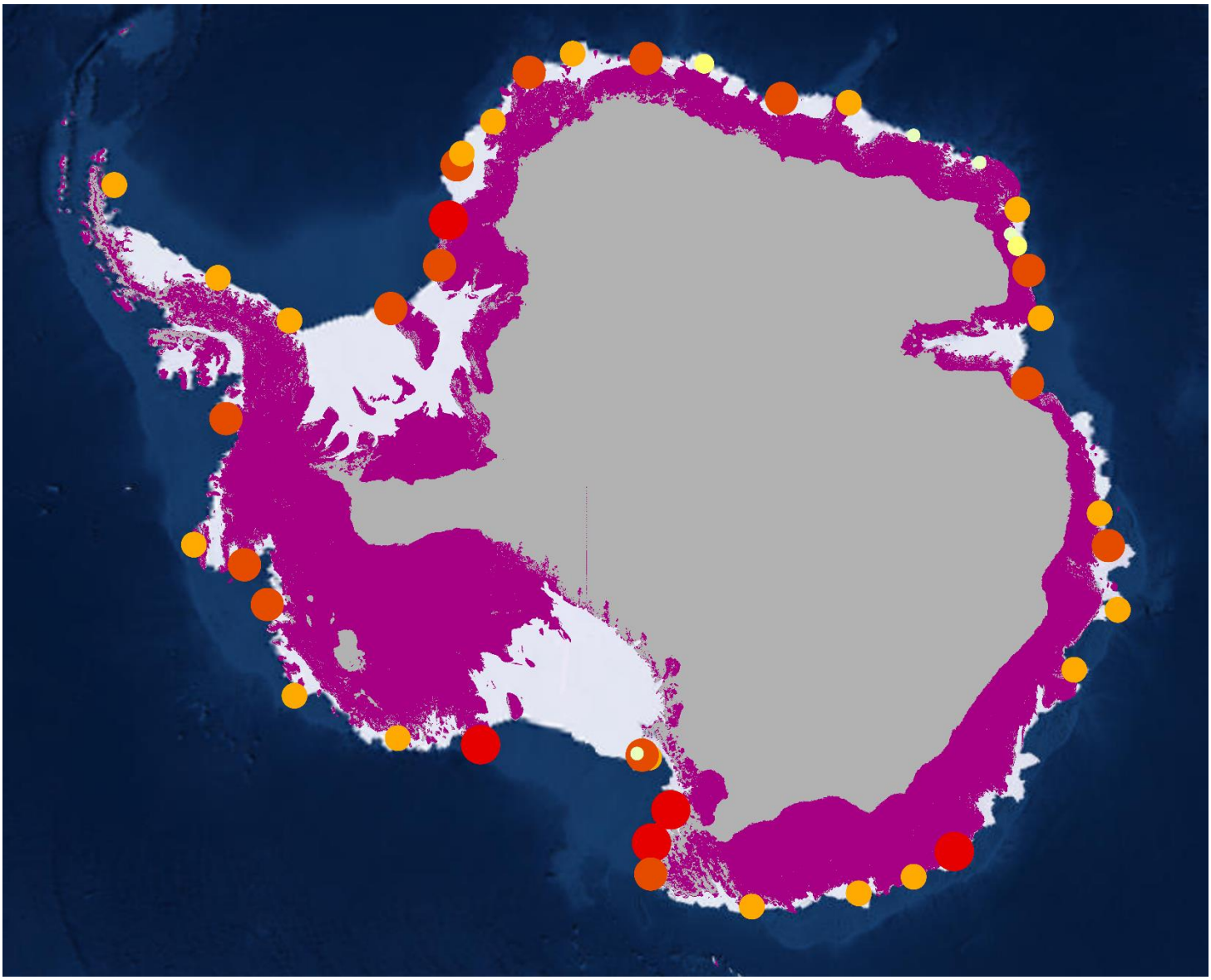
B-1 Emperor occurrence with relation to areas of slope above 2°



C-1 Presence absence under current climate conditions (Objective 2)



C-2 Presence absence under scenario 1 (Objective 3)



C-3 Presence absence under scenario 2 (Objective 3)

