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THE ECOLOGICAL IMPACTS OF CLIMATE CHANGE IN HOT REGIONS – ARE HAWKSBILL TURTLES LIVING ABOVE THEIR OPTIMUM TEMPERATURE IN THE UAE?

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United Arab Emirates University

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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Environmental Sciences and Sustainability

Under the Supervision of Dr. David L. Thomson

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Declaration of Original Work

I, Obaid Ali Alshamsi, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*The Ecological Impacts of Climate Change in Hot Regions – Are Hawksbill Turtles Living Above Their Optimum Temperature in the UAE?*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. David L. Thomson, in the College of Science at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis/dissertation have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

It is getting warmer throughout the world but it is not getting warmer by the same amount in all regions, leading to speculations where the biggest impacts will be. The impact on species living in the hot regions is widely assumed to be slight in comparison to the temperate and higher latitude regions. Temperature changes in hot regions are smaller, but it may be that the species in those regions have reached their optimum temperatures. In which case the effects of even a small temperature increases could be steeply negative. To test this thoroughly in term of demographic parameters I had to quantify demographic parameters and reconstruct their relationship with temperature. For this I needed long term population data which allowed me to quantify the fitness and the probability of species breeding. Within the United Arab Emirates, extensive monitoring programs have been in place for Hawksbill Turtle (*Eretmochelys imbricata*) with systematic nesting counts being conducted annually since 2001. Sea turtles as a species is an endangered one, and are an interest in their own right as well as being a good study species to determine whether a species in hot regions is vulnerable to climate change. Using a Generalized Linear Model (GLM), I reconstructed two separate relationships. One is the relationship between fitness and temperature and the other is the relationship between breeding probability and temperature. Although I was not able to detect any significant relationship between fitness and temperature, I found that there is a direct positive relationship between temperature in the nine months prior to breeding and the probability of female turtle to nest which implies that hawksbill turtles in Abu Dhabi waters may not be living above their optimum temperature yet.

Keywords: Climate change, climate impact, hawksbill turtle.

Title and Abstract (in Arabic)

الآثار الإيكولوجية للتغير المناخي في المناطق الساخنة - هل تعيش سلاحف منقار الصقر فوق درجة الحرارة المثلى في الإمارات؟

الملخص

تزداد درجات الحرارة في جميع أنحاء العالم، ولكن العالم لا يزداد دفئًا بنفس القدر في جميع المناطق، مما يؤدي إلى تكهنات حول موقع التأثيرات الأكبر عالمياً. يفترض على نطاق واسع أن التأثير على الأنواع التي تعيش في المناطق الحارة يكون طفيفًا مقارنة بالمناطق المدارية والقطبية. إن التغيرات في درجات الحرارة في المناطق الحارة أقل إلا أن الأنواع في تلك المناطق قد تكون وصلت إلى درجات الحرارة المثلى. في هذه الحالة، قد تكون تأثيرات ارتفاع درجة الحرارة ولو بشكل طفيف سلبية للغاية. لاختبار هذا بدقة من حيث المعلمات الديموغرافية اضطررت إلى تحديد المعايير الديموغرافية وإعادة بناء علاقتها مع درجة الحرارة. لهذا كنت بحاجة إلى بيانات مجموعات السلاحف على المدى الطويل والتي سمحت لي بتحديد مدى لياقة واحتمالية تكاثر النوع. تم وضع برامج مراقبة واسعة النطاق لسلاحف منقار الصقر في دولة الإمارات العربية المتحدة مع عمليات تعداد منهجية تجرى سنويًا منذ عام 2001. تعتبر السلاحف البحرية كنوع من الأنواع المهددة بالانقراض، وأحد الأنواع ذات الأهمية بذاتها وأنواع دراسة جيدة لتحديد ما إذا كانت الأنواع في المناطق الساخنة معرضة لتغير المناخ. باستخدام نموذج خطي معمم (GLM)، قمت بإعادة بناء علاقتين منفصلتين. الأولى هي العلاقة بين اللياقة ودرجة الحرارة والأخرى هي العلاقة بين احتمال التكاثر ودرجة الحرارة. على الرغم من أنني لم أتمكن من اكتشاف أي علاقة ذات أهمية بين اللياقة ودرجة الحرارة، إلا أنني وجدت أن هناك علاقة إيجابية مباشرة بين درجة الحرارة في التسعة أشهر السابقة للتكاثر واحتمال تعشيش السلحفاة بغرض التكاثر مما يعني احتمالية أن سلاحف منقار الصقر في مياه أبو ظبي لا تعيش فوق درجة الحرارة المثلى حتى الآن.

مفاهيم البحث الرئيسية: تغير المناخ ، تأثير المناخ ، سلحفاة منقار الصقر.

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Dedication

To my beloved parents and family

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List of Abbreviations

AGEDI	Abu Dhabi Global Environmental Data Initiative
EAD	Environment Agency-Abu Dhabi
GLM	Generalized Linear Model
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
TSD	Temperature-dependent Sex Determination
UAE	United Arab Emirates

Chapter 1: Introduction

1.1 Overview

It is getting warmer throughout the world (Schiermeier, 2006) but it is not getting warmer by the same amount in all regions (Intergovernmental Panel on Climate Change, 2014), leading to speculations about where the biggest impacts will be (Sala et al., 2000). The biggest temperature increases are in the higher latitude (Walther et al., 2002), and it has been widely assumed that this is where the biggest ecological impacts will be (Walther et al., 2002). The impact on species living in the hot regions is often considered slight in comparison to the temperate and higher latitude regions. (Intergovernmental Panel on Climate Change, 2007; Tewksbury, Huey, and Deutsch, 2008).

However, there is an emerging interest in the possibility that the biggest ecological impacts might, in fact, be in the hottest regions of the world (Ribot, Najam, and Watson, 1996). Temperature changes in hot regions are smaller (Intergovernmental Panel on Climate Change, 2014), but it may be that the species in those regions have reached their optimum temperatures (Deutsch et al., 2008). In which case the effects of even a small temperature increases could be steeply negative. Based on physiological analysis there is some evidence that some species in hot regions may already have reached their optimum temperature which suggest that the impact might actually be larger on tropical species rather than temperate regions (Tewksbury et al., 2008). As outlined in Figure 1 it may be that tropical species live in climates that are closer to their physiological optima, and thus may be highly vulnerable even to modest climate warming.

