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Vulnerability of sea turtles to climate change: A case study with the northern Great Barrier Reef green turtle population

PhD thesis submitted by
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(BSc Hons)
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"The process of learning is often more important than what is being learned"

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Statement of contribution of others

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"The smallest act of kindness is worth more than the grandest intention"

Publications associated with this thesis

Peer-Reviewed Publications

Fuentes MMPB, Dawson J, Smithers S, Limpus CJ, and Hamann M (in press) Sedimentological characteristics of key sea turtle rookeries: potential implications under projected climate change. Journal of Marine and Freshwater Research. (Chapter 2)

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Fuentes MMPB, Maynard JA, Guinea M, Bell IP, Werdell PJ, and Hamann M (2009) Proxy indicators of sand temperature help project impacts of global warming on sea turtles. Endangered Species Research Journal 9, 33-40 (Chapter 3)

Fuentes MMPB, Limpus CJ, Hamann M, and Dawson J (in press) Potential impacts of projected sea level rise to sea turtle rookeries. Aquatic Conservation: Marine and Freshwater Ecosystems. DOI:10.1002/aqc.1088 (Chapter 4)

Fuentes MMPB, Limpus CJ, and Hamann M (in review) Vulnerability of sea turtle nesting grounds to climate change. Global Change Biology. DOI: 10.1111/j.1365-2486.2010.02192.x (Chapter 7)

Fuentes MMPB and Hamann M (2009) A rebuttal to the claim natural beaches confer fitness benefits to nesting marine turtles. Biology letters, 5, 266-267 (not contained in the thesis)

Manuscripts in review

Fuentes MMPB, and Abbs D (in review) Sea turtles, cyclones and climate change: assessing the affects of projected changes in cyclonic frequency on sea turtles. Journal of Marine Ecology Progress Series (Chapter 5)

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Books and book chapters

Fuentes MMPB (2010) Myrtle's battle against global warming. Published by the Reef & Rainforest Research Centre Limited.

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Reports and popular literature

Hamann M, Sutherland L, Loban F, Kennett R, **Fuentes MMPB** and Limpus CJ (2008) Hot water for marine reptiles: research into sea turtles and climate change. Wildlife Australia 45(4) p12-19.

Fuentes MMPB (2007) Some like it hot. Australasian Science. Nov-Dec. p 34-36.

Fuentes MMPB, Dawson J, Smithers S, and Hamann M (2007) Surficial carbonate facies across key rookeries for the northern Great Barrier Reef green turtle population stock. Technical report for the Environment Protection Agency.

Conference presentations

Fuentes MMPB, Limpus CJ, Hamann M, and Dawson J (2009) Community assistance in determining the potential effects of projected sea level rise on marine turtles. Australian National Network in Marine Science Inaugural Conference: Marine Science in Tropical, Temperate and Southern Oceans (2009) Hobart, Australia

Fuentes MMPB (2009) Sea turtles, climate change and future challenges for management. The 10th International Congress of Ecology: Ecology in a Changing Climate (2009) Brisbane, Australia

Fuentes MMPB, Limpus CJ, and Hamann H (2009) How will the largest green turtle population in the world be affected by climate change? Marine and Tropical Sciences Research facility Annual Conference (2009) Townsville, Australia

Fuentes MMPB, Limpus CJ, Hamann H, and Moloney JM (2009) Assessing the vulnerability of sea turtle populations to predicted geographic shifts in cyclone patterns. 29th Symposium on Sea Turtle Biology and Conservation (2009) Brisbane, Australia

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Fuentes MMPB, Limpus CJ, Hamann M, and Dawson J (2009) Community assistance in determining the potential effects of projected sea level rise on marine turtles. 29th Symposium on Sea Turtle Biology and Conservation (2009) Brisbane, Australia

Fuentes MMPB, Dawson J, Smithers S, and Hamann M (2008) Traits of surficial carbonate sediments at reef Islands: implications of climate change to island fauna. 11th International Coral Reef Symposium (2008) Florida, USA

Fuentes MMPB, and Dawson J (2007) Identifying superficial carbonate facies at key sea turtle rookeries to investigate the potential effects of climate change on turtle populations of the northern Great Barrier Reef. Greenhouse 2007: the latest science & technology (2007), Sydney, Australia

Other publications generated during my candidature

The following publications were also published during my candidature:

Peer-Reviewed Publications

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Fuentes MMPB, Lawler IR, and Gyuris E (2006) Dietary preferences of juvenile green turtles (*Chelonia mydas*) on a tropical reef flat at Green Island, Queensland, Australia. Wildlife Research 32, 671-678

Book Chapter

Cinner JE, and **Fuentes MMPB** (2008) Human Dimensions of Madagascar's Marine Protected Areas. In: Ten years after bleaching consequences and issues facing countries in the Indian Ocean (Eds. Obura D, Tamelander J, and Linden O) pp. 397-404. CORDIO/Sida-SAREC, Mombasa.

Reports and popular literature

Fuentes MMPB (2009) Hawksbill turtles at Masig Island II. Technical report for the Torres Strait Regional Authority and Kailag Enterprises.

Fuentes MMPB (2009) Hawksbill turtles at Masig Island. Technical report for Torres Strait Regional Authority and Kailag Enterprises.

Cinner JE, and **Fuentes MMPB** (2006) A Baseline Socioeconomic Assessment of Fishing Communities in Northern Madagascar. Report to the Wildlife Conservation Society Madagascar Marine Program.

Abstract

Sea turtles are vulnerable to aspects of climate change because they have life history, physiological attributes and behaviour that make them extremely sensitive to environmental changes. Arguably, the more detectable impacts of climate change to sea turtles will occur during their terrestrial reproductive phase (egg laying, egg incubation and hatchling success phase) since there are clear, and relatively straightforward, effects of increased temperature, sea level rise and cyclonic activity on sea turtle nesting sites and reproductive output.

Indeed, there has been a recent increase in research activity focusing on the potential impacts and implications of climate change to sea turtles' terrestrial reproductive phase. While first identified as an issue in the mid 1980s recent studies have begun to investigate and predict how specific climatic processes will affect sea turtle's nesting habitats and reproductive output. However, the studies conducted to date are limited temporally, because (1) they predict how a single climatic process will affect sea turtles, yet processes are likely to occur simultaneously and cause cumulative effects, and (2) they typically focus only on one nesting ground used by a particular turtle population and this approach does not provide a full understanding of how a population (management unit) will be affected. Consequently, there is a need for a structured approach to investigate how multiple climatic processes may affect the full range of nesting grounds used by a turtle population.

In my thesis I address the issue of cumulative impact by using a systematic and comprehensive methodology to assess how multiple climatic processes will affect the northern Great Barrier Reef (nGBR) green turtle population under a conservative and an extreme scenario of climate change for both 2030 and 2070. First, I identified how key processes: (1) change in sediment traits, (2) increased temperature, (3) sea level rise, and (4) cyclonic activity will affect the nesting grounds (n= 7) that represent the nesting habitat for 99% of the nGBR green turtle population. After I determined how each process will potentially affect the selected nesting grounds, I used expert opinion to gather information on the relative impact of each process on sea turtle nesting grounds. This information was then incorporated into a climate change vulnerability assessment framework.

To explore how changes in sediment will impact the nGBR green turtle population I conducted two steps. First, I described the sediment types and identified the reef-building organisms of each nesting ground. I then reviewed the literature on the vulnerability of each identified reef-building organism to climate change and how various sediment characteristics ecologically affect sea turtles. I found that the sediment from each of the studied nesting grounds is predominantly composed of well sorted, medium-grained to coarse-grained, sands and are dominated by Foraminifera, molluscs

or both. Dissimilarities in the contemporary sedimentology between the nesting grounds suggest that each will respond differently to environmental impacts such as increased temperature, sea level rise and ocean acidification. The implications of changes to island sedimentology on sea turtle ecology include changes in nesting and hatchling emergence success, and reduced optimal nesting habitat. Both of these factors can influence sea turtles' annual reproductive output and thus have significant conservation ramifications.

The second key process I examined was potential changes to incubation temperatures. For this, I first conducted a systematic process to select the best predictive model of sand temperature. Using Akaike Information Criterion I determined that a model incorporating both sea surface and air temperature as proxy indicators of sand temperature is the best model to predict future sand temperature for the study region. I then used sand temperature (at clutch depth), the developed models and air and sea surface temperature projected by the International Panel of Climate Change (IPCC) and the Australian Commonwealth Scientific and Research Organisation (CSIRO) to predict sand temperature for the selected nesting grounds. My models predicted a feminization of annual hatchling output into the nGBR green turtle population by 2030. Predictions are bleaker for 2070, when some of the nesting rounds (Bramble Cay and northern Dowar and Milman Island) used by this population are predicted to experience temperatures near or above the upper thermal incubating threshold (e.g. 33 ˚C) and likely cause a decrease of hatching success. Importantly, I identified that some nesting grounds (e.g. Raine Island, western Milman Island and Sandbank 7) will still produce male hatchlings, even under the most extreme scenario of climate change. This is crucial for future management as managers may choose to protect important male-producing regions to balance future population viability.

Further impacts to the nGBR green turtle population will potentially occur from sea level rise. To investigate how SLR will impact the different nesting grounds I first conducted beach profiles at each of the selected nesting ground and used the profile information to create a digital elevation model for each of them. Second, I used geographic information system (GIS) to map and quantify areas that will be inundated under various SLR scenarios. Using the predicted sea level rise values from the IPCC and CSIRO, my results indicated that up to 34% of available nesting area across all the selected nesting grounds may be inundated as a result of predicted levels of SLR. My data indicated that low sandbanks will be the most vulnerable to SLR and nesting grounds that are morphologically more stable, such as Dowar and Raine Islands, will be less vulnerable.

More positively, my study indicates that as climate change progresses it is likely that impacts from cyclones to the nGBR green turtle population will be very low. I used eleven of the latest regional climate models to investigate how cyclonic frequency will alter in a warming climate. Most models predicted a tendency for a reduction in cyclonic frequency in the future. Thus a reduction in the impacts that the nGBR green turtle population will experience from cyclones is likely.

The second part of my thesis involved incorporating the predicted impacts from the climatic processes to each nesting ground into a vulnerability assessment framework for climate change. The framework used is based on the IPCC framework for climate change and is described as a function of sensitivity, exposure and adaptive capacity. The framework allowed me to: (1) assess how multiple climatic processes will affect the terrestrial reproductive phase of sea turtles; and (2) investigate how mitigating different climatic factors individually or simultaneously can influence the vulnerability of the nesting grounds. Thus I was also able to provide informed suggestions of management options to mitigate the potential impacts of climate change to the nGBR green turtle population.

The vulnerability assessment indicated that in the short term (by 2030), sea level rise will cause the most impact on the nesting grounds used by the nGBR green turtle population. However, in the longer term, by 2070 sand temperatures will reach levels above the upper transient range and the upper thermal threshold and cause relatively more impact on the nGBR green turtle population. Thus, in the long term, a reduction of impacts from sea level rise may not be sufficient, as nesting grounds will start to experience high vulnerability values from increased temperature. Therefore, a stronger focus on mitigating the threats from increased temperature will be necessary for long term management.

Some of the potential options to mitigate the impacts of increased temperature include changing the thermal gradient at beaches, nest relocation, and artificial incubation. The best management options will be site specific and dependent on a series of factors, including feasibility, risk (interaction and impact on other species and ecosystems), cost, constraints to implementation (both cultural and social), and probability of success in relation to selected sites. Thus, a “toolbox” with various strategies will be needed to address the impacts of increased temperature across the nesting sites used by the nGBR green turtle population.

The main strengths of the framework used here is that it can easily be adapted when information is obtained, and it can be transferable to different sea turtle populations and sea turtle life cycle phases provided the necessary data exist. This framework provides key information for managers to direct and focus management and conservation actions to protect turtle populations in the face of climate change. Indeed results from my thesis have been used by the Australian Government in their development of the outlook report for species and ecosystems of the Great Barrier Reef.

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Chapter 1.

General Introduction [1,2]

[1] **Fuentes MMPB**, Hamann M, and Lukoschek V (2009) Marine reptiles and climate change. In: A marine climate change impacts and adaptation report card for Australia 2009 (Eds. Poloczanska ES, Hobday AJ, and Richardson AJ) NCCARF Publication 05/09, ISBN 978-192160903-9.

[2] **Fuentes MMPB** (2007) Some like it hot. Australasian Science. Nov-Dec. p 34-36

1.1. A changing climate

According to the latest meteorological data (IPCC 2007), global average air temperature has increased 0.8 °C over the past 100 years (Root et al. 2003; Hansen et al. 2006) and global average precipitation increased by 2% (Hughes 2000; IPCC 2007). Even though the earth has experienced considerable climate change over the past tens of thousands of years, the rate and magnitude of the recent and projected future changes are unprecedented (IPCC 2000). Eleven of the last fifteen years (1995-2009) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850). Predictions are for a rise of between 2 and 4.5 °C over the next century (IPCC 2007). Predicted increases in global temperature will increase sea level by approximately 1-2 mm a year and sea surface temperature by approximately 1-3 °C by 2100 (Pittock 2005; Lough 2007; IPCC 2007). Extreme weather events (e.g. colder winters and warmer summers, cyclonic activity) are likely to occur with greater variability and could combine with other physical climate factors to drive changes in ocean chemistry, such as pH decreases of 0.3 to 0.5 (IPCC 2007).

1.2. Climate change as a threat to biodiversity

Climate change will pose a major threat to the survival of many species and the integrity of broader ecosystems (McCarthy 2001; Thomas et al. 2004; Lee and Jetz 2008). There is already both empirical and anecdotal evidence that biodiversity has been affected by climatic changes, with predictions of further and more severe impacts as climate change progresses (Mclaughlin et al. 2002; Walther et al. 2002). Some of the ecological impacts in response to climate change include, among others, changes in: species distribution, abundance, and morphology, the timing of reproduction or migration events, behaviour, and increases in the frequency of pest and disease outbreaks (Grabherr et al. 1994; Parmesan 1999; Crick and Sparks 1999; McCarhty 2001; Thomas et al. 2001; Brommer 2004; Lehikoinen et al. 2004)

A species' susceptibility to climate change will depend on a variety of biological traits, including its life history, behaviour, physiology and genetic make-up (Foden et al. 2008, IUCN). According to the IUCN assessment of species susceptibility to climate change (2008) and current research, the animals expected to be most affected by climate change are those that have the following traits:

- Dependence on specific environmental triggers or cues that are likely to be disrupted by climate change;

- Particular physiological or phenological traits that make them heavily reliant on environmental temperature;
- Limited climatic range and restricted and/or specialised habitat requirements, where susceptibility is exacerbated where species has several life stages, each with different habitat requirements;
- Habitat that is particularly vulnerable to climate change (e.g. polar habitats, low sand cays); and/or
- Narrow environmental tolerances and/or thresholds that are likely to be exceeded due to climate change.

The susceptibility of an individual species will be even greater if they are species of conservation concern and especially if their populations have endured drastic declines in the past (Foden et al. 2008).

1.2.1. Sea turtles and climate change

Sea turtles are an ancient faunal group and have existed for hundreds of millions of years. During this period, sea turtles have persisted and adapted to dramatic changes in climate, including warming and cooling temperatures and sea level rise, demonstrating a biological capacity to adapt to climate change (Hamann et al. 2007; Hawkes et al. 2009; Poloczanska et al. 2009). For example, past nesting grounds for flatback turtles, *Natator depressus*, near the edge of the continental shelf are now flooded and no longer exist, and current nesting grounds were inaccessible to sea turtles 12 000 years ago (Limpus 2008 a). This demonstrates that flatback turtles adapted to past climatic changes by redistributing their nesting sites and developing new migratory routes (Hamann et al. 2007; Limpus 2008 a). Similarly, other important nesting grounds for sea turtles, such as Raine Island, did not exist 10,000 years ago and only developed into suitable turtle nesting habitat in the last few thousand years (Limpus 1987, 2008).

However, extant species of sea turtles are now faced with a variety of constraints which may impede their capacity to adapt to current and future climate change. Constraints include: accelerated rates of climate change, declining and depleted populations, as well as cumulative impacts of anthropogenic threats and restriction of alternative habitats (see Johannes and Macfarlane 1991; Harris et al. 2000; Lutcavage 2003; Moore et al. 2009). Indeed, in 2006 the IUCN Marine Turtle Specialist group nominated climate change as one of the top ten global threats to sea turtles. A more contemporary question, therefore, would examine whether sea turtles will be able to adapt to an elevated rate of climate change while being simultaneously impacted by an array of anthropogenic activities.

Sea turtles have life history (e.g. slow growth rate, late maturing), physiology (e.g. temperature-dependent sex determination) and behavioural traits (e.g. natal homing, nest in coastal areas that are prone to sea level rise and cyclonic activities) that make them particularly sensitive to climatic changes (Mrosovsky 1994; Spotila and Standora 1985; Davenport 1989, 1997; Janzen 1994; Hawkes et al. 2009). Sea turtle species may therefore be affected by different and multiple climatic processes (e.g. increased temperature, sea level rise, cyclonic activity) at different temporal and geographical scales (Hawkes et al. 2009).

Increases in air and sea surface temperature are likely to cause the most noticeable impact to sea turtles (Witt et al. in press) as they are ectotherms, and as such maintenance of body functions such as digestion, reproduction and metabolism rely on environmental temperatures (Spotila and Standora 1985). Sea turtle thermal requirements and tolerances are believed to restrict their distribution (Davenport 1997; Sato et al. 1998; Milton and Lutz 2003; Hawkes et al. 2007 a). For example, distribution in the family Cheloniidae appears to be constrained by the 20 ˚C surface isotherm (Davenport 1997), while leatherback turtles (Dermochelyidae) are often found in the cooler waters of the Southern Ocean, northern Pacific Ocean and northern Atlantic Ocean. Thermal limits are not known for leatherback turtles, but for cheloniids temperatures below 15 ˚C may impair locomotion and alter foraging behaviour (Read et al. 1996). Given these thermal requirements of sea turtles, it is likely that changes in sea surface temperatures could alter or expand their distribution. Indeed recent studies are indicating that warmer oceans will increase available habitat for sea turtles (McMahon and Hays 2006; Witt et al. in press). In fact, the distribution of leatherback turtles in the north-east Atlantic, which has extended north by around 200 km per decade over the past 20 years, is believed to arise from a poleward expansion of warmer waters (McMahon and Hays 2006).

Warmer temperatures may also affect sea turtle nesting patterns causing earlier onset of nesting and/or peak of nesting, a decrease in the inter-nesting interval, and changes in the length of nesting season (Sato et al. 1998; Webster and Cook 2001; Hays et al. 2002; Weishampel et al. 2004; Pike et al. 2006; Hawkes et al. 2007 b; Hamel et al. 2008). As the specific cues that underlie reproductive cycles are not well known, further research is necessary to explore the potential impacts of changes in temperature regime (Hamann et al. 2007; Hawkes et al. 2009).

Nevertheless, for green turtles in the Australasian region, the interval between breeding seasons is probably resource-dependent (Limpus and Nicholls 1988; Broderick et al. 2003) and the size of the annual nesting population is strongly linked with climate processes such as the El Niño Southern Oscillation (Limpus and Nicholls 1988). A higher proportion of the adult female green turtles breed eighteen months following a major El Niño event and a lower proportion of females breed a similar interval after a major La Niña event. This short-term variation in nesting numbers is believed to be regulated by food availability (quality and abundance), primarily seagrasses and macroalgae, which are, in turn, influenced by temperature. Thus increased sea surface temperatures may have a positive impact on green turtle populations through alterations to growth rates, age at maturity and reproductive periodicity (for examples see Chaloupka and Limpus 2001; Balazs and Chaloupka 2004; and Hamann et al. 2007). In contrast, for loggerhead turtles, warmer foraging grounds are associated with a decrease of ocean productivity and prey abundance and consequently a reduction in loggerhead breeding capacity (Chaloupka et al. 2008).