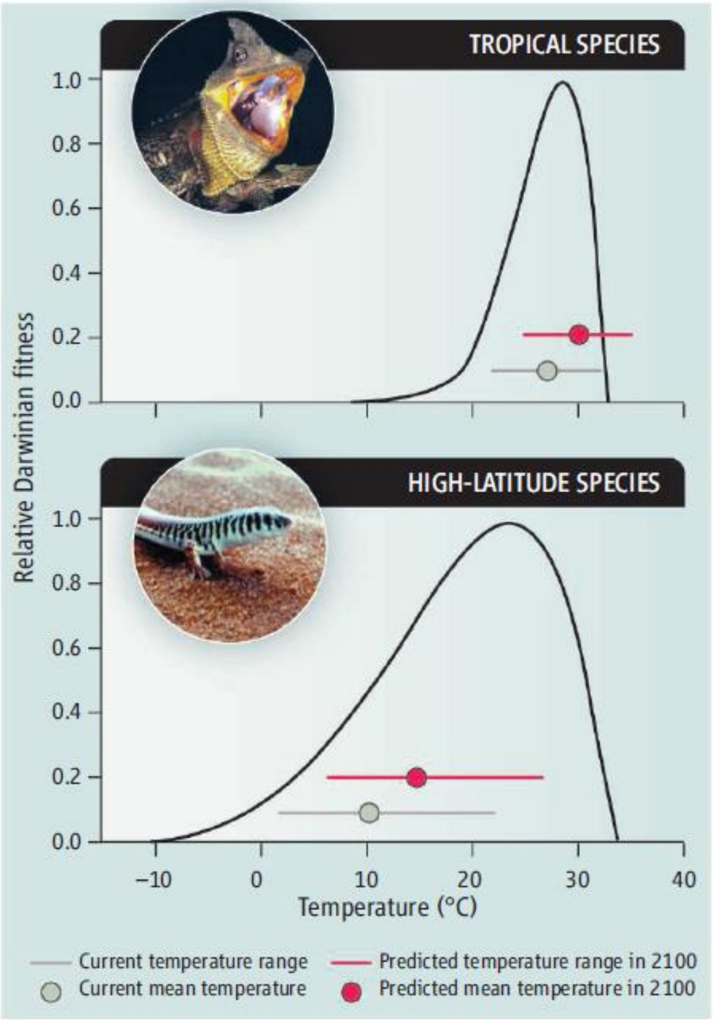

Figure 1: Tropical species may be more vulnerable to climate change. Figure from: (Tewksbury et al., 2008)

Species living in hot regions are often considered unique and with global importance as they often include endangered endemic species (Olson et al., 2001). For instance, the UAE, which is regarded as one of the hyper arid and hot desert areas, is the home of unique fauna and flora. 12% of UAE identified fauna is listed on IUCN Red List, of which 2% are internationally endangered species (Tourenq, and Launay, 2008). Thus, if the impacts on species in these hot regions are greater, it will possibly impact globally important biodiversity.

The bases of these emerging ideas is the assumption that species living in hot regions are already living above there optimum, and while it is possible they are, it perhaps cannot be taking for granted. Approximately 1% of the global research on climate change impact has been carried out in hot region (Rosenzweig et al., 2008), therefore we know very little on climate change impact in hot regions, making this an area of a lot of uncertainty. Biological, biochemical and metabolic processes may run faster under warm conditions (Brown, Gillooly, Allen, Savage, and West, 2004). Indeed, endotherms commonly choose to run their metabolism between 36° and 43°C temperatures which are much above to prevailing environmental conditions in much of the tropics and hot regions (Glanville, Murray, and Seebacher, 2012). So, the impression of species in hot regions are more vulnerable has yet to be tested.

Furthermore, the most meaningful measure of performance is demographic and have to do with ability to survive and reproduce (Damos, 2015), but in practice these demographic parameters have not been studied to a great extent and most of performance curves has been constructed using proximate measures of fitness and in particular physiological performance (Deutsch et al., 2008).

1.2 Statement of the Problem

Using demographic approaches, this study aims to understand the effect of climate change on species in hot regions by focusing on hawksbill turtles as a study species. I aim to reconstruct not only the relationship between fitness and temperature but also the relationship between breeding probability and temperature; and in this way I aim to test whether the hawksbill turtle is already living above its optimum temperature or whether indeed it still living below its optimum temperature.

1.3 Relevant Literature

1.3.1 Climate Change and Hot Regions

Studies have shown that the earth is getting warmer (Schiermeier, 2006) and researchers have speculated where the impacts will be felt the most (Sala et al., 2000). The Intergovernmental Panel on Climate Change (IPCC) in 2014 has asserted how the global temperature rise is non-uniform and studies have posited that higher latitudes shall witness maximum temperature rise and the greatest ecological impacts (Walther et al., 2002). Moreover, the IPCC declared in 2013 that the mean surface air and sea temperatures will increase by up to 2°C by 2100 in the absence of mitigation plans. They further stated how polar ice melting and ocean warming increased sea water levels by 2 mm per year over the last 40 years. By 2100, the mean sea level rise could be as high as 1.14 m depending on loss of ice in Greenland and Antarctica (Butt, Whiting, and Dethmers, 2016).

In the past three decades, the Earth's surface has warmed by 0.6°C which is significant compared to the overall temperature raise of 0.8°C over the past century (Salam, 2015). The temperatures has risen faster in the Arctic, much slower in the tropics, and even slower in the south temperate zones according to data sets of temperature change since 1980 (Dillon, Wang, and Huey, 2010). Due to the retreat of ice and snow, the high latitude regions experience faster farming which causes many biotic shifts. Additionally, arctic amplification or polar amplification which is the rapid warming of high latitudes due to increased heat transfer from the tropic to poles also enhaces the warming in higher latitudes away from the equator (Serreze, Barrett, Stroeve, Kindig, and Holland, 2009). According to several climatic models, the average surface temperature is predicted to rise by 1.1°C to 6.4°C over the 21st century (Salam, 2015).

Since warming is less pronounced in tropics compared to higher latitudes, the temperature shifts in tropical regions are generally expected to be less marked (Dillon et al., 2010). However, new studies argue that the frequency drop in cold extremes and increase in warm extremes will have the most ecological impact (Revadekar et al., 2012). Such studies root from the theory that hottest regions of the world will have the biggest ecological impacts (Ribot et al., 1996). Since mid 1970s, tropical temperatures have risen at an average rate of 0.26 ± 0.05°C per decades and the daily temperature variations across the tropics has increased by 0.29°C (Wang and Dillon, 2014). The available projections suggest that tropical regions will experience extreme conditions sooner than other regions of the world even with warming less than 1°C (Sheldon, 2019). As a result, there is a paradigm shift in scientific research which had previously placed negligible focus on the impact of climate change on hot regions (Rosenzweig et al., 2008).

One of the regions that experience the hottest sea water temperatures which exceed 30°C for sustained periods is the United Arab Emirates (UAE), part of the Persian/Arabian Gulf. According to Tourenq and Launay (2008), the International Union for Conservation of Nature (IUCN) has listed 12 percent of UAE's fauna in their Red List and considers 2% of them, endangered. Due to climate change, and in the absence of mitigation measures the UAE and surrounding regions are expected to be a 'hotspot' with changes in sea levels, sea water salinity, sea surface temperatures and wind patterns (Ksiksi and Al-Blooshi, 2019). Several species living the region are close to their environmental limits due to their high sensitivity to environmental fluctuations (Wabnitz et al., 2018). Due to the high ambient air and water temperatures and slow water circulation in the seas, UAE's marine habitat can be considered the ideal laboratory for studying the effects of climate change and elevated global temperatures on the thermoregulatory behavior of marine species.

Rising temperatures have biological impact on organism depending on their physiological sensitivity to temperature change (Deutsch et al., 2008). Even though the degree of warming may be more in higher latitudes, it is possible that slight change in temperature will increase the rate of biological, biochemical, and metabolic processes in tropical species (Brown et al., 2004) which may be living at temperatures higher than optimum levels. Deutsch et al. (2008) have asserted the importance of considering physiological sensitivity of organisms to rising temperatures in their natural ecosystem while mapping the impact of climate change. Moreover, Liles et al. (2019) has asserted that the biological capacity of thermal sensitive ectotherms to adapt to climatic variables such as temperature, precipitation, humidity, wind speed, and solar radiation is unknown. Understanding the scope of climate change, especially the synergistic effects such as rise in temperature, decrease in oxygen content, sea level rise, and so on, and their impact on ocean biogeochemisty is important to devise sustainable management and conservation plans (Wabnitz et al., 2018).

Several endangered endemic species live in hot regions and they are considered as unique and important part of global ecosystem (Liles et al., 2019). Such species include several marine turtles which have characteristics such as Temperature-dependent Sex Determination (TSD) and climate change can promote extreme sex ratio bias which can threaten their survival (Marcovaldi et al., 2014). One of the endangered turtle species in the UAE is the Hawksbill turtle

(*Eretmochelys imbricate*), and several studies in recent years have focused on the projected impacts of climate change on their nesting and foraging sites (Butt et al., 2016). Due to their dependence on marine and terrestrial habitats during their lifecycle, studying the response of sea turtles to climate change is important (Liles et al., 2019). A year round constant surface water temperature in the 22 to 30°C range is ideal for sea turtles and fluctuations in them due to climate change can affect habitat availability, nesting success, incubation success, nesting time, gender ratios, hatchling fitness, and so on (Pilcher, 2015).

1.3.2 Ecological Impact Of Climate Changes In Hot Regions

The hottest regions on Earth are centered on the equator and positioned between the Tropics of Cancer (23°27 N) and Capricorn (23°27 S). In such tropical locations, the sun is directly overhead at some period during the year and there is a lack of seasonality in temperature (Sheldon, 2019). From a temperate perspective, it is notable that the tropical climates are generally warm and the mean monthly temperature fluctuation in tropics is little during the year. The average temperature increase predicted for the tropical areas by global climatic models range between 1 - 4°C. At such temperature variations, the metabolic rates of species in tropical and north temperate zones will witness the highest impact according to several analyses (Dillon et al., 2010). Moreover, poor dispersal ability, specialization, and low tolerance for ecological changes which are identified as risk factors by the IPCC are characteristics of tropical species, and climatic warming will increase those risks (Sheldon, 2019).

The regional impacts of the climate changes are defined as the long-lasting substantial fluctuations in the weather patterns in the course of a prolonged period of time, being restricted to a particular region as a result of the process of global warming (Ramírez et al., 2017). At the same time as there is an apparent increase in the global average temperatures and the mean global sea surface temperature, the ecological impacts of the climate changes cannot be consistent across the planet due to various reasons (Deser et al., 2010; Rowe and Derry, 2012; Walther et al., 2002). For instance, the lands are believed to be more susceptible to changes compared to the oceans; the areas that are located on the higher latitudes in the North are assumed to be more susceptible to changes as compared to the tropical regions, and so on. The regional ecological impacts of the climate changes are different in their essence as well due to the fact that some ecological changes are a direct outcome of the overall global climate fluctuations, for instance, the growing temperatures and the melting icebergs (Rowe and Derry, 2012; Walther et al., 2002). On the other hand, the ecological changes might be connected to the fluctuations in the weather systems, the ocean currents, and the local ecosystems (Turley et al., 2016). In these cases, the ecological impacts might be different from the overall global trends in climate change across the planet, for instance in the northern and the southern regions, namely hot and cold areas.

Recent research suggests that the hot regions of the world, namely the African continent and the south-western regions of Asia may be more prone to the negative effects of climate change (Ramírez et al., 2017; Xu, Gao, and Giorgi, 2009). The United Arab Emirates has a coastline exceeding 1200 kilometres and its summers (June to September) witness temperatures surpassing 48°C and dampness as high as 80 – 90%. Even though winters in UAE are comfortable with temperature averaging at 25°C, they are expected to become shorter and an increase of 2.44°C in maximum summer temperatures is forecasted by several models. Several other studies which accommodate for green house emissions predict that several Middle Eastern and North African countries will witness a temperature increase of more than 6°C in summer seasons by the end of the century (Blooshi et al., 2019). Although the ecological impacts of the climate changes on species in hot regions is not yet fully understood, there have been case studies which indicates that threats facing the ecosystem those species are part of is emphasized by global warming (Brierley and Kingsford, 2009; Gray, 1997; Walther et al., 2002).

By 2100, UAE is expected to lose up to 6% of its coastline due to ocean thermal expansion and rising sea levels. Moreover, recent climate shifts due to global warming is responsible for the documented changes in geographical ranges, seasonal phenology, community interactions, genetics, and extinctions in UAE and other tropical regions (Dillon et al., 2010). These climatic shifts and their consequences can severely impact the habitats and survivability of marine species such as the hawksbill turtles.