The reproductive output of sea turtles will be particularly affected by global warming as sand temperature during egg incubation influences the development rate and success of incubated eggs and affects the sex, phenotype and health of hatchlings (Yntema and Mrosovsky 1980; Spotila and Standora 1985; Ackerman 1997; Davenport 1997; Matsuzawa et al. 2002; Carthy et al. 2003). Thus, increase in temperature may affect hatchling phenotype, performance and success (Mrosovsky 1980).

Further impact on the reproductive output of sea turtles can occur through changes in the rainfall regime (Poloczanska et al. 2009). Rainfall can influence sea turtles' incubating environment by moistening sand and by increasing the occurrence of potentially lethal fungi (Phillott and Parmenter 2006). Nesting success can also benefit from rainfall, as moist sand makes it easier for females to dig nests (Seabrook 1989). Thus, decreases in precipitation – as predicted for northern Australia (CSIRO 2007) - may affect both nesting and hatching success of sea turtles. Indeed, drier than average years have caused lower rates of nesting success at important nesting grounds such as Raine Island (Limpus et al. 2003; Limpus et al. 2005) and may impact reproductive output (Hamann et al. 2002).

The reproductive output of sea turtles can be further impacted by sea level rise and cyclonic activity as these processes can cause loss and alteration of nesting beaches and egg mortality (Mazaris et al. 2009 a; Fish et al. 2005, 2008; Baker et al. 2006; Pike and Stiner 2007; Prusty et al. 2007; Van Houtan and Bass 2007). Additional impacts to nesting beaches will occur as a result of ocean acidification, as this will affect the carbonate sediment production and budget at each nesting ground (Folk and Robles 1964; Lidz and Hallock 2000; Mutti and Hallock 2003). This can potentially alter reef-island morphology and sediment characteristics and, in turn, affect sea turtles' reproductive output, as they require specific sediment characteristics to incubate their eggs and dig their nests (Mortimer 1990).

Once hatchlings emerge and enter the sea their dispersal occurs via offshore currents (Witherington 2002; Bolten 2003; Lohmann and Lohmann 2003; Hamann et al. 2007; Witt et al. 2007). Thus, any change to ocean circulation may influence post-hatchlings' migration and distribution (Boyle 2006; Hamann et al. 2007). Further impacts from climate change may occur indirectly as sea turtle food sources, habitat and predators are impacted (see Hamann et al. 2007 and Hawkes et al. 2009 for review).

From all the impacts that climate change may have on sea turtles, it is likely that the most detectable impacts will occur in their terrestrial reproductive phase (egg laying, egg incubation and hatchling success phase) since, as explained above, increased temperature, sea level rise and cyclonic activity can directly affect sea turtle nesting sites and reproductive output (McMahon and Hays 2006; Hamann et al. 2007; Hawkes et al. 2009). Consequently, there are a growing number of studies that have investigated and predicted how different climatic processes (e.g. sea level rise, increased temperature) will affect the terrestrial reproductive phase of sea turtles (for review see Hamann et al. 2007; Hawkes et al. 2009; Poloczanska et al. 2009). Although these studies provide valuable information and insights into how each climatic process can or will impact sea turtles, at ecological scales they are limited, as processes will occur simultaneously and potentially cause cumulative and synergistic effects. Further, the majority of these studies focus only on one nesting ground for a particular turtle population. Such approach does not provide a full understanding of how a genetic stock (genetic stocks are also referred to in the literature as genetically distinct populations or management units) will be affected. To provide adequate information for government(s) to manage a specific sea turtle population as climate change progresses and to prioritise their decisions as multiple climatic factors affect sea turtles' reproductive output, studies need to be undertaken at multiple nesting grounds that encompass a high percentage of nesting for a particular population, and should incorporate the impacts from multiple climate processes.

This thesis will therefore use a vulnerability framework to assess how multiple climatic factors will affect the terrestrial reproductive phase of the northern Great Barrier Reef (nGBR) green turtle population.

1.3. Spatial and temporal scale of the study

1.3.1. The northern Great Barrier Reef green turtle population as a case study

The northern Great Barrier Reef (nGBR) green turtle population is arguably the largest green turtle population in the world, with about 41,000 females breeding annually in a typical dense nesting season (Limpus et al. 2003; Limpus 2008 b). Nesting for this population occurs in the northern

Great Barrier Reef and Torres Strait region (Figure 1.1), with 90% of the overall nesting occurring at Raine Island and Moulter Cay (Limpus et al. 2003). Subsidiary nesting occurs at Bramble Cay and Dowar Island, which are the most important green turtle nesting grounds in Torres Strait (Limpus et al. 2003). Moderate nesting occurs at Sandbank 7 and 8, with 50-300 turtles nesting a year, and occasional (trivial, less than 50 nesting females a year) nesting for this population also occurs at Milman Island and approximately 60 other nesting grounds in northern Australia (Figure1.1). For the purpose of this study I selected seven nesting sites used by the nGBR green turtle population that encompass the latitudinal range of key nesting sites used by this population, and represents sites for which 99% of nesting for this population occurs (Figure 1.1). Selected study sites, in order of importance (in accordance to average number of nesting females a year), include: (1) Raine Island (11°36'S, 144°01'E), (2) Moulter Cay (11°26'S, 144°00'E), (3) Bramble Cay (9°09'S, 142°53'E), (4) Dowar Island (9°55'S, 144°02'E), (5) Sandbank 7 (13°26'S, 143°58'E), (6) Sandbank 8 (13°21'S, 143°57'E) and (7) Milman Island (11°10'S, 143°00'E) (Figure 1.1).

The nGBR green turtle population has been systematically monitored by Queensland Parks and Wildlife Service (QPWS) since 1975. Collected data indicates an increasing trend from the mid-1970s until the mid-1990s and, more recently, a decreasing rate of increase in population numbers (Chaloupka et al. 2008). Indeed, the demographic data collected since 1996 (e.g. a decline in the annual size of nesting turtles, low numbers of new recruits into the population, an increase in the interval between nesting years) indicates that this population is in the early stages of overall decline (Limpus et al. 2003). This may be a result of a decrease in adult numbers due to anthropogenic activities (e.g. harvesting) or low hatchling production at Raine Island (Limpus et al. 2003). Low hatchling production may result from low nesting success (the percentage of females able to successfully lay eggs each night) and/or changes in nesting habitat at Raine Island (e.g. erosion and reduced sand depth) (Limpus et al. 2003).

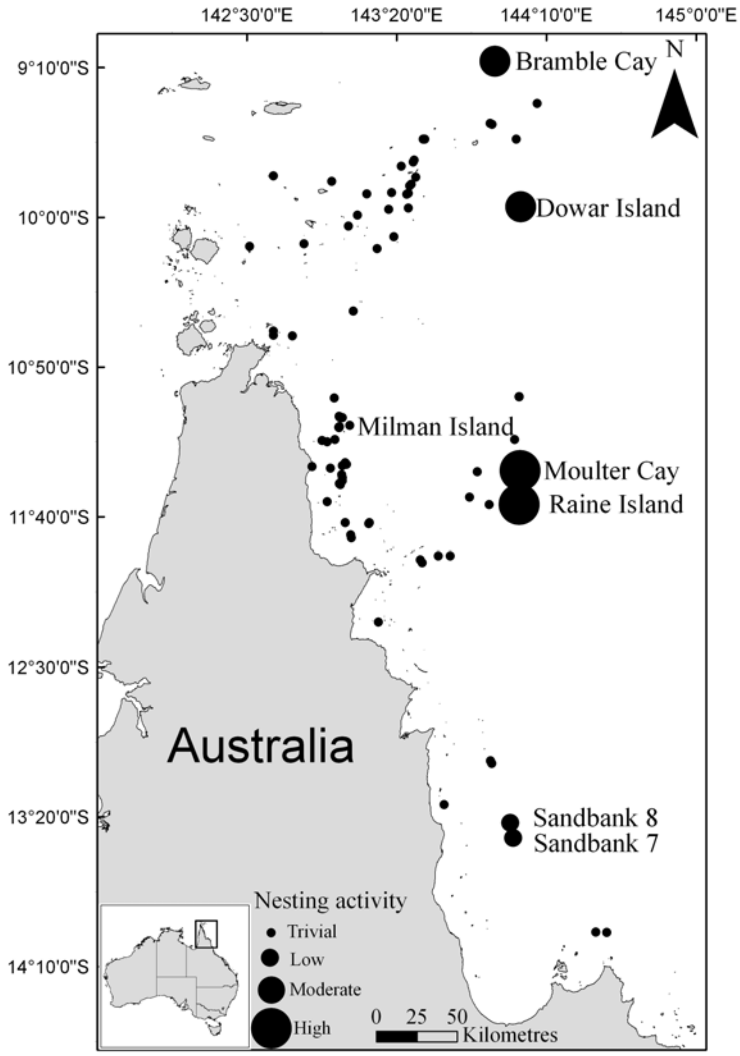

Figure 1.1. Nesting sites used by the nGBR green turtle population and selected study sites. Names of the selected nesting sites are provided.

Nevertheless, a potential decline in this stock is of great concern as this population has important ecological value (e.g. maintenance of seagrass and algal ecosystems (Thayer et al. 1984; Bjorndal and Jackson 2003; Moran and Bjorndal 2005, 2007), economic value (e.g. for the tourism industry (Wilson and Tisdell, 2001), and strong social and cultural value, as Torres Strait Islanders use this population for their consumption as well as for ceremonies and gatherings (Johannes and Macfarlane, 1991). Concern about climate change exacerbating current trends and causing further impacts to this population has been expressed (Hamann et al. 2007, Hopley 2008). Consequently, investigating the impacts of climate change on the nGBR green turtle population has been identified as a priority policy issue for government agencies including the Australian Government's Great Barrier Reef Marine Park Authority, the Torres Strait Regional Authority, and the Queensland Environment Protection Agency (which incorporates the Queensland Parks and Wildlife Service).

1.3.2. Climatic scenarios and temporal scale of the study

For this thesis I predicted the potential impacts of changes in sediment traits, increased temperature, sea level rise, and cyclonic activity on the selected nesting grounds and conducted the vulnerability assessment for both an extreme and conservative scenario of climate change for 2030 and 2070. The extreme scenario is based on A1T emissions and represents a future world of very rapid economic growth, global population that peaks in midcentury and declines thereafter, and rapid introduction of new and more efficient technologies, with high use of non-fossil energy sources (IPCC 2007). In contrast, the conservative scenario is based on B1 emissions, which describe a more integrated, convergent and ecologically friendly world with low population growth and global environmental sustainability (IPCC 2007). Whereas the A1T world invests its gains from increased productivity and know-how primarily in further economic growth, the B1 world invests a large part of its gains in improved efficiency of resource use ("dematerialization"), equity, social institutions, and environmental protection (IPCC 2007).

1.4. Goals, aims and objectives of the research

Given the ecological and cultural importance of the nGBR green turtle population and the potential impacts that climate change can have on them, the goal of this research was to contribute to the effective management and conservation of the nGBR green turtle population as climate change progresses. Thus, the aims of this study were to:

1) Contribute towards a comprehensive understanding of how the terrestrial reproductive phase of the nGBR green turtle population will be impacted by climate change;
2) Provide valuable information to aid the management and conservation of the nGBR green turtle population as climate change progresses.

In order to achieve these aims, my study had three specific objectives:

Objective 1: Investigate how key climatic processes will affect the reproductive output and nesting grounds used by the nGBR green turtle population (Chapters 2 to 5). Identifying how key climatic processes will affect the nesting grounds used by the nGBR green turtle population provides the first steps towards understanding how the terrestrial reproductive phase of this population will be affected by climate change. After conducting a literature review to identify the key climatic processes that can affect sea turtle nesting grounds, and thus their reproductive output, I investigated how changes in sediment traits (Chapter 2), increased temperature (Chapter 3), sea level rise (Chapter 4), and cyclonic activity (Chapter 5) will affect the terrestrial reproductive phase of the nGBR green turtle population.

Objective 2: Assess the vulnerability of nesting grounds used by the nGBR green turtle population to climate change (Chapters 6 and 7). Sea turtle nesting grounds will be affected by multiple climatic processes simultaneously (e.g. changes in sediment traits, increased temperature, sea level rise, cyclonic activity) at different temporal and geographical scales. However, all the studies to date that investigate and predict the impacts of climate change on sea turtle nesting grounds have been conducted for a single climatic process (e.g. sea level rise or increased temperature). Consequently, there is the need for a methodological approach to investigate how multiple climatic processes will impact the nesting grounds used by a specific turtle population. Vulnerability assessments are often used to investigate the impacts of multiple threats (see Halpern et al. 2007) and have been used to assess the vulnerability of marine fauna to climate change (see Hobday et al. 2006; Poloczanska et al. 2007; Chin et al. 2010) and thus was selected as an appropriate methodology for this study (Chapters 6 and 7).

Objective 3: Provide suggestions of management options to mitigate the impact of climate change on the reproductive output of the nGBR green turtle population (Chapter 8). Management of biodiversity in relation to climate change can be very challenging as there is often much uncertainty about the rate, magnitude and likelihood of climatic processes occurring as well as their resulting impacts. The results provided by my data chapters (Chapters 2-6) allowed me to provide informed suggestions of management options to mitigate the potential impacts of climate change to the northern Great Barrier Reef green turtle population. Consequently, a series of management options is provided and suggested as part of this study. Further, in Chapter 8, I assess the feasibility, effectiveness, risks, constraints and opportunities of the identified management options.

1.5. Thesis framework and outline

1.5.1. Conceptual framework

The conceptual framework used for this thesis is based on the environmental vulnerability assessment framework for climate change provided by the IPCC (2007) and recent studies (Turner et al. 2003; Metzger et al. 2005; Schroter et al. 2005). The framework comprises six steps:

1) Define study area together with stakeholders (choose spatial and temporal scales as well as climatic scenarios) (Chapter 1).

2) Identify and predict how key climatic processes may affect the selected study area (Chapters 2-5).
3) Determine the relative impact of each climatic process on nesting grounds (Chapter 6).
4) Assess the vulnerability (exposure, sensitivity and adaptive capacity) of selected nesting sites to each climatic process (Chapter 7).
5) Project future vulnerability of each nesting ground to climate change (Chapter 7).
6) Identify, explore and suggest various management options to mitigate the impacts of climate change to the reproductive output of sea turtles (Chapters 7-8).

1.5.2. Thesis structure and outline

This thesis consists of eight chapters (as outlined below and illustrated in Figure 1.2), arranged in four parts. Part one (Chapter 1) provides the introductory material relevant to my study; part two (Chapters 2-5) assesses how different climatic processes will affect the key nesting grounds used by the northern Great Barrier Reef green turtle population; part three (Chapters 6-7) uses data collected in Chapters 2-5 to predict the vulnerability of each nesting ground to climate change; and part four (Chapter 8) provides a general discussion. The data chapters (Chapters 2-7) were written as a series of stand-alone peer reviewed papers, which are conceptually interconnected. Each of these chapters has been submitted to internationally recognised scientific journals. Six papers have been accepted (from Chapters 1, 2, 3, 4, and 7), two are in review (Chapters 5 and 6), and three are being prepared (Chapters 2-5 and 8) (see list of related publications for further information).

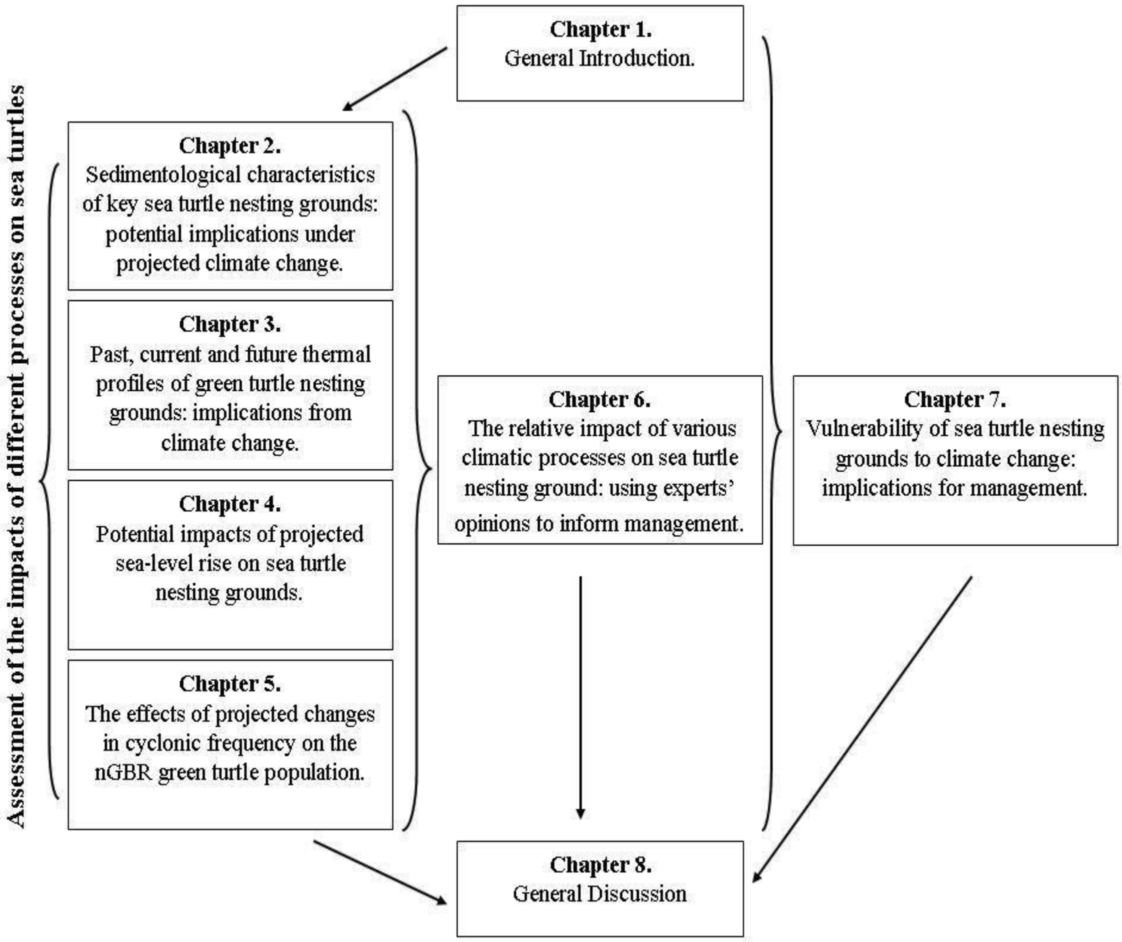

Figure 1.2. Thesis structure and outline.

Chapter 1. General Introduction. In this Chapter I provide a general introduction to climate change and the threat it poses to biodiversity, with a focus on how sea turtles are expected to be impacted. I also describe the methodological approach, define the spatial and temporal scales, and state the climatic scenarios employed in this study.

Publications:

- **Fuentes MMPB**, Hamann M, and Lukoschek V (2009) Marine reptiles and climate change. In: A marine climate change impacts and adaptation report card for Australia 2009 (Eds. Poloczanska ES, Hobday AJ, and Richardson AJ) NCCARF Publication 05/09, ISBN 978-192160903-9
- **Fuentes MMPB** (2007) Some like it hot. Australasian Science. Nov-Dec. p 34-36

Chapter 2. Sedimentological characteristics of key sea turtle nesting grounds: potential implications under projected climate change. In this Chapter I describe the sediment and identify the reef-building organisms of key nesting grounds used by the northern Great Barrier Reef (nGBR) green turtle population. I then review the literature on the vulnerability of each identified reef-building organism to climate change and provide insights into how each nesting ground may be impacted as climate change affects their adjacent reef-flat and reef-building organisms. The ecological implications of altered sediment characteristics to sea turtles is also discussed in this Chapter.