1.3.3 Biology and Habitat of Hawksbill Turtles in UAE

Deutsch et al. (2008) have asserted how marine species in hot regions have reached their optimum temperature limits. Due to the influence of environmental temperature on their physiological functions such as locomotion, growth, and reproduction, climate warming threatens sea turtles more than other organisms leading to biased sex ratios, impact to developing embryos, and so on (Pilcher, 2015). Large body size is the primary contributor to thermal tolerance in sea turtles; however, Gulf turtles such as the Hawksbills in the UAE are among the smallest adult turtles (Pilcher, Antonopoulou, et al., 2014). The small size can be attributed to thermal limits and fluctuation rate stressors, and the possibility that the Hawksbills are nutrient-limited. Moreover, Hawksbills are primarily spongivorous so coral reef areas are necessary to sustain their key habitats (Pilcher, Perry, et al., 2014). Climate change and resultant coral reef bleaching affect the turtle habitats and their summer migration in waters at 15 m depth afford them no reef-like structures to forage.

Hawksbills exhibit Temperature-dependent Sex Determination (TSD) and require a temperature range of 25°– 35°C for successful incubation of eggs (Montero et al., 2018). Studies have revealed that Arabian hawksbills can nest up to six times in a season; however, migration and foraging limits the number closer to three. They spend 20% of the time in migrations, 70% of the time foraging, and devote only 6% of their time to nesting and related activities (Pilcher, 2015). Studies conducted at nesting beaches by measuring sand temperatures have shown that the temperatures have surpassed the numbers pivotal for hawksbill nesting (Liles et al., 2019). Moreover, sea level rise, storms and other extreme events is impacting hawksbill's habitat through nest flooding, loss of vegetation available for nest shading, reduction in beach profiles and area available for nesting, and so on The hawksbill's ability to adapt and evolve can have substantial impact on the species' chances to survive extinction risks due to climate change. However, human involvement is pivotal to conserve their habitat and create an environment ideal for their nesting and foraging activities.

1.3.4 Thermoregulatory Behavior of UAE Hawksbills and Threatening Factors

The marine turtle species may adapt in several ways according to Liles et al., (2019) in order to mitigate unfavorable conditions. Sea turtles exhibit several thermoregulatory behaviors such as short-term mitigation, basking, and body alignment (Pilcher, Perry, et al., 2014). The thermoregulatory response of UAE's hawksbill turtles by spending 20% of their lifetime in migration reveals a potential adaptive measure of the species to cope with rise in sea water temperatures (Pilcher, Perry, et al., 2014). Due to the physiology-threatening conditions during summer in UAE and surrounding regions, the hawksbill turtles migrate to deeper and cooler waters in the northern latitude for 2 to 3 months (Pilcher, 2015). In the months of September-October they migrate back to their original foraging grounds constituting an average total migration of 140 km. Such migratory behavior allows the UAE hawksbills to survive when sea surface temperatures will be around 35°C and air temperatures can be as high as 50°C.

The primary threat to the hawksbill turtle is the rise in temperature due to climate change. As a result of high temperature, reproduction success is lowered, catalytic efficiency of enzymatic reactions is affected, osmoregulation, respiration, and behaviors are impacted, and the population is endangered (Pilcher, 2015). Moreover, Hawksbills are more threatened by traditional fisheries than commercial shipping since they forage primarily in shallow waters (Pilcher, 2015). Nevertheless, harvesting eggs for food, drowning in fishing gear, use of hunted adult turtle carapace as curios, and cold-stunning have led to their population decline (Natoli Phillips, Richardson, and Jabado, 2017). Also, weather disruptions can reduce the number of clutches, egg, and hatchlings during nesting season (Butt et al., 2016). Furthermore, land reclamation and dredging activities in Dubai and surrounding nesting locations also contribute to migrations to alternate nesting sites or failure to nest altogether (Natoli et al., 2017).

Chapter 2: Methods

2.1 Selection of the Study Species and Data

In order to work out whether a species in hot regions is vulnerable to climate change, we need to work out whether it is already living above its optimum temperature. To test this thoroughly we need to quantify demographic parameters and reconstruct their relationship with temperature. For this we need long term population data which allow us to quantify the fitness and the probability of species breeding. Within the United Arab Emirates, extensive monitoring programs have been in place for Hawksbill Turtle (*Eretmochelys imbricata*) with systematic nesting counts being conducted annually since 2001 (Ministry of Climate Change and Environment , 2019). Sea turtles are an endangered species, and a good study species to determine whether a species in hot regions is vulnerable to climate change as well as being an interest in their own right as well (Mazaris et al., 2017). They're also a good indicator species for considering climate change conservation planning because of their interdependence on terrestrial and marine resources. Changes in temperature along coastal interfaces could exert strong effects on the demographic parameters of sea turtles (López-Barrera et al., 2016)

2.2 Data Collection

2.2.1 Hawksbill Turtle Data

The data used in this research composed of hawksbill turtle population data in Abu Dhabi and daily temperature data for the Emirate of Abu Dhabi. The hawksbill turtle data were obtained from Environment Agency-Abu Dhabi (EAD). The data covered the nesting of the hawksbill turtles off the shores of Abu Dhabi Emirate from 2001 to 2016. The data is collected through regular surveys conducted by EAD in nesting season; hawksbill turtles nest in spring, April to June (Environment Agency Abu Dhabi, 2016). The data showed the total number of nests along the Abu Dhabi coastline. It did not specify the number of nests per female (Table 1).

Table 1: Number of hawksbill turtle nests counted annually in Abu Dhabi by EAD

Year	Number of Nests
2001	200
2002	160
2003	169
2004	155
2005	217
2006	152
2007	173
2008	166
2009	177
2010	230
2011	242
2012	171
2013	169
2014	210
2015	204
2016	229

The data then were used to reconstruct the relationship between population growth rate and temperature, and the breeding probability and temperature.

2.2.2 Temperature Data

The temperature data were obtained from the National Oceanic and Atmospheric Administration (NOAA) through their National Centers for Environmental Information (NCEI). By submitting a request online, a data sheet of the daily temperature data from Abu Dhabi airport weather station from 2000-2016, was provided. The data then was used to obtain daily and monthly averages of temperature through Excel. To obtain the average daily temperature, the excel's average function was used on the daily temperature of each year from 2000-2016. Similarly, to obtain the average monthly temperature, the excel's average function was used on the daily temperature of each month from 2000-2016. From there, the average temperatures were extrapolated accordingly. Similarly, I obtained the average, mean minimum, and mean maximum temperatures for the nine, six, and three months before the breeding season (Tables 2-5).