Publication:

- **Fuentes MMPB**, Dawson J, Smithers S, Limpus CJ, Hamann M (in press) Sedimentological characteristics of key sea turtle rookeries: potential implications under projected climate change. Journal of Marine and Freshwater Research.

Chapter 3. Past, current and future thermal profiles of green turtle nesting grounds: implications from climate change. Understanding the rates at which sand temperatures are likely to change as climate change progresses is an immediate priority as it can provide insights into future hatchling success and gender production at nesting grounds. Therefore in this Chapter I describe the systematic process that I undertook to develop and select the best predictive model of sand temperature. The developed models were then used to model past and to predict future sand temperature under various scenarios of global warming for the selected sea turtle nesting grounds used by the northern Great Barrier Reef green turtle population.

Publications:

- **Fuentes MMPB**, Hamann M, and Limpus CJ (2010) Past, current and future thermal profiles for green turtle nesting grounds: implications from climate change. Journal of Experimental Marine Biology and Ecology, 383, 56-64
- **Fuentes MMPB**, Maynard JA, Guinea M, Bell IP, Werdell PJ, and Hamann M (2009) Proxy indicators of sand temperature help project impacts of global warming on sea turtles. Endangered Species Research Journal 9, 33-40

Chapter 4. Potential impacts of projected sea level rise on sea turtle nesting grounds. In this Chapter I investigate how sea level rise may affect the selected nesting grounds used by the northern Great Barrier Reef green turtle population.

Publication:

- **Fuentes MMPB**, Limpus CJ, Hamann M, and Dawson J (in press) Potential impacts of projected sea level rise to sea turtle rookeries. Aquatic Conservation: Marine and Freshwater Ecosystems. DOI: 10.1002/aqc.1088

Chapter 5. The effects of projected changes in cyclonic frequency on the nGBR green turtle population. Understanding how the intensity, frequency and distribution of cyclonic activity will change as climate change progresses is essential to understanding how sea turtle nesting grounds will be exposed and impacted in the future. The latest climatic models suggest that with climate change there will be an intensification of cyclones. This will increase nest flooding and consequently decrease hatchling success. However, there is still great uncertainty as to how the frequency and distribution of cyclones will alter with climate change and thus how the impact that sea turtle experience from cyclones. Therefore, in this Chapter I applied the latest predictive models of cyclones to the study region to investigate how the selected nesting grounds will be impacted by cyclonic activity in the future.

Publication:

- **Fuentes MMPB**, and Abss D (in review) Sea turtles, cyclones and climate change: assessing the effects of projected changes in cyclonic frequency on sea turtles. Journal of Marine Ecology Progress Series
- **Fuentes MMPB**, Moloney J, Limpus CJ, and Hamann M (in prep.) Historical disturbance of cyclones to sea turtles in eastern Australia. To be submitted to Marine Biology

Chapter 6. The relative impact of various climatic processes on sea turtle nesting grounds: using experts' opinions to inform management. Managing sea turtles in the face of climate change will require an understanding of the relative impacts of different climate processes. However, no study to date has systematically investigated the relative impact of different climatic processes to sea turtles, making it challenging for managers to prioritise their decisions and to focus their management. Consequently, in this Chapter I explore how scientific and management experts quantify the relative impact of climatic processes to sea turtles.

Publication:

- **Fuentes MMPB**, and Cinner JE (in review) Impact of climate change to sea turtle nesting grounds: using experts' opinions to inform management. Journal of Environmental Management

Chapter 7. Vulnerability of sea turtle nesting grounds to climate change : implications for management. In this Chapter I synthesise the information presented in my four data chapters (Chapters 2-6) to assess the vulnerability of the selected nesting sites to climate change. Through this process I identify which nesting ground will be most vulnerable to climate change and how the vulnerability of nesting grounds will change if impacts from specific climatic processes are mitigated. Further, I identify a series of management strategies that can be used to mitigate the impacts of climate change on the reproductive output of sea turtles.

Publication:

- Fuentes MMPB, Limpus CJ, and Hamann M (in press). Vulnerability of sea turtle nesting grounds to climate change. Global Change Biology

Chapter 8. General discussion and management recommendations. In this Chapter I provide a summary of the outcomes of this thesis and discuss the implications for the management of sea turtles in the face of climate change. I also discuss the effectiveness of the vulnerability assessment as a methodological approach to inform management about sea turtles and other species as climate change progresses. Lastly, I describe knowledge gaps and prioritise future research directions.

Publication:

- **Fuentes MMPB**, Grech A, Fish M, and Hamann M (in prep.) Constraints and opportunities for management of sea turtles in the face of climate change. To be submitted to Biological Conservation (Chapter 8)

Chapter 2.

Sedimentological characteristics of key northern Great Barrier Reef green turtle nesting grounds: potential implications under projected climate change [1]

[1] **Fuentes MMPB**, Dawson J, Smithers S, Limpus CJ, and Hamann M (in press) Sedimentological characteristics of key sea turtle rookeries: potential implications under projected climate change. Journal of Marine and Freshwater Research.

2.1. Abstract

Sea turtles often rely on reef islands for key parts of their reproductive cycle and require specific sediment characteristics to incubate their eggs and dig their nests. However, little is known about the sedimentological characteristics of sea turtle nesting grounds, how these sediment characteristics affect nesting grounds' vulnerability to climate change, and the ecological implications of different sediment or altered sediment characteristics to sea turtles. Therefore, I described the sediment and identified the reef-building organisms of the selected nesting grounds used by the northern Great Barrier Reef (nGBR) green turtle population (as identified and illustrated in Figure 1.1). I then reviewed the literature on the vulnerability of each identified reef-building organism to climate change and how various sediment characteristics ecologically affect sea turtles. Sediments from the studied nesting grounds are predominantly composed of well sorted medium-grained to coarse-grained sands and are either dominated by Foraminifera, molluscs or both. Dissimilarities in the contemporary sedimentology of the nesting grounds suggest that each may respond differently to projected climate change. Potential ecological impacts from climate change include: (1) changes in nesting and hatchling emergence success and (2) reduction of optimal nesting habitat. Each of these factors will decrease sea turtles' annual reproductive output and thus have significant conservation ramifications.

2.2. Introduction

Reef island beaches have a wide range of socio-economic and ecological values (e.g. tourism, recreation and recycle nutrients) (Schlacher et al. 2008) and offer unique ecological services such as critical nesting habitat for endangered sea turtles (Schlacher et al. 2007). However, reef islands are facing escalating anthropogenic pressures from intense development, recreational activities, pollution, resource exploitation and sea level rises (Schlacher et al. 2007; Schlacher and Thompson 2008; Defeo et al. 2009), compromising their human use and the fauna and flora that depend on them (Fish et al. 2008). Projected climatic changes are expected to cause additional impact to reef island stability and dynamics (Smithers et al. 2007).

A projected sea level rise of 18-59 cm by 2100 (IPCC 2007) is expected to cause exacerbation of shoreline erosion, saline intrusion into the water table, changes in sediment deposition patterns, shoreline retreat, and inundation and flooding of beaches (Klein and Nicholls 1999; Mimura 1999; Schlacher et al. 2007). Further changes to island morphology can occur as a result of cyclones (Taylor 1924; Hopley 1982; Perry 1996; Frank and Jell 2006). Processes associated with cyclones such as increased wave heights, strong winds, heavy rainfall and storm surges can erode and change the beach profile, altering beach morphology (Defeo et al. 2009).

Additional stress to reef island stability is likely to occur through impacts to sediment supply caused by changes in reef platform morphology and its resident carbonate producers as a result of increased temperature and ocean acidification (Eakin 1996; Perry 1996; Orr et al. 2005). Reef island beaches are dynamic sediment bodies intimately related to the surrounding reef platform on which they have accumulated. They are commonly composed of sand-sized skeletal remains produced directly by reef-building organisms (primary carbonate) and/or the mechanical and biological breakdown of rigid reef framework into sands (secondary carbonate) (Milliman 1974; McLean and Stoddart 1978). The distribution of reef communities and reef-building organisms, and consequently the constituent composition and productivity rates of reefal carbonate sediments, is affected by environmental parameters such as temperature, salinity, water pH, light intensity and nutrient availability (Eakin 1996; Mutti and Hallock 2003). Therefore, any alteration to environmental parameters, such as the ones predicted by the IPCC 2007 may drive changes in reef platform morphology and its resident carbonate producers (Eakin 1996; Perry 1996; Orr et al. 2005) and ultimately change the type and rates of net carbonate production and delivery to islands. If such projections are accurate, the longer-term prospects of reef islands may be compromised (Palandro et al. 2003) and human societies, ecosystems and the fauna and flora that depend on them may be impacted (Smithers et al. 2007).

Sea turtles depend on reef island beaches for nesting and thus are likely to be impacted by projected climatic change. To date, most research on the effects of climate change on sea turtle populations has focused on their biological attributes (e.g. Hawkes et al. 2007 b) or on how their nesting grounds may be inundated as sea level rises (e.g. Fish et al. 2005, 2008; Baker et al. 2006). However, as sea turtles require specific sediment characteristics to incubate their eggs and dig their nest (Mortimer 1990), alteration to the sedimentological characteristics of their nesting grounds as climate change progresses is also an issue of concern. Little is known about the sedimentological characteristics, especially the compositional structure, of sea turtle nesting grounds, how nesting grounds' sediment characteristics affect their vulnerability to climate change and the ecological implications of different sediment or altered sediment characteristics to sea turtles. Therefore, the aim of this Chapter is to elucidate some of these issues. This is accomplished by: (1) describing the sediment and identifying the reef-building organisms of the selected nesting grounds (this will provide important baseline data to monitor future changes in sediment characteristics as climate change progresses), and (2) reviewing the literature on how various sediment characteristics ecologically affect sea turtles and the vulnerability of each identified reef-building organism to climate change. Using this as a basis, I then speculate on the ecological implications of changed sediment regimes and altered island morphology to sea turtles.

2.3. Methods

2.3.1. Sediment sampling strategy

Sediment samples were systematically collected from each nesting beach following a sampling design stratified by bio-geomorphic zones that were identified along shore-normal transects. At each island, transects were placed at each beach orientation (e.g. north, east, south and west). Sediment samples were collected along each transect at six different bio-geomorphic zones: (1) reef flat (the quasi-horizontal surface extending from the toe of the beach toward the reef crest, usually at an elevation close to the MLWS tide level); (2) toe of the beach (where the sloping beach face intersects the more horizontal reef flat); (3) high water mark (HWM); (4) beach berm (the often broad low relief area extending from the top of the swash limit to the base of the cliff zone); (5) dune (windblown sand ridge only present at Milman Is., Dowar Is. And Bramble Cay) and (6) cliff (an escarpment of up to 1.5 m high separating unconsolidated beach sediments from phosphatised higher inland areas only present at Raine Island and Moulter Cay); further descriptions and illustrations of each bio-geographic zone can be found in Baker et al. (1998). Not all of these zones were encountered on each island or across each transect. 40 transects were examined across the seven nesting grounds, and a total of 144 sediment samples were collected - one sample from each bio-geomorphic zone on each transect. Sediment sample numbers varied according to island size and geomorphology (Table 2.1). All sample locations were recorded by GPS using the GCS_Australian_1984 geographic coordinate system.

Table 2.1. Summary of sampling activity at each of the selected nesting grounds.

Nesting ground	Transects	Number of samples	Zones of which samples were collected
Raine Island	4	16	Cliff, beach berm, toe of beach, and reef flat
Moulter Cay	4	16	Cliff, beach berm, toe of beach, and reef flat
Bramble Cay	4	16	Dune, beach berm, high water mark, beach toe
Dowar Island	12	48	Dune, beach berm, high water mark, beach toe
Sandbank 7	4	8	Beach toe and beach berm
Sandbank 8	4	8	Beach toe and beach berm
Milman Island	8	32	Dune, beach berm, high water mark, beach toe
Total	**40**	**144**	**Dune, beach berm, high water mark, toe of beach, and reef flat**

2.3.2. Textural analysis

Textural traits were determined for all 144 sediment samples collected using a Rapid Sediment Analyser (RSA), a settling tube from which grain sizes can be calculated using settling velocities (Zeigler and Whitne 1960). The diverse size, shape and density of biogenic carbonates can confound their analysis and interpretation of data yielded using traditional sieving methods, and thus the RSA approach is considered more appropriate.

Samples were air-dried and split into 10–15 g sub-samples using Ingram's (1971) methods before being run through the RSA. A 'settling' runtime of 10 minutes was used for all samples, and log files generated by the RSA were transferred into SedRep (School of Geography and Environmental Science, University of Auckland, New Zealand). SedRep calculates grain-size statistics based on the settling velocities of sediment grains using Gibbs et al.'s (1971) equation. Derived grain-size statistics included the distribution of the entire sample, mean grain-size, sorting, skewness and kurtosis; modal size classes were also identified.

2.3.3. Compositional analysis

Compositional analyses were undertaken for all 144 samples to identify the skeletal constituents that comprise each sediment sample. Sub-samples were dry-sieved into 1.5, 1.0, 0.5, 0.0, –0.5 and ≥/ –1.0 φ size fractions and point-counted under a binocular microscope using the ribbon method described by Galehouse (1971). At least 100 grains were point-counted for each sieve fraction whenever possible, giving a sum of approximately 600 per sample and over 98,000 identified grains. I identified the organism from which each grain was derived by using keys from Milliman (1974) and Scoffin (1987). Eighteen different component categories were identified: (1) coral; (2) coralline algae; (3) bivalves; (4) gastropods; (5) undetermined molluscs; (6) *Amphistegina* sp.; (7) *Baculogypsina sp*. and *Calcarina sp*.; (8) *Marginopora vertebralis*; (9) *Homotrema rubra*; (10) other foraminiferans; (11) *Halimeda*; (12) echinoid plates and spines; (13) alcyonarian spicules; (14) bryozoans; (15) serpulid worms; (16) crustaceans; (17) indeterminate and (18) non-carbonate material. The total composition of each sample was calculated by multiplying the composition counts of each grain size fraction by the weight percent of that fraction (derived from the RSA output) to the total sample. The benthic foraminiferans *Baculogypsina* and *Calcarina* were combined as a single component category as they were difficult to distinguish under the microscope because of physical abrasion of the grains.

2.3.4. Statistical analysis

Textural and compositional data were tested for normality and equal variance to ensure they met assumptions for parametric statistics. The composition data met all of the assumptions; however, the grain-size distributions of many samples were polymodal and did not meet the normal distribution assumption. Therefore, only compositional data could be examined using ANOVAs. A series of two-way ANOVA tests, with beach zone (e.g. reef flat, toe, HWM, beach berm, dune and cliff) as factor 1 and orientation (e.g. north, east, south and west) as factor 2 was used to investigate the differences in sediment compositional structure at each nesting ground. I used SPSS 16.0 to conduct One-way ANOVAs between nesting grounds to determine if there was a difference in their composition.

Raw textural and compositional data and derived descriptive statistics (mean grain size, sorting, etc.) were first examined for patterns and trends before a multivariate analysis was performed to evaluate the nature and distribution of sediments across the seven nesting grounds. Grain size and compositional assemblage data were analysed separately using a non-metric multidimensional scaling (nMDS) based upon similarity matrices of Euclidean distances.

2.4. Results

2.4.1. Textural characteristics

The surficial sediment across the selected nesting grounds is similar, with most nesting grounds showing well-sorted coarse-grained sands (Table 2.2). Some differences are encountered regarding sediment grain size, with Dowar and Milman Islands having medium-grained sands (Table 2.2).

Table 2.2. Textural characteristics of sediments collected from rookeries used by the northern Great Barrier Reef green turtle population. Grain sizes were classified based on the Udden-Wentworth scale (from Stoddart 1978) and Sorting was classified according to Graham 1988.

Nesting ground	Grain size	Sorting	General notes
Raine Island	Coarse to very coarse-grained sands (-0.59 to 0.89 φ)	Moderately sorted to well sorted (0.26 to 0.96 φ)	Fine-grained sand and mud-sized sediments are rare
Moulter Cay	Coarse-grained sands (0.06 to 0.63 φ)	Very well sorted to moderately well sorted (0.2 to 0.65 φ)	Minor pebble (2.5%) and mud-sized (0.3%) sediments
Bramble Cay	Coarse–grained sands (0.26 to 0.96 φ)	Very well sorted to moderately sorted (0.26 to 0.9 φ)	Sand-sized (98.1%), with a few pebbles (1.9%)
Dowar Island	Coarse-grained to medium-grained sands (0.07 φ to 1.23 φ)	Very well sorted to moderately sorted (0.25 to 1.0 φ)	98.5% sands
Sandbank 7	Very coarse-grained to coarse-grained (-0.11 to 0.67 φ)	Very well sorted (ranging from 0.24 to 0.43 φ)	99.2 % sands, mud-sized sediments absent.
Sandbank 8	Coarse-grained (-0.30 to 0.74 φ) sand	Well sorted to moderately sorted (0.28 to 0.82 φ)	4.5 % pebbles
Milman Island	Medium sized-grained (vary from 0.21 φ to 1.94 φ)	Well sorted (0.2 to 0.87 φ),	1.2% of pebbles

The non-metric multidimensional scaling (nMDS) plot indicates that the selected green turtle nesting grounds cannot be distinguished based on textural data alone. However, the nMDS plots show that Milman Island presents the most distinct textural characteristics based on grain size, with higher proportions of medium sand than any other nesting grounds (Figure 2.1).

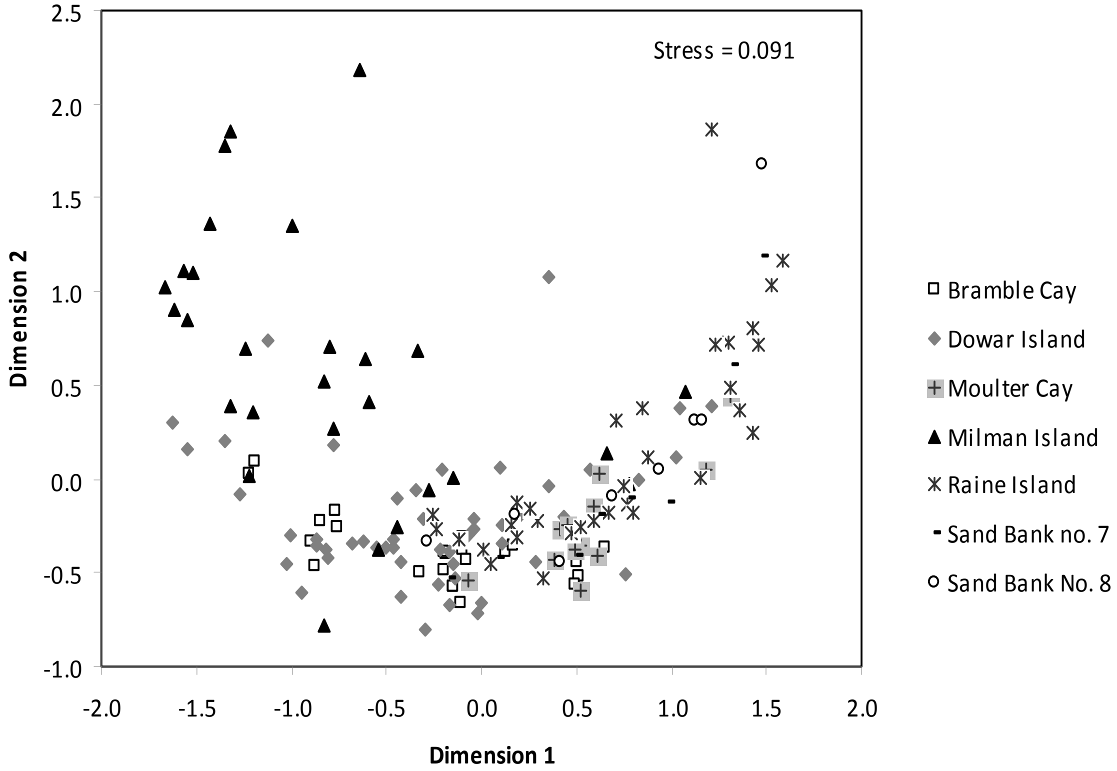

Figure 2.1. Non-metric multi-dimensional scaling (NMDS) ordination plot (dimensions 1 and 2) of the textural characteristics of sediment samples from the studied nesting sites used by the northern Great Barrier Reef green turtle population.

2.4.2. Compositional characteristics

The composition of sediment is significantly different across the seven nesting sites ($F_{36,595}$ = 15.237, P < 0.01). For instance, Moulter Cay, Milman Island and Sandbank 7 have significantly more molluscs than the other sites ($F_{6,140}$ = 23.567, P < 0.01), with 44.9%, 45.6% and 47.8% of molluscs respectively (Figure 2.2); Raine Island, Bramble Cay and Dowar Island have significantly more foraminiferans than all the other nesting sites ($F_{6,\ 140}$ = 48.071, P < 0.01) and Dowar Island is distinct from the other nesting grounds, being the only site with non-carbonate material (Figure 2.2). Further differences between nesting sites include: (1) Sandbank 8 has significantly more coral than Bramble Cay ($F_{6,140}$ = 27.883, P < 0.01); (2) Raine Island has significantly more coralline algae than Bramble Cay and Dowar Island ($F_{6,140}$ = 10.75, P < 0.01) and (3) Sandbank 8 and Milman Island have significantly more *Halimeda* than Raine Island, Moulter Cay and Sandbank 7 ($F_{6,140}$ = 12.01, P < 0.01) (Figure 2.2).

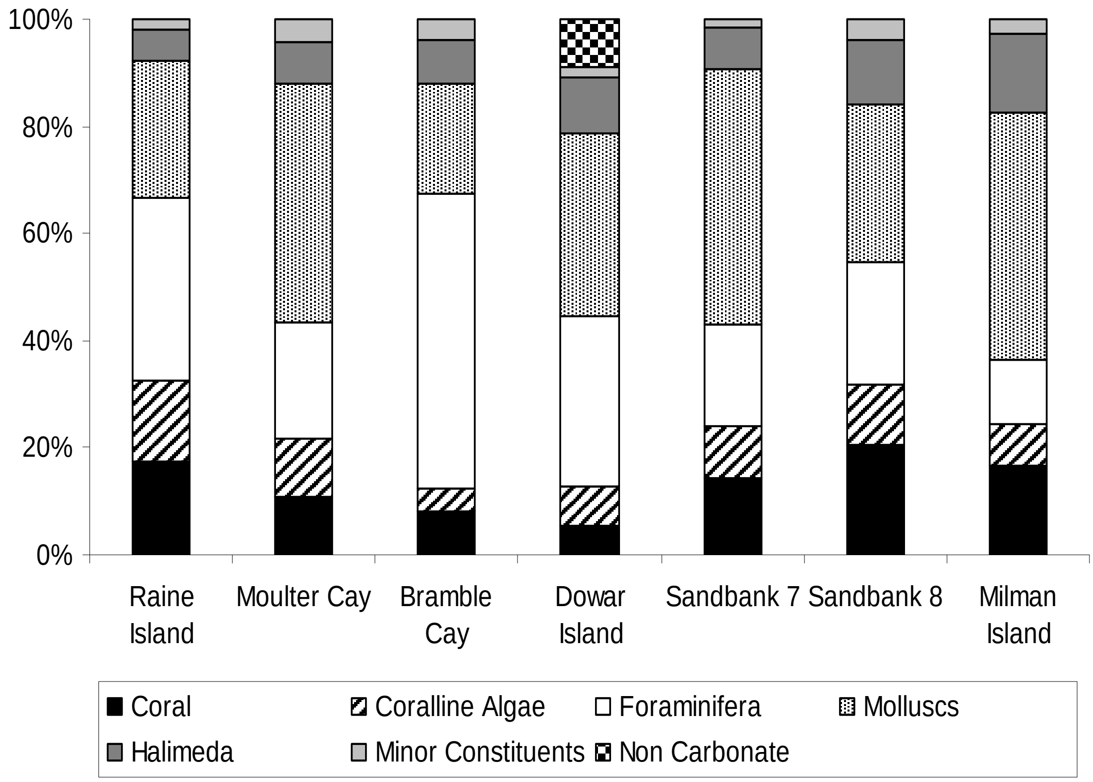

Figure 2.2. Constituent composition of sediment samples from each nesting ground studied.

The differences among the nesting sites are further supported by the non-metric multidimensional scaling (nMDS) (Figure 2.3), where the nesting sites are distinguished from each other based on the proportion of Foraminifera, molluscs and non carbonate material. The nMDS plot for composition clusters the points from Milman Island together as it is the site with least Foraminifera (Figure 2.3).

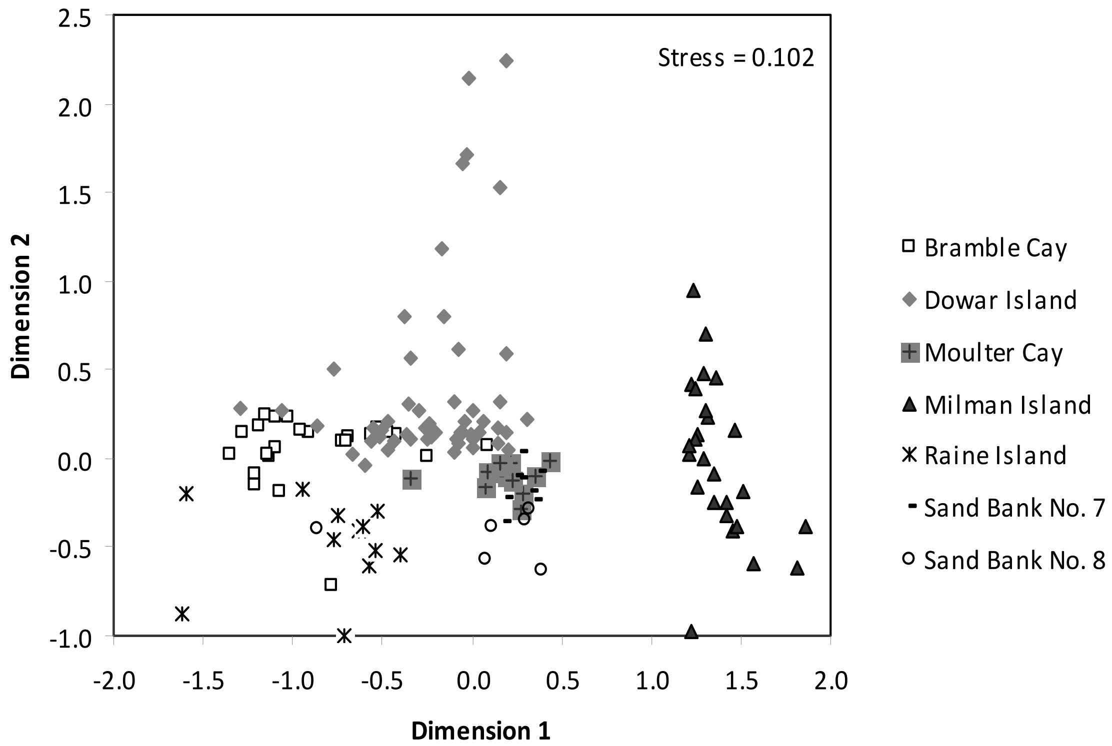

Figure 2.3. Non-metric multi-dimensional scaling (NMDS) ordination plot (dimensions 1 and 2) of the compositional characteristics of sediment samples from the studied nesting sites used by the northern Great Barrier Reef green turtle population. C = Coral, CA = Coralline algae, F = Foraminiferans, H = *Halimeda*, I = Indeterminate, M = Molluscs, MC = Minor components, NC = Non carbonate.

Differences in compositional structure were also observed between bio-geomorphic zones and orientation within each nesting ground. At Raine Island, Moulter Cay, Bramble Cay and Dowar Island, a significant difference in *Halimeda* distribution was found as a result of an interaction between beach orientation and bio-geomorphic zones ($F_{6,14}$ = 3.46, P = 0.044; $F_{6,14}$ = 3.84, P = 0.035; $F_{8,24}$ = 3.114, P = 0.028; $F_{8,51}$ = 8.858, P < 0.01, respectively). A similar interaction was also found with the distribution of molluscs at Milman Island, Sandbank 8 and Dowar Island ($F_{9,27}$ = 4.816, P = 0.002; $F_{4,7}$ = 18.81, P = 0.018; $F_{8,51}$ = 6.932, P < 0.01). Sandbank 7 is the only island where sediment composition does not vary across bio-geomorphic zones or between transects.

2.5. Discussion

Sediments from all seven nesting grounds used by the northern Great Barrier Reef (nGBR) green turtle population are predominantly composed of well-sorted, medium-grained to coarse-grained sands, which provide suitable sedimentological characteristics for sea turtle activity and egg incubation (Yalcin-Ozdilek et al. 2007). Most of the world's major green turtle nesting grounds are characterised by similar textural characteristics, with moderately sorted sand and mean particle size ranging from very coarse to medium sand (0–2 φ) (Mortimer 1990; Yalcin-Ozdilek et al. 2007). The nesting grounds used by the nGBR green turtle population have great compositional diversity and are either dominated by Foraminifera or molluscs, or both. Even though such foramol assemblages are usually more indicative of temperate carbonate regions (Kennedy et al. 2002; Smith and Nelson 2003), other tropical beaches and islands similar to the nesting grounds from this study are constructed mainly of foraminiferans (e.g. Yamano et al. 2000; Hohenegger 2006). No other study to date has systemically described the compositional structure of sand from other sea turtle nesting grounds, thus comparisons cannot be made.

The specific textural and compositional traits of the nesting grounds "facies" studied here reflect a combination of both the composition and productivity of the reef-building organisms and post-depositional sediment transport or remixing (Hewins and Perry 2006). Environmental conditions determine the distribution and boundary conditions for the biota that forms the carbonate reef platform (Mutti and Hallock 2003; Halfar et al. 2004). Therefore, processes that can modify these environmental conditions, such as projected climatic change, can affect the composition of reef-building organisms, sediment production and durability. Since the majority of reef-building organisms are associated with photosynthesis, either directly (calcareous algae) (Nelson 2009) or through photosymbiotic associations (large foraminiferans and zooxanthellate corals) (Hallock 2000), most of them are very sensitive to small increases in sea surface temperature (SST) and/or light intensity (Hoegh-Guldberg 1999) (Table 2.3).

Table 2.3. Reef-building organisms, their thresholds and predicted impacts with projected increase of sea surface temperature.

Increase sea surface temperature- Current SST in the GBR : ranges from approximately 29 ºC to 22 ºC Projection: + 1- 3 ˚C by 2100 (IPCC 2007)			
Reef-building organisms	**Thresholds**	**Impacts**	**References**
Reef-building Corals	Thermal tolerance of corals varies between locations, species and growth forms +1 ºC of current SST in the GBR causes bleaching and + 2-3 ºC causes coral death. Upper thermal bleaching threshold of around 30 ºC for most 'tropical' reef systems.	Reduced coral cover and structural complexity Reduce calcification rate and sediment budget Projected increase in temperature by the end of the century will result in ~80-100% bleaching of the GBR.	Berkelmans et al. 2004 ; Hoegh- Guldberg et al. 2007; Smithers et al. 2007.
Foraminiferans	Species-specific temperature tolerance range from 14-34 ºC, some species tolerate up to 39 ºC	Larger symbiont bearing foraminifera tolerate rising temperatures and successfully occupy empty niches to take on the role as dominant reef builders	Hallock 2000; Scheibner et al. 2005; Langer 2008.
Coralline Algae / *Halimeda*	Tropical macroalgal can tolerate temperatures up 33 ºC to 35 ºC	Impact distribution Loss of pigment Coralline Algae and *Halimeda* may thrive under a wide range of temperatures.	Pakker et al. 1995; Halfar and Mutti 2005; Diaz Pulido et al. 2007.
Molluscs	Thresholds vary with species. Lack of precise information on thresholds	Affect metabolic rate, reproduction, development growth	Shirayama and Thornton 2005.

Current literature indicates that corals are the most sensitive carbonate producer to increased temperature (Table 2.3). Indeed, 80 to 100% of the Great Barrier Reef is predicted by the IPCC (2007) to be bleached as a result of the projected increase in temperature (Hoegh-Guldberg et al. 2007). Symbiont-bearing foraminiferans (*Baculogypsina* and *Calcarina*) can tolerate higher SST, with some species tolerating up to 39 °C, however, they are also susceptible to increases in temperature and may die as a result of increased thermal stress (Hallock 2000). Furthermore, an increase in SST will also affect the physiology of non-photosynthetic carbonate producers, such as molluscs. Fossil records indicate that increased SST played an important role in molluscan migrations and extinctions. However, despite these associations, molluscs are also known for their adaptive capacity to broad-scale change, usually migrating to cooler waters and higher altitudes

(Hutchings et al. 2007). The latter characteristic suggests that molluscs may be less sensitive to an increase in SST than corals or foraminiferans.

Reef-building organisms will also be affected by projected ocean acidification whereby changes in water pH will impact the production and calcification of their shells, skeletons and tests (Orr et al. 2005; Hutchings et al. 2007; Smith 2009) (Table 2.4). Ocean acidification will impact reef-building organisms differently in accordance with the form of crystalline calcium carbonates they lay down (Table 2.4). Since aragonite is more soluble than calcite and thus more susceptible to pH changes, marine organisms that lay down calcium carbonate as aragonite crystals (e.g. corals and many molluscs) may be more susceptible than those that lay down calcite (e.g. foraminiferans) (Orr et al. 2005; Andersson et al. 2007; Guinotte and Fabry 2008) (Table 2.4). Indeed, it is expected that predicted doubling of atmospheric CO_2 by 2065 will decrease coral calcification by 10–40% (Marubini et al. 2001; Feely et al. 2004). The overall sensitivity of different reef-building organisms will vary with their physiological threshold, developed tolerances, adaptive capacity and the habitat in which they are found. Thus, each reef-building organism will be affected differently by climate change processes (Table 2.3 and 2.4) and the potential impacts on different islands will vary in accordance with the dominant carbonate producers at their adjacent reefs.

Table 2.4. Predicted impacts to reef-building organisms with projected ocean acidification.

Ocean acidification **Projection: double the pre-industrial partial pressure of CO2 by 2065 (Mheel et al. 2007)**		
Reef-building organisms	Impacts with predicted projection	References
Reef- building corals	Decrease of coral calcification by 10 - 60% Weaker coral skeletons Slower growth rates	Marubini et al. 2001 ; Langdon et al. 2003 ; Feely et al. 2004 ; kleypas et al. 2006.
Foraminiferans	Decrease calcification and shell weight	Spero et al. 1997; Bijma et al. 1999; Barker and Elderfield 2002.
Coralline Algae	40% reduction in growth rates 78% decrease in recruitment 92% reduction in total area	Leclercq et al. 2000 ; Kuffner et al. 2008.
Halimeda	Decrease calcification response Change in distribution	Borowitzka and Larkum 1976 ; Breeman 1990.
Molluscs	Impacts not well known Decrease ability to secrete protective skeletons Impact shell weight and size effects of ocean acidification on calcification and dissolution	Feely et al. 2004; Shirayama and Thornton 2005; Gazeau et al. 2007; Hutchings et al. 2007.

Impacts caused by increase in SST and ocean acidification will influence the sediments that are transported to islands, which will affect the carbonate sediment production and budget at each nesting ground and possibly alter islands' sediment grain size, sorting and facies dynamics (Folk and Robles 1964; Lidz and Hallock 2000; Mutti and Hallock 2003). For instance, the death of carbonate producers may lead to an increase in rates of reef framework degradation and increase sediment supply to islands in the short-to medium-term, potentially changing the sediment characteristics at islands. This could be an issue for sea turtles as they require specific sediment characteristics to dig their nest and incubate their eggs (Mortimer 1990; Chen et al. 2007; Yalcin-Ozdilek et al. 2007). Sediment size influences turtles' reproductive success and hatchling activity (Yalcin-Ozdilek et al. 2007). Smaller grain size compacts the sand and obstructs excavation by nesting turtles (Ehrhart and Raymond 1983; Fletemeyer 1980), slows down emerging hatchlings from the nest chamber (Fletemeyer 1980) and slows embryo development by reducing diffusion of gases (Mortimer 1981). Beaches with coarser, poorly sorted sands have lower hatchling emergence success and are more difficult for turtles to dig their nests (Mortimer 1990; Chen et al. 2007). Thus, coarse to medium sand (0.25-2.25φ) is indicated to be an optimal range for grain size at nesting grounds (Mortimer 1981). Therefore, a reduction of live coral cover, which usually contributes to coarse grain sizes, at reef-flats adjacent to nesting grounds such as Raine Island and Sandbank 8 (which have the highest percentage of derived coral sediments) will increase the supply of coarse grain sizes to these islands in the short- to medium-term. This will potentially decrease sea turtles' nest digging success and hatchling emergence as beaches with coarser sands usually have coarser hatchling emergence. However, in the long term, after all sediment available in the reef (e.g. dead carbonate producers) is delivered to islands and carbonate productivity is reduced from ocean acidification and increased in SST, a negative sediment budget is expected, potentially causing island erosion (Smithers et al. 2007). Erosion can be a major issue for sea turtle nesting habitats and nests because it can cause habitat destruction and flood and kill eggs, consequently lowering annual hatchling success (Eckert 1987).

Changes in grain sizes, sorting and facies dynamics may also alter the temperature of sand at nesting grounds since sand grain size is correlated with thermal conductivity and thus influences sand temperature. Sands with larger grain sizes have poorer thermal conductivity and are cooler (Speakman et al. 1998). For example, cyclones physically disturb and destroy reef-flats turning them into reef rubble, shingles and sand, which are usually larger sediment sizes. This material is then remobilized and redistributed across the reef surface on to islands (Nott 2006; Hopley et al. 2007). Sea level rise may also aid sediment transportation in the short term by remobilizing sediments deposited on currently inert reef flats and moving them towards reef islands (Kench and Cowell 2001; Hopley et al. 2007, Chapter 4). The input of sediment to nesting grounds after cyclonic activities and sea level rise may increase the proportion of larger sediment sizes, which have poorer thermal conductivity and may reduce sand temperature at these sites. Sand temperature is also influenced by the sand albedo (that is the fraction of incident solar radiation reflected from the surface (Hays et al. 2001; Godley et al. 2002) where sands with greater absorption of the incident solar radiation have higher temperatures and are usually composed of dark grains (Hays et al. 2001). As sand temperature, during incubation of sea turtle eggs, influences the incubation length, hatching success and hatchling sex ratio (Miller 1985), different sediment characteristics may influence these parameters and affect the dynamics of sea turtle populations. However, no study to date has investigated the specific thermal properties of sand with different characteristics and/or quantified how sand temperature and albedo changes with changes in sedimentological characteristics. Therefore, at this stage, we do not know how potential changes in sediment characteristics may influence hatching success and hatchling sex and phenotype. As more information on the thermal properties of sand is determined, we can start to examine the potential of altered sediment characteristics to significantly change sand temperatures and to counteract the impacts of increased temperatures on incubating eggs.