Given that marine turtles nest every two years (Sea Turtle Conservancy, 2019), the data were reorganized to start with turtles who nested in odd years followed by turtle who nested in even years. Furthermore, due to the fact that hawksbill turtle's nesting season starts in April, the data was re-organized to mark April as the onset of the breeding year.

Table 2: The annual Average daily temperature

Year	Average daily temperature
2001	28.50396
2003	28.34775
2005	28.27166
2007	27.77571
2009	27.77444
2011	28.44759
2013	28.44285
2002	28.29659
2004	28.43327
2006	27.99039
2008	27.68968
2010	28.03333
2012	28.47889
2014	28.26593

Table 3: The average monthly temperatures data

Year	Annual Avarage temperature	9 months before the breeding season	6 months before the breeding season	3 months before the breeding season
2001	28.58659047	26.34428311	24.10051069	20.3780722
2003	28.39891449	26.30611538	23.79532002	22.22411674
2005	28.07568356	25.86606076	23.3034639	21.09854071
2007	27.64631557	25.67205155	22.57008449	20.4874808
2009	27.81582309	25.65891108	22.80177163	21.08056835
2011	28.6443446	26.35530295	23.53146697	21.453149
2013	28.57224974	25.76742021	23.45666795	21.25272657
2002	28.29659498	26.36893668	23.79284946	21.74784946
2004	28.46762699	26.19357434	23.82075578	22.12706711
2006	27.90509601	25.72759639	23.18456477	20.97941628
2008	27.73305309	25.14554031	22.29802373	19.75024101
2010	28.25084229	26.40293907	23.64888889	21.85537634
2012	28.31344364	25.82455568	22.92247868	20.83044123
2014	27.95961598	25.87135177	23.04735023	20.66459294

Table 4: The maximum monthly temperatures

Year	Annual maximum temperature	9 months before the breeding season	6 months before the breeding season	3 months before the breeding season
2001	31.54166667	30.75555556	26.83333333	25
2003	32.775	31.4	28.63333333	28.73333333
2005	31.69166667	30.33333333	26.58333333	25.23333333
2007	31.675	31.40833333	27.26666667	26.2
2009	31.81666667	31.07777778	27.4	27.1
2011	32.81666667	31.7	27.8	27.36666667
2013	32.4	31.1	26.9	25.56666667
2002	32.29166667	31.58888889	28.53333333	28.73333333
2004	32.10833333	31.12222222	28.05	27.13333333
2006	31.275	29.94444444	26.5	25.66666667
2008	31.40833333	31.81666667	26.28333333	25
2010	32.475	31.36666667	28.91666667	28.16666667
2012	32.25	31.28888889	28.11666667	28.3
2014	31.76666667	30.87777778	26.96666667	25.26666667

Table 5: The minimum monthly temperatures

Year	Annual minimum temperature	9 months before the breeding season	6 months before the breeding season	3 months before the breeding season
2001	25.06666667	24.44444444	20.01666667	17.06666667
2003	24.95	24.04444444	19.7	17.5
2005	24.625	23.74444444	19.98333333	17.9
2007	25.03333333	24.25833333	19.83333333	17.5
2009	24.8	23.83333333	19.68333333	17.3
2011	25.44166667	24.45555556	20.23333333	18.13333333
2013	25.25	24.35555556	19.95	17.53333333
2002	25.175	24.42222222	20.55	17.76666667
2004	25.325	24.71111111	20.83333333	19
2006	24.84166667	24.21111111	20.43333333	17.8
2008	24.25833333	24.8	18.26666667	15.03333333
2010	24.925	24.55555556	20.56666667	18.3
2012	24.66666667	23.65555556	19.1	16.36666667
2014	24.65	24.11111111	19.85	17.56666667

2.3 Research Design

The average absolute fitness of individuals in a population is mathematically equivalent to its population multiplication rate (Pickett et al., 2015):

$$\text{Population multiplication rate}(\lambda) = (N_{t+1}/ N_t) \tag{1}$$

Which can also be formulated in term of its natural log (r) where

$$r = \log_e(N_{t+1}/N_t) \tag{2}$$

Given that hawksbill turtles breed every two years, in practice, the population multiplication rate is modeled over two years' period for each of the two non-overlapping breeding sub-population, therefore:

$$\text{Population multiplication rate}(\lambda) = (N_{t+2}/ N_t) \tag{3}$$

and its natural log is

$$r = \log_e(N_{t+2}/N_t) \tag{4}$$

Table 6 shows the value of population growth rate (λ) and its natural log (r) computed from data of the annual number of nests t.

Using the available date over the period of 2001 to 2016, I aim to reconstruct the relationship between fitness and temperature throughout the year using monthly average temperature by building a statistical model which combines the long-term population data and the long-term temperature data.

Table 6: Population growth rate (λ) and its natural log (r) computed from data of the annual number of nests

Year	N_t	N_{t+2}	R	λ
2001	200	169	-0.168	0.845
2003	169	217	0.249	1.284023669
2005	217	173	-0.226	0.797235023
2007	173	177	0.022	1.023121387
2009	177	242	0.312	1.367231638
2011	242	169	-0.359	0.698347107
2013	169	204	0.188	1.207100592
2002	160	155	-0.031	0.96875
2004	155	152	-0.019	0.980645161
2006	152	166	0.088	1.092105263
2008	166	230	0.326	1.385542169
2010	230	171	-0.296	0.743478261
2012	171	210	0.205	1.228070175
2014	210	229	0.086	1.09047619

Conceptually the population growth rate through the two years' period is made up of a series of population growth rates through each individual month. For each individual month I have modeled the monthly population growth rate as a quadratic function of the average monthly temperature. From there, the population growth rate through the two years' period is the sum of these individual population growth rates.

$$\text{Population growth rate } (r) = \Sigma \text{ (24 monthly intercepts)} + \beta * \Sigma \text{ (24 monthly average temperatures)} + \gamma * \Sigma \text{ (24 monthly average temperature)}^2 \qquad (5)$$

The sum of the 24 monthly average temperatures and the sum of the 24 monthly average temperatures squared are both large unwieldy numbers, and model which is formulated to capture the relationship between the population growth rate (r) and average temperature is more biologically meaningful than a model formulated to capture the relationship between population growth rate (r) and the sum of monthly temperature. in practice, therefore, the model was scaled using the average temperature and the mean square temperature.

$$\textit{Population growth rate } (r) = a + b * (\textit{monthly average temperatures}) + c * (\textit{mean square temperature}) \quad (6)$$

Note that in fitting the model, separate intercepts for each individual month do not need to be estimated seperatly; the sum of the monthly intercepts can be considered a constant and can be denoted as “a”.