2.6. Chapter Summary

Projected rates and patterns of climate change may modify the composition and/or productivity of reef-building organisms. These changes can potentially alter reef-island morphology and sediment characteristics and, in turn, affect sea turtles' reproductive output, as they require specific sediment characteristics to incubate their eggs and dig their nests (Mortimer 1990). Therefore, for effective management and conservation of sea turtles as climate change progresses, it is important to consider potential changes in sediment at sea turtle nesting grounds and the ecological implications of these changes. However, there are still several knowledge gaps that make it difficult to determine how sediments at sea turtle nesting grounds will change as their adjacent reef platform and reef-building organisms are affected by climatic changes (or other natural or anthropogenic processes), and how this may affect sea turtles.

To properly investigate this, the following research gaps need to be addressed: (1) the responses/tolerance levels of the different reef-building organisms to projected climate change. At this stage, studies on the effects of increased SST and ocean acidification have generally been confined to a few species of corals, algae and foraminiferans and, therefore, large gaps still remain in our knowledge on the physiological and ecological impacts of increased SST and ocean acidification on other reef-building organisms, such as coralline algae and *Halimeda*; (2) calcification response to ocean acidification; (3) threshold levels at which sediment production rates may change in the future; (4) how decreased calcification rates affect biological function or organism survival; (5) specific sediment requirements of sea turtles, especially how the compositional characteristics of sand affects their reproductive ecology and (6) thermal properties of different sediment characteristics.

Nevertheless, distinctions in the contemporary sedimentology from the nesting grounds studied here suggest that each nesting ground may respond differently to projected climatic change impacts and, consequently, there will be variable impacts on sea turtles. Although we cannot tease out the future differences in morphological and sedimentological responses, we can foresee some impacts that may occur to sea turtles from altered sediment regimes. This is particularly an issue for the islands studied here, as the sea turtle population using these islands is threatened and has high ecological and cultural value (Limpus et al. 2003). As gaps in our knowledge are addressed and we have a better understanding of how carbonate producers and sediment production will be affected by projected climatic changes, results such as those presented here will become more important and will support interpretation of how these nesting grounds may be impacted by climate change. Similarly, as information on how specific nesting grounds will be affected become more available, weighted risk scores (as per Chapters 6 and 7) can be generated together with information on the ecological importance of each nesting ground to aid prioritization of island management and conservation.

Chapter 3.

Past, current and future thermal profiles of key northern Great Barrier Reef green turtle nesting grounds: implications from climate change [1,2]

[1]**Fuentes MMPB**, Hamann M and Limpus CJ (2010) Past, current and future thermal profiles for green turtle nesting grounds: implications from climate change. Journal of Experimental Marine Biology and Ecology, 383, 56-64

[2]**Fuentes MMPB**, Maynard JA, Guinea M, Bell IP, Werdell PJ, and Hamann M (2009) Proxy indicators of sand temperature help project impacts of global warming on sea turtles. Endangered Species Research Journal 9, 33-40

3.1. Abstract

Predicted increase in temperature poses serious threats to sea turtle populations since sex determination and hatching success is influenced by nest temperature. Warmer sand temperatures may skew sea turtle population sex ratios towards predominantly females and decrease hatching success, as eggs may be consistently exposed to temperatures that exceed thermal mortality thresholds. Consequently, understanding the rates at which sand temperatures are likely to increase as climate change progresses is an immediate priority. Thus, in this Chapter I conduct a systematic process to select the best predictive model of sand temperature. I explored the efficiency of three regression analyses, which had the following variables as proxy of sand temperature: (1) sea surface temperature (SST) only, (2) air temperature (AT) only and (3) SST and AT. The fit of these three models were compared using the Akaike Information Criterion (AIC) and a best model was selected. The selected model (SST + AT) was then used to model past and to predict future sand temperature under various scenarios of global warming for the selected sea turtle nesting grounds used by the northern Great Barrier Reef green turtle (as illustrated in Figure 1.1). Reconstructed temperatures from 1990 to 2008 suggest that sand temperatures at the nesting sites studied have not changed significantly during the last 18 years. Current thermal profile at the nesting grounds suggests a bias towards female hatchling production into this population. Inter-beach thermal variance was observed at some nesting grounds with open areas in the sand dune at northern facing beaches having the warmest incubating environments. My model projections suggest that a near complete feminization of hatchling output into this population will occur by 2070 under an extreme scenario of climate change (A1T emission scenario). Importantly, I found that some nesting grounds will still produce male hatchlings by 2070, even under the most extreme scenario of climate change; this finding differs from predictions for other locations. Information from this study provides a better understanding of possible future changes in hatching success and sex ratios at each site and identifies important male producing regions.

3.2. Introduction

Oviparous reptiles, such as sea turtles have life history, physiology and behavioural traits that are influenced by environmental temperature (Jazen 1994). This is particularly the case during the egg incubation phase (Spotila and Standora 1985) because successful incubation of sea turtle eggs occurs within a narrow thermal range of 25 to 33 °C (Miller 1985). Incubation above the thermal threshold will result in hatchlings with higher morphological abnormalities and lower hatching success (Miller 1985). Additionally, sea turtles have temperature dependent sex determination (TSD), where the sex of hatchlings is determined by the nest temperature during the middle third of incubation (Mrosovsky 1980; Yntema and Mrosovsky 1980). Warmer temperatures, above the pivotal temperature - a temperature whereby a1:1 sex ratio is produced - yield more females while temperatures below the pivotal temperature shift the ratio towards more males (Yntema and Mrosovsky 1980). The pivotal temperature differs slightly within and between species and is usually around 28.0-29.5 °C (for review of pivotal temperatures see Hawkes et al. 2009). The proportion of males produced depends in part on the steepness of the transitional range temperature (TRT) curve, which is the range of temperatures in a nest whereby sex ratio shifts from all male to all females. Higher sand temperature also decreases the incubation period of sea turtle eggs (Miller 1985) and decreases hatchling body size and mass (Booth and Astil 2001; Burgess et al. 2006). It is likely that smaller body size reduces hatchling survival chances since some studies indicate that smaller hatchlings are more susceptible to predation as they cross the reef (Gyuris 1994). Therefore, even small increases in temperature will alter hatchling phenotype and potentially their survival (Mrosovsky 1980).

Consequently, global warming has the potential to impact sea turtles. If sea turtles do not adapt to future climate change, predicted increases in temperature could potentially cause increased incidence of scale and morphological abnormalities as well as an increase in hatchling mortality rates (Miller 1985; Broderick et al. 2001; Godley et al. 2001; Hamann et al. 2007; Hawkes et al. 2007 b) and/or a gradual shift towards a feminisation of sea turtle populations (Mrosovsky et al. 1984, 1994; Janzen 1994, Davenport 1997, Glen and Mrosovsky 2004, Hawkes et al. 2007 b). If the impacts persist they may compromise the viability of sea turtle populations, especially those severely threatened by other factors (e.g. direct and indirect take, pollution). Consequently, it is critical to understand both the rate at which sand temperatures are likely to change and the extent to which associated changes in hatching success and sex ratios will vary spatially as climate change progresses. Given the conservation concern for sea turtle species coupled with future scenarios of global warming, researchers are trying to provide an understanding of the likely impacts of global warming on hatching success and sex ratios (e.g. Hawkes et al. 2007 b). However, most studies focus on only one or a few nesting grounds for a particular turtle population. While still important, such an approach does not provide a full understanding of how a genetic stock (management unit), which encompasses multiple nesting grounds, will be affected and thus limits its utility to managers.

Predicting changes to sand temperature in space and time is challenging because the relative importance of the large number of variables that influence sand temperature are not well understood. Variables that influence sand temperature include: air temperature (AT), sea surface temperature (SST), wind speed/direction, rainfall, cloud cover, solar radiation, local vegetation types, beach aspect angle and sand characteristics like albedo, heat capacity, density, solar radiation absorption and emission and convective heat transfer (Mrosovsky et al. 1984; Godfrey et al.1996; Hays et al. 1999, 2001; Matsuzawa et al. 2002; Reece et al. 2002; Houghton et al. 2007). All of these variables vary spatially and temporally and of them AT and SST are the easiest to be monitored in near real-time, as data from weather stations and environmental monitoring satellites are readily available. Previous studies have related AT to sand temperature and have found the two to be correlated strongly enough to predict and reconstruct sand temperature at nesting grounds in Ascension Island, Pasture Bay (Long Island, Antigua), Thomson Causeway (Mississippi, USA) and Bald Head Island (North Carolina, USA) (see Janzen 1994; Hays et al. 1999, 2003; Glen and Mrosovsky 2004; Hawkes et al. 2007 b). However, many sea turtle nesting grounds, such as those in northern Australia, are remote and *in situ* data on AT are usually unavailable. In such cases previous studies have used data from weather stations that are located closest to the nesting grounds, potentially reducing the validity and applicability of the projections made, even if only slightly (e.g. Hays et al. 1999, Godley et al. 2001). In contrast, high-resolution (~1km) SST data, calibrated to ship-based sensors and drift buoys, are available all over the world from polar orbiting satellites. Also, unlike AT over the oceans, projections of SST are readily available for a range of emissions scenarios put forward by the Intergovernmental Panel on Climate Change (IPCC 2007).

Consequently, in this Chapter I tested the extent to which SST can be used as a proxy indicator of sand temperature and its proficiency as a predictor of sand temperature against *in situ* measurements of AT. I then used the relationship between a combined AT and SST model and sand temperature to project nest temperatures at the selected nesting grounds and hence improve our understanding of the likely impacts of global warming on sea turtles in the region. To understand the variability of sand temperature at each nesting ground and the necessity of developing multiple models to predict sand temperature I also investigated how beach orientation, shading and the location of nests in relation to the high water mark influences incubation temperatures. In addition, I reconstructed sand temperature to investigate whether sand temperature at the selected nesting beaches have already started to increase. The results are discussed in light of the adaptive capacity of sea turtles as well as options currently available to resource managers.

3.3. Methods

3.3.1. Sand temperature data

Sand temperature was recorded every hour at the study sites from November 2006 to January 2009 (sampling period varied between sites- see Table 3.1) using Tinytag TK-4014 data loggers (Hasting Data Loggers, Port Macquarie, Australia). The sampling period encompasses the nesting period and embryonic development for sea turtles at each nesting ground. All data loggers were calibrated before and after deployment against a mercury thermometer and had an accuracy of ± 0.1°C. Data loggers were located in representative nesting areas and deployed at a standard depth of 50 cm, which is close to green turtles average nest depth (as per Spotila and Standora et al. 1987; Hewavisenthi and Parmenter 2002; Matsuzawa et al. 2002; Van de Merwe et al. 2006) and also the standard depth adopted by research and government agencies in Australia. I deployed loggers in all types of nesting habitat used at each nesting ground (e.g. shaded and open areas, different beach orientation, etc. - Table 3.1).

Table 3.1. Summary of sampling effort at each of the selected nesting grounds for the northern Great Barrier Reef green turtle population. * Data loggers that were lost or disturbed by nesting turtles.

Site	Total loggers	Orientation	Shading	Duration	Number of measurements (per logger)
Bramble Cay	4	North (1), east (1*), south (1*) and west (1*)	Open	April 07- November 08	14352
Dowar Island	7	North (4) and South (3)	Open and shaded	November 06 - November 08	17904
Milman Island	5	North (2), east (1), south (1) and west(1)	Open and shaded	November 06 - January 09	19344
Moulter Cay	4	North (1) east (1), south (1) and west (1)	Open	May 07- May 08	9312
Raine Island	4	North (1), east (1*), south (1*) and west(1*)	Open	November 07- November 08	9312
Sandbank 8	2	North (1) and South (1)	Open	May 07- May 08	9312
Sandbank 7	2	North (1) and South (1)	Open	May 07- May 08	9312

3.3.2. Meteorological data

Air temperature data for Bramble Cay, Milman Island and Moulter Cay were obtained from calibrated Tinytag TK-4014 data loggers (Hasting Data Loggers, Port Macquarie, Australia) deployed according to requirements by the Australian Bureau of Meteorology (see Canteford 1997). Air temperature data for Sandbank 7 and 8 were obtained from the Australian Bureau of Meteorology (BOM) weather station at Coen airport (less than 100km from Sandbank 7 and 8). Air temperature data for the remaining nesting grounds were obtained from the International Comprehensive Ocean Atmosphere Data Sets (ICOADS) (http://www.cdc.noaa.gov/coads). ICOADS is an extensive dataset which provides various meteorological data for all oceans of the world since 1854 and has been used by other similar studies (e.g. Hays et al. 2003; McMahon and Hays 2006). Data from ICOADS was only used for months for which more than 10 observations were recorded (as in Hays et al. 2003).

Sea surface temperature for all the nesting grounds, except for Sandbank 7 and 8, was obtained from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua spacecraft. Approximately 2,900 spatially-extracted MODIS-Aqua Level-2 SST files containing all or part of each nesting ground were acquired from the NASA Ocean Biology Processing Group (McClain et al. 2006). Only the night time series was used, which contains 11-μm (thermal infrared) SST measurements (Minnett et al. 2004) made from February 2005 to February 2008 at ~1 km^2 spatial resolution. Quality-control metrics were applied to the SST retrievals and only pixels with a quality level ≤ 2 were retained (on a scale of 0 to 4, with 4 being completely unusable), thereby eliminating measurements with extreme viewing geometries (> 75 degrees), with high degrees of spatial inhomogeneity, or outside physically realistic ranges of SST (e.g. < -2 °C or > 45 °C). For each satellite file, the mean of all remaining pixels within a 3x3 pixel box centred on each *in situ* target (e.g. nesting grounds) was recorded. Data gaps were back-filled unless more than 7 days long (see Maynard et al. 2008) and monthly average temperatures were used in regression analyses. Sea surface temperature data for Sandbank 7 and 8 were obtained from the Commonwealth Scientific and Industrial Research Organisation in Australia (CSIRO).

Historical AT and SST for each nesting beach were also obtained from ICOADS. Since I only used data for months where more than 10 observations were recorded I could only reconstruct nest temperature for the past eighteen years and for Bramble Cay, Milman Island and Moulter Cay. ICOADS dataset is sparse prior to 1990 and not available for the other remote sites

3.3.3. Analysis

3.3.3.1. Variation in sand temperature and current thermal profiles

To investigate if sand temperature varies as a function of beach orientation and shading I used sand temperature from five sites: Dowar Island, Milman Island, Moulter Cay, Sandbank 8 and Sandbank7, during the 2007/2008 nesting season (November to April). I could not use loggers deployed at Raine Island and Bramble Cay since some of the data loggers deployed at these locations were disturbed and misplaced by nesting turtles. I also investigated if sand temperature significantly changed across the beach profile (berm to back dune -5 to 40 m from high water mark) by recording sand temperature across a beach profile transect at south Dowar Island during 3 days in February 2008 (72 measurements).

Sand temperature data were tested for normality and equal variance to ensure they met assumptions for parametric statistics. The data met all the assumptions and therefore a series of independent one-way ANOVA tests were used to investigate the differences in sand temperature at each nesting beach with respect to orientation, shading and profile and between the different nesting grounds (during the 2007/2008 nesting season- November 2007 to April 2008). When a significant difference was found post hoc testing (least significant difference -LSD) was conducted to identify which groups were significantly different.

3.3.3.2. Predicting sand temperature

Regression analyses were used to determine the relationship between mean monthly sand temperature at our study sites and mean monthly SST and AT. Three linear regression models were used to predict sand temperature: (1) SST only, (2) AT only and (3) SST and AT. The fit of these three models were compared using the Akaike Information Criterion (AIC). AIC is a model selection tool that quantifies the relative goodness-of-fit of various previously derived statistical models (Hurvich and Tsai 1989, Burnham and Anderson 2004). A corrected AIC (AICc) was used on our study - as suggested by Burnham and Anderson (2004) - since our sample size is small ($n < 40$) (as used in Johnson and Omland 2004, Cinner et al. 2009). As individual AIC values are affected by sample size, AICc values were rescaled using the following equation:

$$\Delta i = AICi - AICmin$$

Where Δi represents the loss of information from using model "i" instead of the best fit model (best model has $\Delta i = 0$), and AICmin is the minimum of the different AICi values (Burnham and Anderson 2004). Support for each model is thus quantified based on these Δi values, where models with values ≤ 2 have substantial support, values between 4 and 7 indicate some support and values >10 no support (Burnham and Anderson 2004). The AICc weight (wi)- which reflects the relative likelihood of each model being the best fitting model among those considered - was also calculated for each model (Burnham and Anderson 2004).

After the best model was selected for each nesting ground sand temperatures for 2030 and 2070 were predicted based on 'conservative'- B1 emission scenario (IPCC 2007) - and 'extreme' -A1T emission scenario (IPCC 2007 – as explained in Chapter 1) - air and sea surface temperatures projected by the Commonwealth Scientific and Industrial Research Organisation in Australia (CSIRO 2007; IPCC 2007; Table 3.2). During the incubation of eggs there is an increase in sand temperature caused by metabolic heating from developing embryos (Booth and Astill 2001; Broderick et al. 2001; Booth and Freedan 2006; Chu et al. 2008) therefore we added an estimation of metabolic heating for green turtles for the region (Booth and Astill 2001, 0.5 °C) to the current thermal profile at each nesting beach and predicted sand temperatures to calculate nest temperature during the middle third of incubation for each time period (as per Hays et al. 2003; Hawkes et al. 2007 b).

The pivotal temperature for the nGBR green turtle population has been previously measured at 29.3 °C (Limpus 2008 b) and therefore sand at this temperature during the middle third of incubation produces 50% females and 50% males. As no data exist delimiting the full transitional range of temperature (TRT) for this population, I assumed the TRT to be 3 °C wide centred around the pivotal temperature as suggested by Mrosovsky (1994). Considering this, I assumed that temperatures below 27.8 °C produced all males, above 30.8°C produced all females and that the proportion of females increased linearly between 27.8 °C and 30.8 °C.

Table 3.2. Projected regional increases in air, sea surface and sand temperature, under conservative (based on B1 emission scenario of the IPCC 2007) and extreme (based on A1T emission scenario of the IPCC 2007) scenarios (CSIRO 2007).

Year	Scenario	Projected increase in SST (◦C)	Projected increase in AT (◦C)
2030	Conservative	0.3	0.7
2030	Extreme	0.6	1.2
2070	Conservative	1.2	1.8
2070	Extreme	1.5	3.4

3.4. Results

3.4.1. Current thermal profile

Sand temperature was significantly different across the various nesting grounds (One way ANOVA, $P < 0.00$, $DF = 11$, $F = 221.9$), with the west facing beach at Milman Island having the coolest temperatures and the north facing beach at Dowar Island having the warmest temperatures during the 2007/2008 nesting season (Figure 3.1).

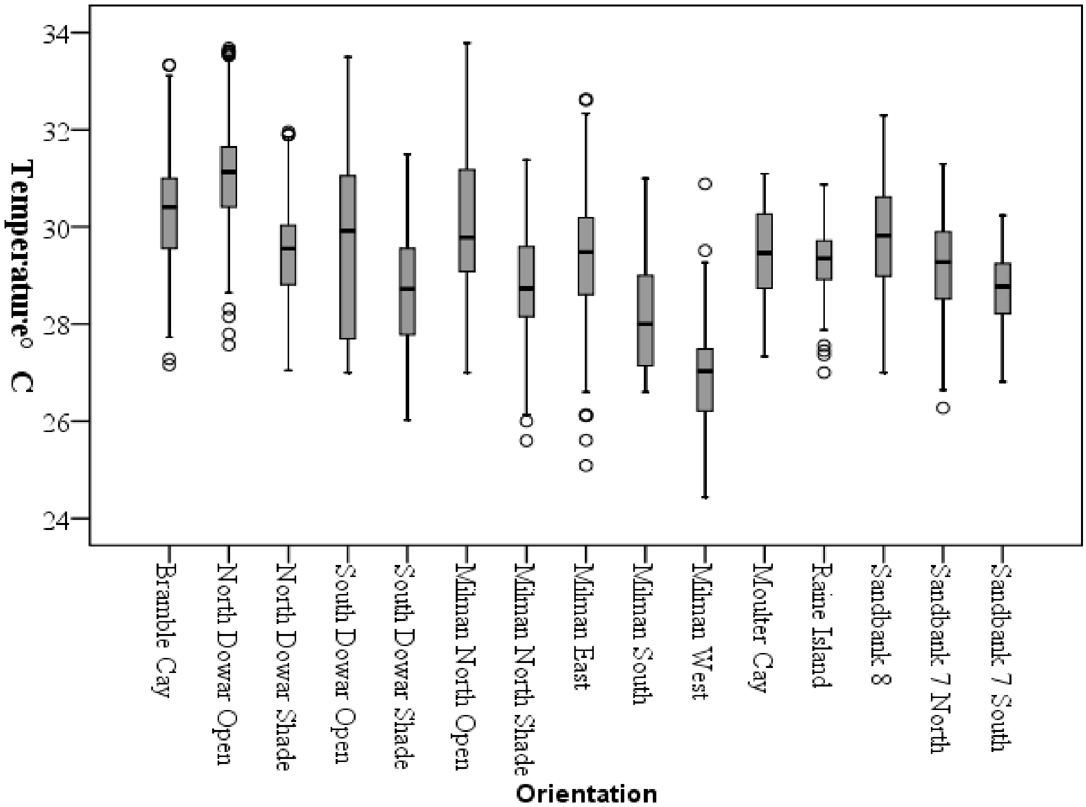

Figure 3.1. Comparison of the thermal profile for each of the selected nesting grounds used by the northern Great Barrier Reef green turtle population during the 2007/2008 nesting season.

No pattern was found between the latitude of each nesting ground and their thermal profile (Figure 3.2).

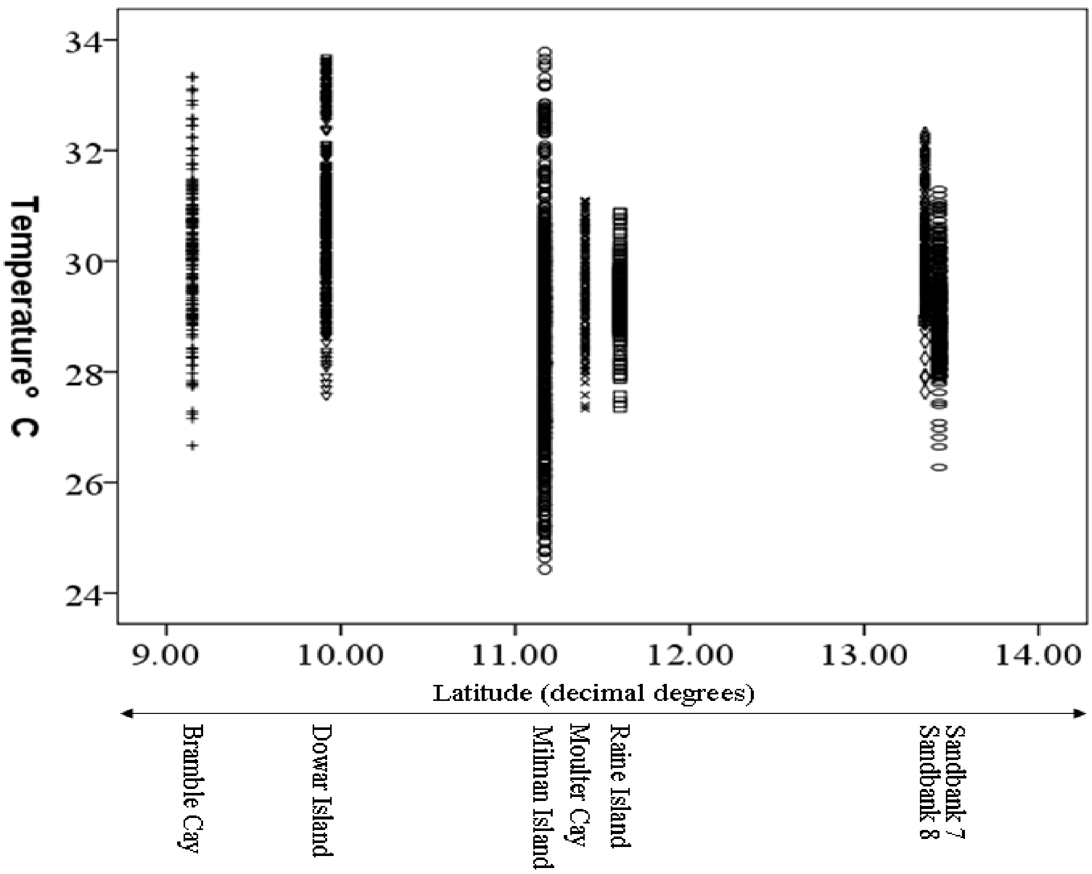

Figure 3.2. Comparison of the temperature range found at each nesting ground used by the northern Great Barrier Reef green turtle population during the 2007/2008 nesting season across their different latitudinal range.

3.4.1.1. Current hatchling production

The thermal profile during the 2007/2008 nesting season indicates that Bramble Cay and north (open and shaded) and south Dowar Island (open), north and east (open) Milman Island, Moulter Cay and Sandbank 8 are producing mainly female hatchlings, with 74%, 93%, 65%, 73%, 60%, 56%, and 82% of their temperatures during the 2007/2008 nesting season, respectively, above the pivotal temperature. In contrast, the west and south facing beaches at Milman Island, the south (shaded) facing beach at Dowar Island, south Raine Island and south Sandbank 7 are producing mainly males, with 98%, 86%, 67%, 52%, 80% of their temperatures during the 2007/2008 nesting season, respectively, below the pivotal temperature (Figure 3.3).

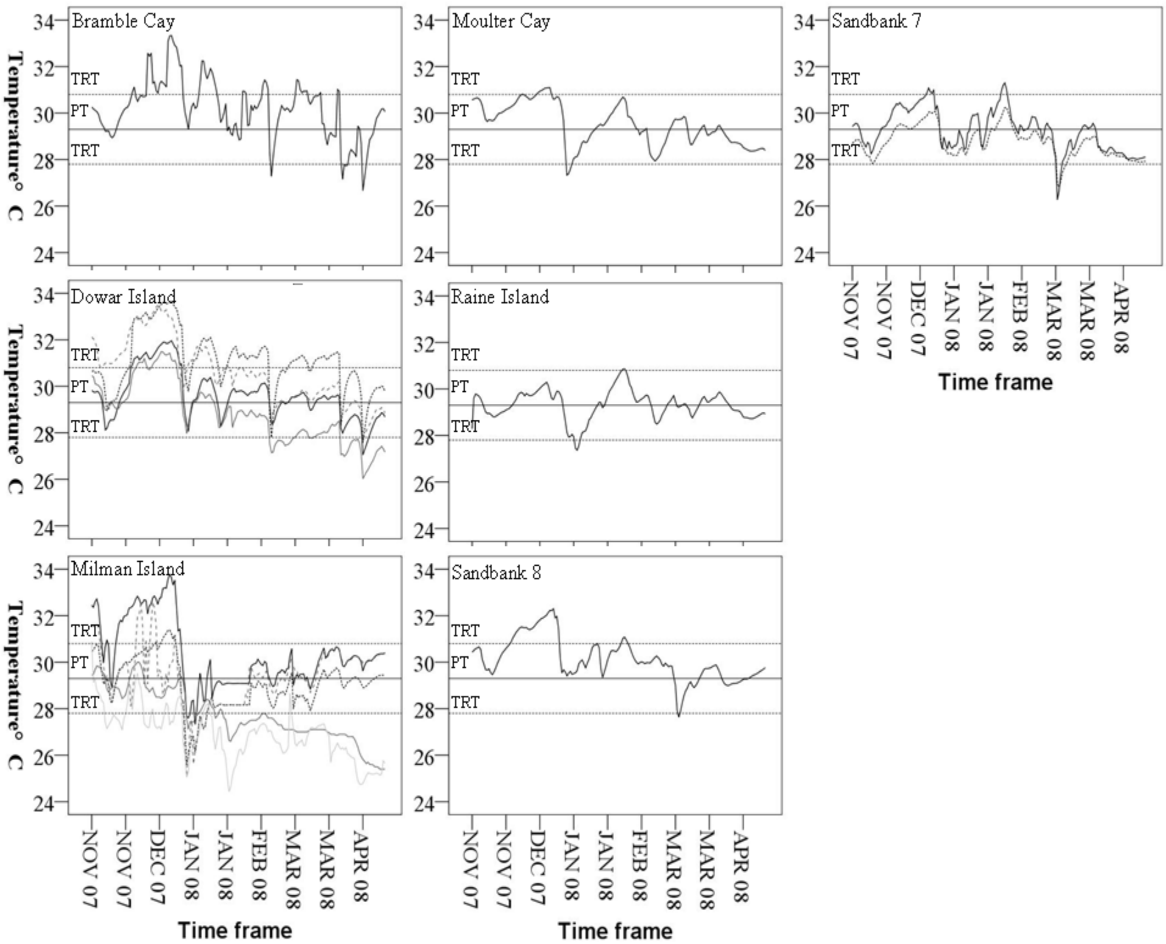

Figure 3.3. Thermal profile for the key nesting grounds used by the northern Great Barrier Reef green turtle population during the 2007-2008 nesting season. Pivotal temperature (PT) refers to the temperature where a 50:50 male to female sex ratio is produced and transitional range temperature (TRT) is the range of temperature where sex ratio shifts from all male to all females. North open, North Shade, South open, South shade, West open, East open (only for Milman Island).

3.4.1.2. Variation of sand temperature within the nesting grounds

Sand temperature varied as a function of beach orientation, north facing beaches were generally warmer than south facing beaches (median difference 0.8 °C and range 0.4 to 1.2 °C) at Dowar Island, Milman Island and Sandbank 7 (Figure 3.4). No significant difference was found across the different beach orientations at Moulter Cay and Sandbank 8 (Figure 3.4).

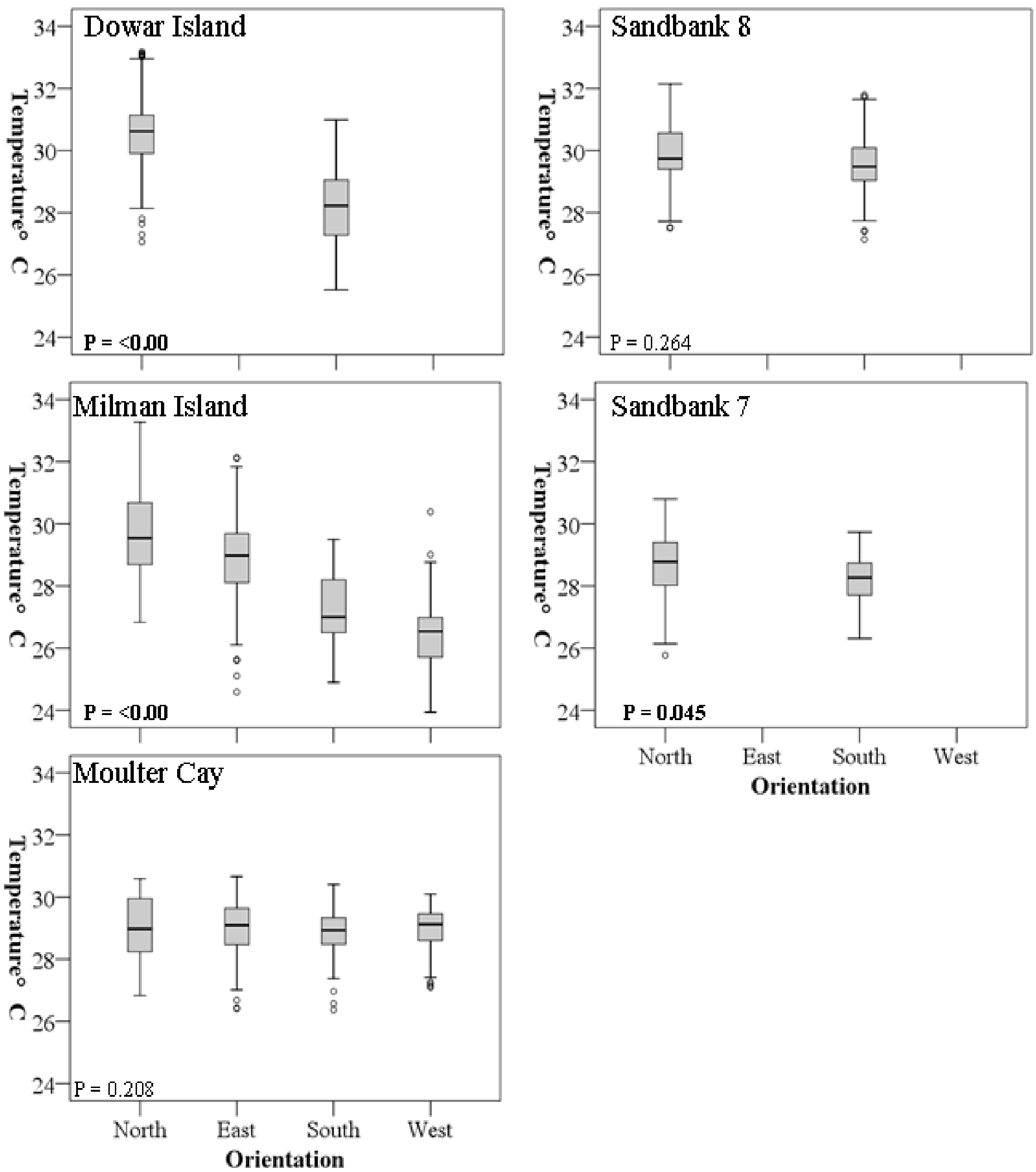

Figure 3.4. Comparison of sand temperature at different beach orientations for the selected nesting grounds used by the northern Great Barrier Reef green turtle population during the 2007-2008 nesting season. Bold indicates a significant difference in sand temperature between the different profiles.

Sand temperature was significantly cooler at sites with full shade (One way ANOVA, P < 0.00, DF = 2190, F = 598.2), with the shaded sand being on average of 1.3 ± 0.05 °C (± SE), 1.9 ± 0.05 °C (± SE) and 0.7 ± 0.07 °C (± SE) cooler at North Dowar Island, South Dowar Island and Milman Island, respectively (Figure 3.5 and Table 3.5).

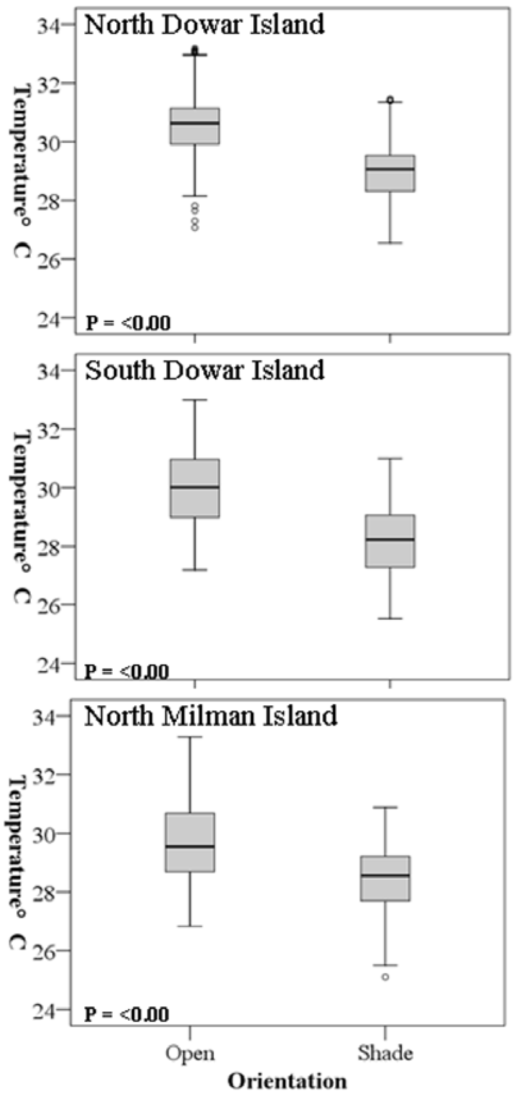

Figure 3.5. Comparison of sand temperature at open and shaded areas for selected nesting grounds used by the northern Great Barrier Reef green turtle population during the 2007-2008 nesting season.

Sand temperature significantly increased across the beach profile away from the sea (One way ANOVA, $P < 0.00$, $DF = 282$, $F = 6456.1$, Post- Hoc Test - LSD- all $P < 0.00$) (Figure 3.6), with an average increase of 1.7 ± 0.03 °C from the beach berm to the back dune.

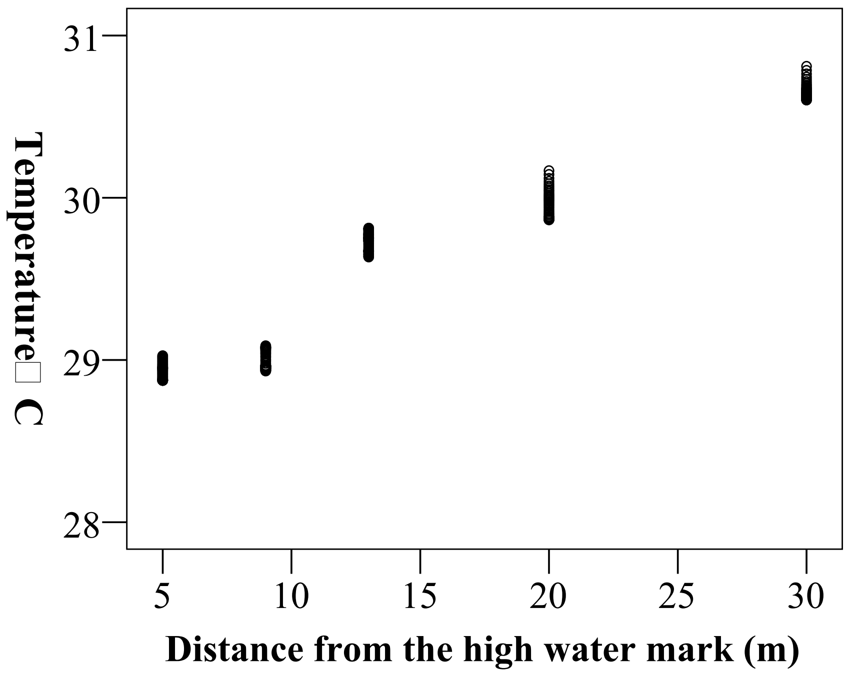

Figure 3.6. Sand temperatures across a beach profile at South Dowar over 3 days during February 2008.

3.4.2. Regression Analyses

Both sea surface temperature and air temperature are strongly correlated with sand temperature at our study sites, during the survey years (Table 3.3). Air temperature was more strongly correlated with sand temperature at most of the nesting environments than sea surface temperature alone (Table 3.3). However, a combination of SST and AT best explained sand temperature, with more than 50% ($r^2 > 0.50$) of the variability explained at all nesting grounds and environment, except for Dowar Island (north – open; south - shade) (Table 3.3). As the AICc Δi values are lower than two for more than one model at each environment (Table 3.3), there is no substantial support for "a best" model. However, the AICc, AICc weight (wi) and r^2 values indicated that the model that best describes sand temperature at all nesting beaches is a combination of SST and AT (Table 3.3).