Before carrying out the analysis I had no prior understanding regarding the timescale over which temperature has its effect on this study species. Although average monthly temperatures are quite standard, sensitive species may be affected by fluctuation in temperature from one day to the next rather than the cumulative effect of temperature over each month, and less sensitive species may be effected by the cumulative effect of fluctuation in temperature over longer seasonal time scale (Chatting, et al., 2008; Hofmann and Somero, 1995; Portner and Knust, 2007).

Because I did not know the scale at which temperature would have an impact, I therefore checked whether the model was improved by reconstructing the relationship on a daily time scale and on a seasonal time scale (three months and six months), as shown in Tables 3-5, but these did not improve the model.

It is unknown how temperature affects population growth rate, however, it is possible that various diverse components play a role which impacts the species whether directly or indirectly with immediate or delayed effects. With this analysis these individual components were not separated but rather modeled their combined action as they work together in one overall composite effect. Population growth rates are determined by the balance between birth rates and death rates (Lande, 2007; Fisher, 1930; Crow, 2002), so any effect of temperature on either birth or death will affect population growth. The action of temperature is not limited to direct immediate effects of temperature on reproductive performance during the breeding season, so the model built for this study also include any effects of temperature on death rates at any time of year, and any indirect effects which temperatures might have on reproductive performance throughout the year (Pickett et al., 2015).

Pickett et al. (2015) showed that when building the relationship between population growth rate and temperature, the effects of temperature on population growth rate are mathematically distinguishable from the effects of temperature on detection probability (p) – the percentage of the population which is detected and counted in a particular year. In a given year, the observed population size (O_t) is not the true population size (N_t) but rather the true population size (N_t) multiplied by the percentage of population that is detected (p_t):

$$O_t = N_t * p_t \tag{7}$$

Building on that equation, the apparent population multiplication rate based on annual nest count ($\frac{O_{t+2}}{O_t}$) is not necessarly the true population growth rate but rather ($\frac{N_{t+2} * p_{t+2}}{N_t * p_t}$). This means that the ratio of consecutive population count is equals to true multiplation rate multiplied by the ratio of consecutive detection prbailities:

$$\frac{O_{t+2}}{O_t} = \frac{N_{t+2} * p_{t+2}}{N_t * p_t} = \lambda * \frac{p_{t+2}}{p_t} \tag{8}$$

If detection probability is constant and does not vary with temperature, then detection probabilities do not bias our estimate of the relationship between multiplication growth rate and temperature. If, however, detection probabilities are a function of temperature, then they could distort the estimated relationship if not controlled for. We can consider the case where the detection probability is an exponential function of temperature:

$$p_t = K_0 e^{dT_t} \tag{9}$$

This function can be inserted into the model:

$$\frac{O_{t+2}}{O_t} = \lambda * \frac{p_{t+2}}{p_t} = e^{a+b\Sigma T+c\Sigma T^2} * \frac{K_0 e^{dT_{t+2}}}{K_0 e^{dT_t}} = e^{a+b*\sum T+c*\sum T^2} \times e^{d(T_{t+2}-T_t)}$$
$$= e^{a+b*\sum T+c*\sum T^2+d(T_{t+2}-T_t)} \tag{10}$$

Equation (6) can therefore be rearranged as follows:

$$r = a + b^{*}(temperature) + c^{*}(mean\ square\ temperature) + d^{*}\,\Delta_T \tag{11}$$

Where $\Delta_T = (T_{t+2} - T_t)$

In Pickett et al. (2015) analysis these detection probabilities were considered nuisance parameters. However, in the case of hawksbill turtle, the proportion of the population which is detected and counted each year is determined by the proportion of the population which is breeding and this parameter therefore has considerable biological meaning which allows us to reconstruct the relationship between temperature and breeding probability. Hence, in the case of hawksbill turtle we can reconstruct not just the relationship between fitness and temperature but also breeding probability and temperature. These are two different phenomena but they are estimated using the same model in a single analysis.

In order to implement this statistically, the mathematics can be rearranged, and rather than having the population growth rate ($Ln(N_{t+2}/N_t)$) as a dependent variable, it can be separated such that the dependent variable becomes ($Ln(N_{t+2}$), the natural log of population count in year$_{t+2}$.

$$Ln(N_{t+2}) = Ln(N_t) + a + b*(temperature) + c*(mean\ square\ temperature) + d*\Delta_T \tag{12}$$

Count data typically follow a statistical distribution from the poisson family. $Ln(N_{t+2})$ has a statistical distribution which is more standard and, therefore, more easily modled than ($Ln(N_{t+2}/N_t$).

This was then implemented by using a Generalized Linear Model (GLM) with a log link function, in which the natural log of the number of nests in years (t+2) was a dependent variable. The natural log of the number of nests in year t was fitted as an offset; an offset is a term added to a linear predictor with a known coefficient 1 rather than an estimated coefficient (R Core Team, 2019).

The model estimates a relationship which includes the linear component and the quadratic component, as well as the change in temperature. In formulating the difference in temperature between years N_t and N_{t+2} the temperature was calculated as the average daily and monthly temperature over the 24 months period between years N_t and N_{t+2}, as well as the average temperature over the nine months' periods leading to the nesting season. Before testing the model, there was no prior insight into the time scale over which temperature could have an effect on the turtles.

Therefore, I also tested whether the model will be improved by using mean maximum and mean maximum monthly temperatures. As well as a shorter period of three and six months prior to breeding. However, as indicated in the results chapter, these parameters did not improve the model.

The general model formula was fitted using R software as the following:

$$glm\ (N_{t+2} \sim Linear\ component + Quadratic\ component + Change\ in\ temperature + offset(log(N_t)) \qquad (13)$$

Note: The model utilizes the family function of Poisson regression

Note that this analysis is not simply looking for correlation between two trends. Over the study period, the reconstructed relationship between demographic parameters and temperature is modelled using shorter fluctuations which has limited confusion with many other gradual long-term trends in for example population size, breeding probability and habitat quality. Furthermore, short-term fluctuations in temperature drive parallel fluctuations in factors (Rasconi et al., 2017) like food availability, infection risk, or other aspects of habitat quality, to correlate fitness but they are part of the impact of temperature and they are included and not separate out.