Table 3.3. Comparison of candidate models to describe sand temperature at each nesting ground. Bold indicates models with the best fit (lowest AICc values and highest AICc weight and r^2).

Site	Environment	Variable	r^2	AICc	AICc Δi	AICc weight (*wi*)
Bramble Cay	**North - open**	**SST+AT**	**0.79**	**3.12**	**0.00**	**43.19%**
Bramble Cay	North - open	SST	0.69	3.55	0.43	25.74%
Bramble Cay	North - open	AT	0.78	3.39	0.27	31.08%
Dowar Island	**North - open**	**SST+AT**	**0.51**	**3.14**	**0.00**	**35.29%**
Dowar Island	North - open	SST	0.21	3.18	0.04	33.46%
Dowar Island	North - open	AT	0.24	3.24	0.10	31.25%
Dowar Island	**North - shade**	**SST+AT**	**0.45**	**3.09**	**0.00**	**36.80%**
Dowar Island	North - shade	SST	0.14	3.15	0.16	30.46%
Dowar Island	North - shade	AT	0.26	2.99	0.10	32.73%
Dowar Island	**South - open**	**SST+AT**	**0.50**	**3.05**	**0.00**	**48.89%**
Dowar Island	South - open	SST	0.20	3.72	0.67	21.99%
Dowar Island	South - open	AT	0.19	3.48	0.43	29.12%
Dowar Island	**South- shade**	**SST+AT**	**0.45**	**2.79**	**0.00**	**44.31%**
Dowar Island	South- shade	SST	0.02	3.33	0.53	23.44%
Dowar Island	South- shade	AT	0.24	3.06	0.26	32.25%
Milman Island	**North- open**	**SST+AT**	**0.57**	**4.03**	**0.00**	**41.12%**
Milman Island	North- open	SST	0.36	4.50	0.48	23.26%
Milman Island	North- open	AT	0.56	4.15	0.12	35.62%
Milman Island	**North - shade**	**SST+AT**	**0.64**	**2.88**	**0.00**	**44.50%**
Milman Island	North - shade	SST	0.29	3.68	0.79	17.16%
Milman Island	North - shade	AT	0.54	3.01	0.12	38.34%
Milman Island	**East – open**	**SST+AT**	**0.56**	**3.28**	**0.00**	**50.29%**
Milman Island	East – open	SST	0.21	4.08	0.80	19.21%
Milman Island	East – open	AT	0.29	3.70	0.42	30.50%
Milman Island	**South - open**	**SST+AT**	**0.89**	**2.58**	**0.00**	**59.69%**
Milman Island	South - open	SST	0.39	4.35	1.76	7.15%
Milman Island	South - open	AT	0.80	3.07	0.49	33.16%
Milman Island	**West - open**	**SST+AT**	**0.69**	**3.10**	**0.00**	**44.17%**
Milman Island	West - open	SST	0.40	3.74	0.76	17.76%
Milman Island	West - open	AT	0.67	2.98	0.12	38.07%
Moulter Cay	**North - open**	**SST+AT**	**0.94**	**4.00**	**0.00**	**71.64%**
Moulter Cay	North –open	SST	0.66	9.87	5.87	0.06%
Moulter Cay	North – open	AT	0.90	4.77	0.77	28.30%
Raine Island	**South – open**	**SST+AT**	**0.84**	**2.73**	**0.00**	**35.35%**
Raine Island	South – open	SST	0.80	2.76	0.03	34.29%
Raine Island	South – open	AT	0.76	2.86	0.13	30.35%
Sandbank 8	**North - open**	**SST+AT**	**0.76**	**1.18**	**0.00**	**37.84%**
Sandbank 8	North - open	SST	0.57	1.17	0.16	31.12%
Sandbank 8	North - open	AT	0.47	1.01	0.17	31.04%
Sandbank 7	**North - open**	**SST+AT**	**0.83**	**2.97**	**0.00**	**81.81%**
Sandbank 7	North - open	SST	0.46	4.90	1.93	8.12%
Sandbank 7	North - open	AT	0.73	3.15	1.75	10.07%
Sandbank 7	**South - open**	**SST+AT**	**0.76**	**2.83**	**0.00**	**50.82%**
Sandbank 7	South - open	SST	0.36	4.34	1.51	8.33%
Sandbank 7	South - open	AT	0.57	3.01	0.18	40.86%

The combined SST and AT model was used to predict sand temperature - for 2030 and 2070 – for all nesting grounds as this model best described the sand temperature for the study region. For description of models used see Table 3.4.

Table 3.4. Models used to predict sand temperature at each nesting ground.

Site	Environment	Model used to project sand temperature	r^2
Bramble Cay	North - open	Sand temperature = [(SST* -0.029) + (AT* 0.991) + 2.786]	0.79
Dowar Island	North - open	Sand temperature = [(SST* -0.1) + (AT* 0.519) + 18.836]	0.51
Dowar Island	North - shade	Sand temperature = [(SST* 0.106) + (AT* 0.3) + 17.995]	0.45
Dowar Island	South - open	Sand temperature = [(SST* -0.759) + (AT* 1.249) + 14.553]	0.50
Dowar Island	South- shade	Sand temperature = [(SST* -0.538) + (AT* 1.007) + 14.747]	0.45
Milman Island	North- open	Sand temperature = [(SST* 0.122) + (AT* 0.876) + 0.736]	0.57
Milman Island	North - shade	Sand temperature = [(SST* -0.043) + (AT* 0.748) + 7.938]	0.64
Milman Island	East - open	Sand temperature = [(SST* -0.487) + (AT* 0.95) + 15.191]	0.56
Milman Island	South - open	Sand temperature = [(SST*-0.578) + (AT* 2.032) -14.119]	0.89
Milman Island	West - open	Sand temperature = [(SST* 0.054) + (At* 0.763) + 4.106]	0.69
Moulter Cay	North - open	Sand temperature = [(SST*-0.236) + (AT* 1.022) + 6.915]	0.94
Raine Island	South – open	Sand temperature = [(SST* -1.2) + (AT* 0.784) + 40.564]	0.84
Sandbank 8	North - open	Sand temperature = [(SST* 0.083) + (AT* 0.446) + 14.929]	0.76
Sandbank 7	North - open	Sand temperature = [(SST* -0.007) + (AT* 0.604) + 11.893]	0.83
Sandbank 7	South - open	Sand temperature = [(SST*0.006) + AT * 0.450) + 15.351]	0.76

Since the AICc Δi values did not indicate a single 'best' model to describe sand temperature at each site but only the model that best described sand temperature, a two tailed paired-sample T-test was conducted between the generated sand temperature from all three different models for all sites to investigate whether the selected models improved our projections. The significant difference between the predicted sand temperatures when using different models (all Two tailed paired sample T-test had values lower than 0.009) - under both climate change scenarios and years – indicate that the models selected, a combine AT and SST, provide an improved model prediction and an increase in statistical confidence when compared to the other models.

3.4.3. Reconstructed thermal profile

For the past 18 years there has been no changes in the mean monthly sand temperature at Bramble Cay (north), Milman Island and Moulter Cay (Figure 3.7) (Regression, $P = 0.48$, $r = 0.07$, $F = 0.5$; $P = 0.76$, $r = 0.03$, $F = 0.09$; $P = 0.82$, $r = 0.02$, $F = 0.05$; respectively).

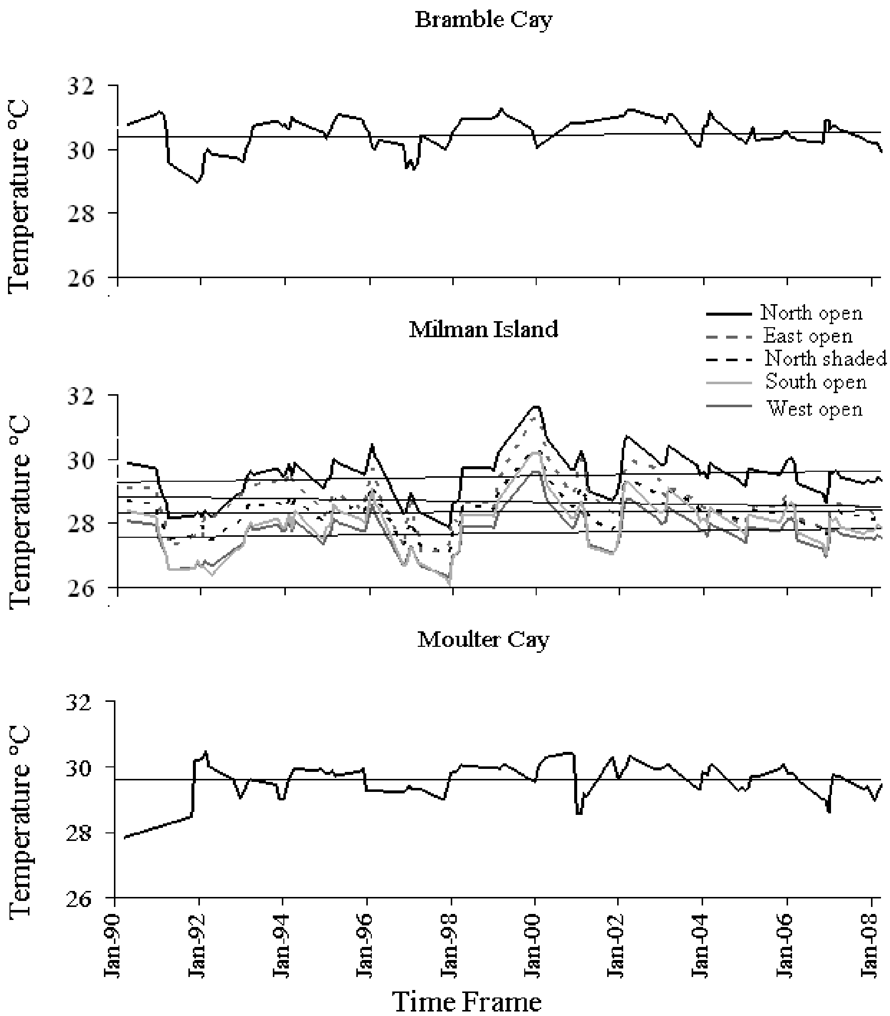

Figure 3.7. Reconstructed mean monthly (November- April) sand temperature for nesting grounds used by the northern Great Barrier Reef green turtle population. Lines represent best fitting line. . North open, North shade, East open, South open, West open.

3.4.4. Future thermal profile

With the projected increase in air and sea surface temperatures (see IPCC, 2007) sand temperatures will also rise and consequently cause a reduction in the production of male hatchlings. My models indicate that by 2030 almost no male hatchling will be produced at Bramble Cay and at open areas at the northern facing beach at Dowar Island, since these nesting grounds will only experience temperature above the pivotal temperature and near the upper transient range temperature (30.8 °C).

All the other locations will be producing different proportions of male and female hatchlings (Table 3.5). By 2070, under an extreme scenario of climate change only west Milman Island, south Raine Island and south Sandbank 7 will have temperatures that produce male hatchlings. Additionally, Bramble Cay, the northern and southern facing beaches at north Dowar and Milman Islands will regularly incubate at temperatures near/above the maximum thermal threshold (Table 3.5) increasing hatchlings abnormalities and decreasing hatching success.

Table 3.5. Current and modelled mean sand temperature (◦C) during nesting season (November to April) for each of the selected nesting grounds under conservative and extreme climate change scenarios for 2030 and 2070.

Site	Environment	2007/2008 Current	2030 Conservative	2030 Extreme	2070 Conservative	2070 Extreme
Bramble Cay	North - open	30.4 ± 0.09	30.9 ± 0.210	31.4 ± 0.210	32.1 ± 0.300	33.7 ± 0.300
Dowar Island	North - open	31.1 ± 0.009	31.6 ± 0.070	31.9 ± 0.070	32.1 ± 0.070	32.9 ± 0.070
Dowar Island	North - shade	29.6 ± 0.008	30.2 ± 0.080	30.4 ± 0.080	30.6 ± 0.080	31.2 ± 0.080
Dowar Island	South - open	29.9 ± 0.010	30.1 ± 0.220	30.7 ± 0.220	30.8 ± 0.220	32.5 ± 0.220
Dowar Island	South- shade	28.8 ± 0.090	29.5 ± 0.160	29.9 ± 0.160	30.0 ± 0.160	31.5 ± 0.160
Milman Island	North- open	30.0 ± 0.050	30.3 ± 0.040	30.7 ± 0.040	31.3 ± 0.04	32.7 ± 0.020
Milman Island	North - shade	28.8 ± 0.010	29.0 ± 0.030	29.4 ± 0.030	29.8 ± 0.03	30.9 ± 0.040
Milman Island	East - open	29.4 ± 0.030	29.6 ± 0.030	29.9 ± 0.030	30.3 ± 0.030	31.6 ± 0.030
Milman Island	South - open	28.3 ± 0.04	29.3 ± 0.031	30.1 ± 0.031	30.9 ± 0.031	33.9 ± 0.031
Milman Island	West - open	26.9 ± 0.010	28.3 ± 0.030	28.7 ± 0.020	29.3 ± 0.030	30.5 ± 0.020
Moulter Cay	North - open	29.4 ± 0.060	30.2 ± 0.010	30.7 ± 0.010	31.2 ± 0.020	32.7 ± 0.020
Raine Island	South- open	29.0 ± 0.040	29.6 ± 0.250	29.9 ± 0.250	30.2 ± 0.250	30.8 ± 0.250
Sandbank 8	North - open	29.5 ± 0.070	29.8 ± 0.300	30.0 ± 0.300	30.5 ± 0.300	31.2 ± 0.300
Sandbank 7	North - open	28.8 ± 0.050	29.3 ± 0.370	29.7 ± 0.370	30.1 ± 0.370	31.0 ± 0.370
Sandbank 7	South - open	28.2 ± 0.070	28.8 ± 0.280	29.0 ± 0.280	29.3 ± 0.280	30.0 ± 0.280

3.5. Discussion

3.5.1. Current thermal profile

Sand temperature varied greatly between and within the nesting grounds, reflecting a high level of complexity and variability in thermal profiles. Nevertheless, some patterns in sand temperature were observed at my study sites. Northern facing beaches were found to continually experience warmer incubating environments than beaches at other orientations. Similar observations have been made at other Great Barrier Reef nesting grounds and have been attributed to northern beaches' exposure to solar radiation (Limpus et al. 1983; Booth and Freeman 2006). My study also found warmer temperatures at beach dunes; however this pattern may be different at other beaches that have dune vegetation as vegetation may act as insulation.

By nesting at nesting grounds with a wide range of thermal profiles, nesting turtles ensure that both male and female hatchlings are produced. However, my results suggest a likely bias towards female hatchling production because the majority of nesting grounds, including two of the most important nesting grounds for this population (Moulter Cay and Bramble Cay), are producing mainly females. To confirm this, further investigation on the sex ratio of hatchlings being produced at Raine Island and Bramble Cay, where data from only one data logger was available, will be necessary, as will generating information on the variation of sand temperature found at these sites. Nevertheless, for the past 20 years, female-biased sex ratios of immature and adult turtles have been observed widely at green turtle foraging grounds in Australia (Heithaus et al. 2005; Limpus 2008 b). The only exception to this generalization has been the male biased adult sex ratios recorded at sites in the southern Great Barrier Reef that are both foraging and courtship areas (Chaloupka and Limpus 2001; Limpus 2008 b). Indeed, a female bias has been commonly reported for different sea turtle species and nesting grounds (e.g. Mrosovsky and Provancha 1992; Booth and Astill 2001; Godley et al. 2001) with populations appearing to function successfully with 1:2 or 1:3 male to female ratio (Hamann et al. 2007).

3.5.2. Predictive regression models

For the selected nesting grounds a combined AT and SST model best predicts sand temperature. Indeed, spatial variation in the capacity of AT, and SST, to predict sand temperature at my sites was high enough to suggest that the efficiency of combined models should at least be explored for other locations. Previous studies that have only included AT to drive model projections (e.g. Hays et al. 1999, 2003, Hawkes et al. 2007 b), would likely have benefited, with respect to the accuracy of projections, from the incorporation of high resolution SST data. Certainly a structured selection process - to decide which meteorological variable (s) to incorporate in projecting models - would aid the selection of the best fitting model for a particular nesting ground. If such a process is undertaken, projections made will be as accurate as possible and, therefore, best assess the likely impacts of global warming on the subject sea turtle population.

Since sand temperature is dependent on the interaction of many variables, including numerous descriptors of the sand itself there could still be room for improvement of the models trialled here by incorporating other variables, such as sand colour and topography. An example of this is the novel approach by Mitchell et al. (2008) to develop a mechanistic model that shows how climate, soil and topography interact with physiology and nesting behaviour to determine sex ratios.

3.5.3. Future thermal profiles

My models predict that climate change will increase sand temperature at the nesting grounds studied, resulting in increased feminization of annual hatchling output into this population by 2030. Climate change-related feminization of turtle populations has also been predicted for other nesting grounds, such as Cape Canaveral and Bald Head Island, North Carolina, USA (see Hawkes et al. 2007 b). Predictions are even bleaker for 2070, when some of the nesting grounds used by the nGBR green turtle population will experience temperatures near or above the upper thermal incubating threshold and likely cause a decrease of hatchling success. All projections presented here are likely to vary slightly since our models used sand temperatures from a standard depth and did not account for variation in nest depth. Similarly, we were unable to account for variation in sand temperature from aperiodic rainfall and cyclonic events (as observed by Reed 1980 and Houghton et al. 2007). Regardless, the results presented here provide a broad scale indication of the likely future temperature at each nesting site (as per other studies, see Janzen 1994; Hays et al. 1999, 2003; Glen and Mrosovsky 2004; Hawkes et al. 2007 b).

If the nGBR green turtle population is not able to adapt to predicted increase in sand temperatures there will be ecological implications for the region as well as social and cultural impacts. For example, under the *Native Title Act* 1993 indigenous Australians (Aboriginal and Torres Strait Islander people who are descendents of the tribe or ethnic group that occupied a particular region before European settlement) are given the legal right to hunt turtles for traditional purposes and, therefore, Torres Strait Islanders still rely on sea turtles for food and as a cultural symbol during social gatherings and ceremonies (see Johannes and Macfarlane 1991 and Limpus et al. 2003). Thus, a potential decline in this stock could greatly impact indigenous Australians.

The mechanisms through which sea turtles may adapt to increased temperatures include: (1) changing the distribution of their nesting grounds, nest-site choice and nest depth (Hays et al. 2001; Limpus 2006); (2) adapting *in situ* by adjusting their pivotal temperature (Davenport 1989; Hawkes et al. 2007 b); and (3) shifting nesting to cooler months (Hays et al. 2003; Weishampel et al. 2004; Pike et al. 2006). Earlier nesting has already been observed for several populations of turtles as a response to current climatic warming (e.g. Weishampel et al. 2004; Pike et al. 2006; Tucker et al. 2008). However, shifts in nesting phenology are thought to be insufficient to counteract the negative effects of global warming on the sex ratio of freshwater turtle offspring since increase in temperature is found to have a much stronger influence on nest sex ratios than earlier nesting (Schwanz and Janzen 2008). Similarly, Morjan (2003) suggests that changes in nest-site choice, as an adaptation response, can not quickly offset the effects of climate change on sex ratio of freshwater turtles because it is likely to evolve more slowly than threshold temperatures and female turtles have low potential to adaptively adjust sex ratios through nest-site choice. Further, Janzen (1994) uses genetic analysis and behavioural data to suggest that species with temperature-dependent sex determination (TSD), such as sea turtles, may be unable to evolve fast enough to counter the negative effects of global warming.