Chapter 3: Results

As outlined, the analysis allowed me to reconstruct two separate relationships in a single model. One is the relationship between fitness and temperature and the other is the relationship between breeding probability and temperature. Fitness and breeding probability were tested using the model against average, maximum, minimum temperature for the period of data.

3.1 The Relationship Between Fitness and Temperature

The model tested the relationship between population growth rate and average daily temperature. The analysis didn't detect any significant relationship between fitness and temperature, as outline in Table 7.

Table 7: The parameters of the quadratic relationship between population growth rate and average daily temperature

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-82.8698	407.1308	-0.204	0.843
Linear component	6.0983	28.8994	0.211	0.838
Quadratic component	-0.1120	0.5128	-0.218	0.832

As indicated in the methodology chapter, I had no prior insight on the scale at which temperature affects fitness, so an analysis was carried out to test the relationship between population growth rate and annual average temperature. However, The analysis didn't detect any significant relationship (Table 8).

Table 8: The parameters of the quadratic relationship between population growth rate and annual average temperature

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-79.5572	642.3081	-0.124	0.904
Linear component	5.8779	45.5910	0.129	0.900
Quadratic component	-0.1083	0.8089	-0.134	0.896

Furthermore, I have also tested whether the model will be imporved by analyzing the relationship between population growth rate and the minimum monthly temperature and the maximum monthly temperature. The analysis didn’t detect any significant relationship between population growth rate and temperature, as outline in Tables 9 and 10.

Table 9: The parameters of the quadratic relationship between population growth rate and minimum annual temperature

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-48.26945	346.55737	-0.139	0.892
Linear component	4.17585	27.81239	0.150	0.884
Quadratic component	-0.08978	0.55797	-0.161	0.876

Table 10: The parameters of the quadratic relationship between population growth rate and maximum annual temperature

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-77.97060	374.33639	-0.208	0.840
Linear component	4.96558	23.34568	0.213	0.836
Quadratic component	-0.07899	0.36394	-0.217	0.833

3.2 The Relationship Between Breeding Probability and Temperature

The model have also tested the relationship between breeding probability and average monthly temperature. The relationship was tested with the avarage temperature over the nine months prior to breeding. The model detected a significant relationship between breeding probability and the average temperature over the nine months' periods leading to the nesting season (Table 11).

Table 11: The parameters of the relationship between breeding probability and temperature over the nine months' periods leading to the nesting season

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-417.7933	525.3216	-0.795	0.4469
ΔT	0.2791	0.1108	2.518	0.0329 *

As indicated earlier, I had no prior insight on the scale at which temperature affects breeding probability, therefore, I have also tested the relationship between breeding probability and the average temperature over the three and six months prior to breeding (Tables 12, 13), as well as the relationship between breeding probability and the mean maximum and mean minimum monthly temperature over the nibe months leading to nesting season (Tables 14, 15). However, these results did not further enhance the model.

Table 12: The parameters of the relationship between breeding probability and average temperature over the six months' periods leading to the nesting season

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-698.1731	580.9751	-1.202	0.2601
ΔT	0.2572	0.1084	2.372	0.0418 *

Table 13: The parameters of the relationship between breeding probability and average temperature over the three months' periods leading to the nesting season

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-307.90074	742.07827	-0.415	0.688
ΔT	0.05995	0.07911	0.758	0.468

Table 14: The parameters of the relationship between breeding probability and mean minimum temperature over the nine months' periods leading to the nesting season

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	27.58758	323.39746	0.085	0.934
ΔT	0.11082	0.14134	0.784	0.453

Table 15: The parameters of the relationship between breeding probability and mean maximum temperature over the nine months' periods leading to the nesting season

Parameters				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	-34.24520	367.07409	-0.093	0.928
ΔT	-0.08774	0.11017	-0.796	0.446

Thus, the model found no evidence that the temperature experienced by the turtles during the intervening period is affecting their population growth rate, but Table 11 indicates that there is a direct positive relationship between temperature in the nine months prior to breeding and the probability of female turtle to nest. While it might not seem intuitive, the relationship between breeding probability and temperature is reconstructed in this model using the relationship between the ratio of the consecutive population counts and the difference in temperature between the two consecutive counts. This can be visualized in Figure 2, the visible positive linear relationship between the ratio of counts in the Y axis and difference of temperature in the X axis means that the underlying relationship between the breeding probability and temperature is positive. These findings suggests that hawksbill turtles in Abu Dhabi waters are not yet living above their optimum temperature.

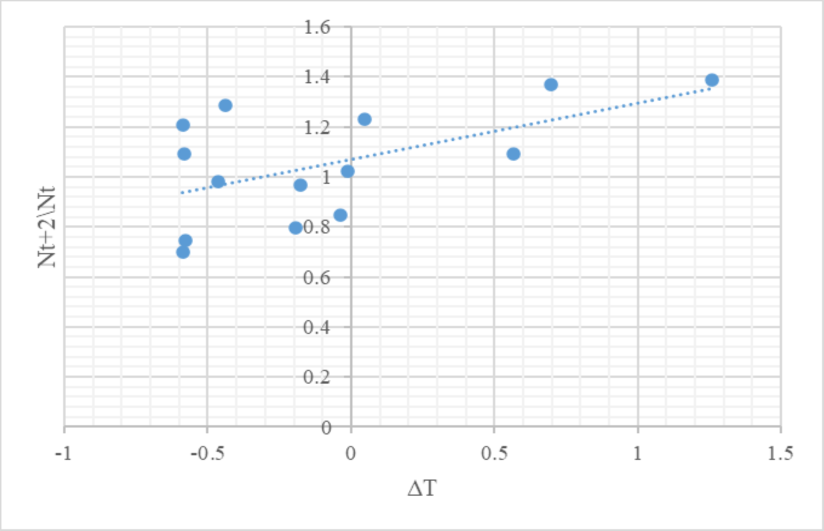

Figure 2: The relationship between the ratio of the population count and change in temperature

Chapter 4: Discussion

This study has been carried out to understand the impact of climate change on the biodiversity of hot regions. In order to do so, I have selected hawksbill turtle as a study species. It is well known that the biology of sea turtles is closely tied to the thermal conditions of their environment (Steban et al., 2018; Hawkes et al., 2007). Turtles further rely on the same thermal conditions to define the sex and gender of their hatched young ones. Eggs laid on hot sea sand beaches could have a reduces hatching rate and further worsen the turtle population. Additionally, a mere 2°C rise in the terrestrial and sea surface temperature will lead to near 100% all-female hatching rate that will greatly affect the sex ratio of the already endangered turtles (Butt et al., 2016). Female sea turtle comes to land to nest where temperature plays an important role in the biology of the nesting process, equally important is the water temperature which is relatively stable and varies based on depth and geographic location (Lutz et al., 1997; Hays et al., 2017; Jensen et al., 2018). Since the Hawksbill Turtle barely lays over 300 eggs in a full season, the probability of a quarter of the eggs hatching and fingerlings surviving is minimal amid the climate change effects. The high-water levels could distract the endangered turtles from laying their eggs in the coral reefs habitat, consequently reducing their laying cycle from their highest 8 to a bare 2 times per season (Butt et al., 2016). In addition, risen sea water poses a risk to nesting beaches, as they could flood at the slightest waves or disruption of the surface pressure by huge water vessels (Abella Perez et al., 2016).

Furthermore, Many of the turtle in the Arabian Gulf region suffer from cold-stunning winter conditions (Robinson et. al. 2017). This study has found that there is no evidence that turtle's populations growth rate is affected by the fluctuation in temperatures. However, it concluded that the average temperature affects the probability of turtle individual to breed and consequently nest on the beach. Although temperatures in Abu Dhabi is expected to continue to increase as part of the global climate change (Coles and Riegl, 2013; Lokier and Fiorini, 2016; Riegl, 2002), I found no evidence that turtles' population would been negatively affected.

The relationship between the temperature and the probability for a female turtle to lay its eggs is positive. In another word, the continued increase in temperature in the UAE has not yet negatively impacted the chances for a female turtle to nest in Abu Dhabi.

So far in this analysis, I have not been able to detect any effect of temperature on population growth rate. One of the possible reasons for this could be that these turtles are long lived and do not breed until the average age of thirty years old (Mortimer and Donnelly, 2008). It is possible that if the population monitoring continues over a long period, it will become possible to detect a relationship between population growth rate and temperature. It is possible that there is an effect but it has not been picked up yet with a dataset of this length. The long term monitoring programs of hawksbill turtle populations allow us to better understand the long-term impact of climate change on hawksbill's fitness. Moreover, it is believed that the nature of the monitoring programs compromise the ability to determine reproduction potential in the region. This data is essential for the program managers to apply effective conservation strategies and track the turtles (Abu Dhabi Global Environmental Data Initiative, 2016). Overall, further monitoring and enhanced data collection on species in hot regions might contribute to enhance the outcome of similar studies in the region, and contribute to our understanding of the impact of climate change on species in hot regions in relations to their vulnerability.

As outlined earlier, the study has been carried out keeping in mind that not only temperature have an impact but there are other factors which change too in the environment. By using analytical methods from mathematical demography and statistics it was possible to separate these. Although long-term climate trends are an issue of key interest, it accounts for just a small bit of the total variance in temperature, and the relationship between demographic parameters and temperature was constructed based on short-term fluctuations. it need not be reconstructed on the basis of coincident long-term trends. That was possible by focusing on fluctuations over a short time scale.

That is said, if there are underlying trends in the environment, these could have negative impacts on the turtles and these would not necessarily be picked up using the analytical methods used here. One of climate change possible impacts in hot regions is its impacts on marine environment through disrupting weather patterns and coastal vegetations which limits the habitats that supports turtles (Limpus and Musick, 2017). A recent study carried by Abu Dhabi Global Environmental Data Initiative (AGEDI) to study marine biodiversity vulnerability to climate change showed that on the long-term hawksbill turtle population in the Arabian gulf will be impacted negatively by the loss of habitat suitability (Abu Dhabi Global Environmental Data Initiative, 2017). In particular, they highlighted issues of gradual long time changes in salinity and water quality which could be driven by climate change. The fact that these are not picked up in analysis based on short term fluctuations does not mean it is not important. It seems that hawksbill turtles in the

UAE will be impacted by climate change as a result of impacting their population fitness through the loss of habitat due to the impact of increased temperature on the marine environment.

Therefore, the emerging concept that the biggest ecological impacts of climate change might be in the hottest regions of the world, and that the species in hot regions are more vulnerable to climate change is not supported by this study. In fact, this study has shown that species in hot regions are not necessarily more vulnerable. There was no evidence that the fitness is influenced by temperature, however the breeding probability analysis indicated that the species is living below its optimum temperature. In this case, as temperature continue to rise in hot regions, the species of hawksbill turtles will not be impacted significantly in a negative way.

Chapter 5: Conclusion

The aim of this study was to better understand the impact of climate change in hot region and to study the vulnerability of species in hot region to warming temperature. Using statistical methods and long term monitoring data for the study species, I was able to test the hypothesis which is species in hot regions are more vulnerable to climate change. The research has been carried out in an attempt to understand the impact of climate change on species in the UAE, using hawksbill turtles as a study species. The study concluded that there is no evidence that the warming temperature have negatively impacted hawksbill turtles' population fitness. Furthermore, I found that temperature actually have a positive effect on the breeding probability of turtles which indicates that the species is living below its optimum temperature, which shows that while species in hot regions are impacted by climate change, the impact is not negative its actually positive.

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Appendix

R Code

```
> #Set working directory

> setwd ("C:/Users/al muwahib/Documents/Masters") #Ensure correct directory

> #attach data

> HBT <- read.csv("TurtleData2.csv", header=T)

> modelQDCP <- glm(Nnx ~ AvgTemp + AvgTempSQ + Delta9m + offset(log(NestNo)),
data=HBT, family=quasipoisson(link=log))

> summary(modelQDCP)
```

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Temperature changes in hot regions are smaller, but it may be that the species in those regions have reached their optimum temperatures. In which case the effects of even a small temperature increases could be steeply negative. To test this thoroughly in term of demographic parameters, this thesis quantifies demographic parameters for the Hawksbill Turtle (*Eretmochelys imbricata*) and reconstruct their relationship with temperature.

Obaid Alshamsi received his Master of Science in Environmental Sciences from the Department of Biology, College of Science and his Bachelor of Science in Biology from the College of Science, United Arab Emirates University.

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