However, it is important to note that throughout the millions of years that sea turtles have existed they have demonstrated to have a biological capacity to adapt to climate change. During their existence, sea turtles have persisted through dramatic changes in climate (temperature and sea level rise) (Hamann et al. 2007; Hawkes et al. 2009) and adapted by re-distributing their nesting sites and developing new migratory routes (Limpus 2008 a). For example, current nesting grounds for flatback turtles, *Natator depressus*, were inaccessible to sea turtles 12,000 years ago and past nesting grounds near the edge of the continental shelf are now flooded and no longer exist (Limpus 2008 a). Similarly, Raine Island has developed as a green turtle nesting beach only in the last few thousand years (Limpus 1987, 2008 a). It is important to note, however, that predicted climate change impacts are expected to occur at a much more accelerated rate than historical changes (Brohan et al. 2006; IPCC 2007).

Adaptation by turtles, through changes in the spatial distribution of nesting grounds, can occur in the short term when first time breeders choose their nesting sites (Hamann et al. 2007). If nesting habitat is unsuitable, turtles may choose alternative nesting sites to the ones they were born. If this happens, a degraded nesting beach could be effectively abandoned within one turtle generation- 40 years (Hamann et al. 2007). However, changes in nesting phenology are more likely to occur in a longer time frame as progressive selection across several generations take place (Limpus 2008 a). Clearly, investigating the extent to which different sea turtle species can or will exhibit any of the adaptive responses described here and determining whether the responses can counteract predicted impacts of global warming both represent fruitful areas of future research.

Further constraints for sea turtles to adapt include cumulative impacts of anthropogenic threats and restriction of alternative habitats. Sea turtle populations are now impacted by a range of anthropogenic activities (see Johannes and Macfarlane 1991; Harris et al. 2000; Lutcavage 2003; Moore et al. 2009). Consequently, their resilience and capacity to adapt at a population level to climate change is thought to be lower than in the past (Hamann et al. 2007). Therefore, precautionary actions and adaptive management may be necessary to mitigate the predicted impacts from climate change and to ensure that sea turtles have a more realistic opportunity to adapt. Managers may choose to protect important male-producing regions to promote future population viability (Booth and Astill 2001; Hawkes et al. 2007 b), or use more manipulative methods such as modifying the sand temperature (through artificial shading, vegetation cover, sprinkling cool water) on nesting beaches to maintain temperatures within the thermal tolerance for the species' incubation (Naro-Maciel et al. 1999). Relocating nests to more suitable incubating environments may also be an option (see Chapter 7, Table 7.6). For the nGBR green turtle population we suggest that management efforts should focus on Raine Island and Moulter Cay (because 90% of nesting for this population occurs at these sites) and also on Milman Island and Sandbank 7 (because, from the studied nesting grounds, they have the coolest thermal profiles). A strategy for Bramble Cay and Dowar Island, where egg collection occurs, may be to allocate warmer areas for egg harvest (e.g. open areas in the top dune at northern facing beaches) and limit harvest at regions that are cooler and produce males. In the future, as nesting grounds experience temperatures above the thermal threshold more often, harvest of eggs in known warmer areas may be a great management strategy for places, such as the nesting beaches in Torres Strait, where egg harvest is allowed as a cultural tradition. It is also important that the future suitability of the other minor nesting grounds used by this population and coastal areas in northern Australian be investigated to identify areas that may potentially serve as functional green turtle nesting grounds under predicted climate change. Additionally, managers should aim at reducing the impacts of other anthropogenic threats that sea turtles currently face and protect known habitat so that turtles can increase their resilience and have a better chance to adapt (for further discussion on this see section 8.3).

Implementing any of these strategies, even at small spatial scales, could be cost and time-intensive, which works to vary the extent to which such solutions will be realistic in developed and developing nations. Given the severe implications of the projections presented here the realities of implementing each strategy type at a nesting ground rather than population scale warrant further research. As researchers and managers test strategies it seems likely there will be a lot of benefits to information sharing through workshops, and in the preparation of general guidelines that help managers to reduce any negative side effects associated with strategies.

3.6. Chapter summary

Timely and targeted implementation of strategies that work to mitigate the impacts of predicted increase in temperature on sea turtle populations is going to require an understanding of spatial variability in impact severity. This information can be obtained by broadly applying predictive models like those used here. The combined SST and AT model improved our capacity to project future nesting conditions in Northern Australia and Torres Strait and may improve the accuracy of projections made in other regions. Thus, I suggest that it is highly likely that incorporating SST can improve the accuracy of models used to project sand temperature and resultant impacts on sea turtle populations. If the projected increases in temperature presented here eventuate then global warming will seriously impact the population gender and size of the northern Great Barrier Reef green turtle population. Importantly, I was also able to identify nesting grounds that will still produce male hatchlings under the most extreme scenario of climate change. This is extremely important as protection of these sites will aid the viability of the nGBR green turtle population.

Chapter 4.

Potential impacts of projected sea level rise on sea turtle nesting grounds [1]

[1] **Fuentes MMPB**, Limpus CJ, Hamann M, and Dawson J (in press) Potential impacts of projected sea level rise to sea turtle rookeries. Aquatic Conservation: Marine and Freshwater ecosystems.

4.1. Abstract

Projected sea level rise (SLR) is expected to cause shoreline erosion, saline intrusion into the water table and inundation and flooding of beaches and coastal areas. This will cause a reduction of available nesting area for sea turtles and thus will amplify density-dependent issues at nesting grounds, potentially increasing nest infection and destruction of nests by co-specifics. Sea level rise will also increase the impact of storm events, causing periodic beach erosion and washing away and flooding of nests. This will potentially increase egg mortality affecting the overall reproductive success of sea turtle populations. Considering the potential threat that sea level rise may have on sea turtles I investigated how sea level rise might affect the selected nesting grounds utilised by the northern Great Barrier Reef green turtle population (nGBR). For this, I developed 3-D elevation models and quantified how much of each nesting ground may be inundated under a conservative and extreme scenario of sea level rise (SLR) by 2030 and 2070. Results indicate that up to 34% of available nesting area across all the nesting grounds may be inundated as a result of SLR by 2070. Flooding will increase egg mortality and loss of nesting area at these nesting grounds affecting the overall reproductive output of the northern Great Barrier Reef (nGBR) green turtle population.

4.2. Introduction

Sea level is anticipated to rise significantly in the future, with a projected sea level rise (SLR) of 33 to 40 cm by 2070 in the study region (CSIRO 2007), and a possible additional 10 to 20 cm increase from melting ice sheets and glaciers'(Overpeck et al. 2006; IPCC 2007; McInnes and O'Farrell 2007). Small, tropical low-lying islands, especially those that are not vegetated or lie on exposed reefs in areas of high tidal range, are the most vulnerable to sea level rise (SLR) (Woodroffe et al. 1999; Church and White 2006). Impacts anticipated from SLR include saline intrusion into the water table as well as inundation and flooding of beaches and shoreline erosion of coastal areas (Klein and Nicholls 1999; Mimura 1999). Previous studies indicate that the most significant impacts will be in residential and recreational areas, agricultural land (Nicholls 2002; Snoussi et al. 2008), wetlands (Nicholls et al. 1999; Nicholls 2004) and habitats for threatened, endangered and endemic species (Daniels et al. 1993; Fish et al. 2005, 2008; Baker et al. 2006; LaFever et al. 2007). This is expected to cause a plethora of biogeophysical and socio-economic consequences producing a cascade of impacts (Klein and Nicholls 1999). Assessments of the impacts of projected sea level rise at areas of high human population density, economic importance and/or areas that have high environmental value (e.g. areas important for threatened species), can aid resource management planning and conservation of wildlife that rely on areas at risk (Baker et al. 2006; Cowell et al. 2006).

Currently, concerns exist regarding the impacts of SLR on the most important nesting ground, Raine Island, and several of the other nesting grounds (e.g. Bramble Cay) used by the northern Great Barrier Reef (nGBR) green turtle population. Over the last ten years a reduction in hatching success has been observed at Raine Island, which is thought to be caused by rising groundwater and other geomorphic processes (e.g. movement of sand) (Limpus et al. 2003). It is believed that SLR is likely to exacerbate these processes and the frequency of nest inundation (Limpus et al. 2003).

The present study uses geographic information system (GIS) to map the impacts of projected SLR, in terms of inundated area, for a conservative and extreme scenario of sea level rise for 2030 and 2070. The impacts of sea level rise to sea turtle nesting grounds has been previously quantified in Bonaire and Barbados (Fish et al. 2005, 2008), the east coast of the United States (Daniels et al. 1993) and the Hawaiian Islands (Baker et al. 2006). However, there has been no study in Australia, an area that contains globally significant marine turtle populations. In addition, prior studies, with the exception of Baker et al.'s (2006), focus on the impacts to only one nesting ground for a particular turtle population. Such an approach does not provide a full understanding of how a genetic stock (management unit) will be affected and respond to SLR. Since sea turtles may shift nesting grounds when nesting habitat is no longer available (Hamann et al. 2007) there is also the need to investigate how a variety of nesting grounds for the same population will be impacted. Here, I investigated the impacts of SLR to the selected nesting sites which represents where 99% of nesting activity for the nGBR green turtle population occurs (Limpus et al. 2003). Thus, I ensure that the results from this Chapter will be able to direct and focus management and conservation actions strategically to protect the nGBR green turtle population from impacts of SLR. Furthermore, in this Chapter I also discuss the ecological impacts of loss and alteration of nesting habitat to the nGBR green turtle population.

4.3. Methods

4.3.1. Nesting grounds characteristics

Beach profiles were measured at Bramble Cay, Dowar Island (north, south and west beaches) and Milman Island relative to low water mark at 100 m intervals (except at Dowar where a 50m interval was conducted), using the dumpy level standard surveying technique (see Mwakumanya and Bdo 2007), where elevation of points (z) along the transect are calculated from slope and ground distances. Waypoints (*x* and *y*) were recorded at each elevation point from the profile transects using a GPS as well as bearings. The *x*, *y* and *z* coordinates for each point from the beach profiles were used to construct triangulated irregular network (TIN) models for each beach using the 3-D analyst tool in ArcGIS®. Data from Raine Island were collected using Real Time Kinematic (RTK) GPS. Beach width, mean and maximum elevation values and the area available for nesting for each beach were obtained from the TIN models. Beach profiles for Moulter Cay, Sandbank 8 and 7 were derived from existing information on their elevation profiles and morphology (King and Limpus 1983; King et al. 1983a, 1983b). Spatial information for Moulter Cay was obtained from an aerial photograph taken in 1990 (0.25m pixel resolution).

4.3.2. Nesting activity

Surveys of nest location were carried out to determine the spatial distribution of nests and the preferred nesting habitat - in terms of elevation and distance from high water mark- at each nesting ground. Due to logistical and time constrains, surveys for turtle nests were only carried out at Bramble Cay, Dowar Island, Milman Island and Raine Island. Monitoring occurred during the 2006/2007 nesting season, which was a high nesting season with up to 21,000 turtles nesting per night at Raine Island (CJL unpublished data). Monitoring at Raine Island was conducted by Queensland Parks and Wildlife (QPW) as part of their annual monitoring programme, which has taken place since the 1970s (Limpus et al. 2003). Turtles nested on all available un-vegetated beach area and therefore this study assumes that turtles nested everywhere above high water mark and below the cliff line and outside any central rock area. Nesting activity at Dowar and Milman Islands was monitored for ten days during peak nesting and nest locations were recorded with a global positioning system (GPS) (Garmin Etrex). Nesting at Bramble Cay was monitored for a single day during the 2006/ 2007 nesting season; therefore nesting information collected during the 2007/2008 season was also used as an indication of the location of nests at this site. The preferred elevation range - where >70% of nesting takes place - was calculated for each of the nesting grounds for which nesting information was available, by using zonal statistics (ArcGIS 9.0).

4.3.3. Sea level scenarios and threat to nesting area

To investigate the impact of sea level rise to the selected nesting grounds I considered sea level rise scenarios based on ‘conservative’- B1 emission scenario (IPCC 2007) - and ‘extreme’ - A1T emission scenario (CSIRO 2007) for 2030 and 2070 (as described in Chapter 1 - Section 1.3.2), as well as an additional scenario that accounted for ice melting into the system (0.2m added to the highest scenario from the CSIRO 2007 (Overpeck et al. 2006; McInnes and O'Farrell 2007) (Table 4.1).

Table 4.1. Projected regional sea level rise under conservative (based on B1 emission scenario of the IPCC 2007) and extreme scenarios (based on A1T emission scenario of the IPCC 2007 and CSIRO 2007).

Year	Scenario	Projected sea- level rise (m)	Scenario ID
2030	Conservative	0.13	1
2030	Extreme	0.15	2
2070	Conservative	0.33	3
2070	Extreme	0.40	4
2070	Extreme + Ice melting	0.60	5

Similar to other studies (e.g. Fish et al. 2005) I considered impacts through inundation of nesting area. For this, the TIN models were used to identify nesting area below each of the elevations (0.13, 0.15, 0.33, 0.40 and 0.60m) and therefore areas that would be inundated by sea level rise. The area inundated was measured from the high water mark. Analyses were conducted using the Surface Volume tool in the ArcGis 9.0 - 3D Analyst Toolbox.

4.3.3.1. Predicting the threat to nesting grounds where beach profiles were not conducted

Due to logistical constraints it was not possible to measure beach profiles at Moulter Cay, Sandbanks 8 and 7. To calculate the likely inundation at these nesting grounds I first examined if there was a significant correlation between the maximum elevation at each nesting ground where a beach profile was conducted and the percentage of area lost for every SLR scenario. After this relationship was established a linear regression model was created to predict the likely percentage of area inundated for the nesting grounds where profiles were not conducted. To validate the predictive efficiency of the linear model created paired-T tests were run with the values of percentage of lost area calculated from the beach profile models with the values generated from the linear model for the field study sites (Raine Island, Bramble Cay, Dowar Island and Milman Island).

4.3.3.2. Vulnerability as a result of nesting ground characteristics

The relationship between threat to nesting area and different physical attributes of each nesting ground (e.g. beach width, nesting area as well as maximum and mean elevation) was also investigated. For this, I considered the proportion of beach under threat from an intermediate sea level rise scenario (0.33 m) as a measure of vulnerability (modified method from Fish et al. 2005) and used Pearson's Correlation to examine the effects of each physical attribute and vulnerability to sea level rise.

4.3.3.3. Threat to nesting area during storm events

As it is anticipated that waves will penetrate even further inland during episodic storms (Gornitz 1991; Fletcher III 1992; Church et al. 2006), I also explored how nests and nesting areas will be impacted during storms under an intermediate SLR scenario of 0.33 m rise. Due to lack of storm tide predictions previous highest astronomical tide (HAT) measurements were used as an indication of possible intrusion by storms (wave run-up). Using data from the Environmental Protection Agency, Australian Bureau of Meteorology website (http://www.bom.gov.au/index.shtml) and Seafarer tides HAT was calculated to be 1.0 and 0.45 m above mean spring high tide level in Torres Strait and the nGBR region correspondingly. As HAT data are only available at a regional level, these are used only as an indicative measurement. It was then assumed that nesting area under 1.33 m (0.33 m SLR + 1.0 m run-up) and 0.78 m (0.33 m SLR + 0.45 m run-up) in Torres Strait and nGBR, respectively, would be affected by wave run-up during storm events and consequently the nests laid in this area would be inundated.

4.4. Results

4.4.1. Characteristics of nesting grounds and nesting activity

Raine Island, Moulter Cay, Milman Island and north Dowar provide the largest available nesting areas respectively, and conversely, western Dowar provides the smallest area for turtle nesting (Table 4.2). The highest elevations were found at north Dowar and Raine Island (9.13 m and 4.9 m respectively), while the lowest nesting beaches were at Sandbank 7, Sandbank 8 and west Dowar (Table 4.2).

Table 4.2. Characteristics of nesting grounds during the 2006/2007 nesting season. nesting grounds are listed in order of importance. N/A = not available.

Nesting ground	Width (m)	Nesting area (m²)	Mean elevation (m)	Maximum elevation (m)
Raine Island	90.0	152247	1.2	4.9
Moulter Cay	N/A	78200	N/A	3.0
Bramble Cay	44.4	21980	1.34	4.1
North Dowar	37.5	36719	2.36	9.1
South Dowar	28.0	8803	1.021	3.9
West Dowar	19.4	3844	0.77	2.1
Sandbank 7	45.0	22000	N/A	0.8
Sandbank 8	60.0	32000	N/A	1.3
Milman Island	17.0	58648	1.8	4.3

Preferred nesting habitat varied at each nesting ground (Table 4.3), with turtles at north Dowar nesting at higher elevation and turtles at west Dowar nesting at lower elevations (Table 4.3). Preferred nesting elevation was found to be a result of the elevation range found at each nesting ground, as the mean nest elevation was significantly and positively correlated with maximum and mean elevation at each nesting ground ($r = 0.959$, $n = 5$, $P = 0.01$ and $r = 0.989$, $n = 5$, $P = 0.001$, respectively). Mean distance of nest to HWM also varied between nesting grounds (Table 4.3), with mean nest distance being positively correlated with beach width ($r^2 = 0.855$, $n = 5$, $P = 0.001$).

Table 4.3. Characteristic of preferred nesting habitat at each nesting ground during the 2006/2007 nesting season and 2007/2008 for Bramble cay. Nesting grounds are listed in order of importance. Data for Raine Island, Moulter Cay, Sandbank 7 and 8 are not available. Preferred elevation range is where >70% of nesting takes place at each nesting ground. Elevation is measured from high water mark.

Nesting ground	Preferred elevation range (m)	Mean nest elevation (m)	% of nesting at preferred nest elevation	Mean distance from high water mark (m)
Bramble Cay	1.5 – 3.5	2.1	77.0	19.6
North Dowar	2.5 – 4.5	3.3	73.4	24
South Dowar	1.0 – 2.5	1.6	82.1	13
West Dowar	1.0 – 2.0	1.2	71.4	8
Milman Island	2.0 – 3.5	2.4	75.2	11.5

4.4.2. Threat to nesting area

4.4.2.1. Validation of methods for nesting grounds where beach profiles were not conducted

As a significant correlation existed between the maximum elevation at each nesting ground and percentage of area lost for every SLR scenario, for the beaches where beach profiles were conducted (Scenario 1, r = -0.792, n = 8, P = 0.041; scenario 2, r = -0.865, n = 8, P = 0.050; scenario 3, r = - 0.940, n = 8 , P = 0.001; scenario 4, r = -0.955, n = 6, P = 0.001; and scenario 5, r = -0.863, n = 8, P = 0.001), a linear regression model was created to predict the likely percentage of area inundated for the beaches for which it was not possible to measure profiles (Moulter Cay, Sandbank 8 and 7). Paired-T tests validated the linear models, as there was no significant difference between the values from the beach profiles and the values calculated from the linear models for all four scenarios of SLR (all pairs, T = 0.001, df = 5, p > 0.05).

4.4.2.2. Vulnerability and nesting ground characteristics

Between 6% and 34% of the total area available for nesting (438,441 m²) across the beaches studied are predicted to be inundated under the various SLR scenarios (Figure 4.1). Sandbank 7 is predicted to lose the greatest amount of beach (9 to 36 %), followed by Sandbank 8 where approximately 9 to 34% of its area is predicted to be lost. Similarly, Milman Island is predicted to lose 10 to 21% of its nesting area. North Dowar is predicted to be the least vulnerable nesting ground with a predicted area inundated of 3-11% (Figure 4.1).

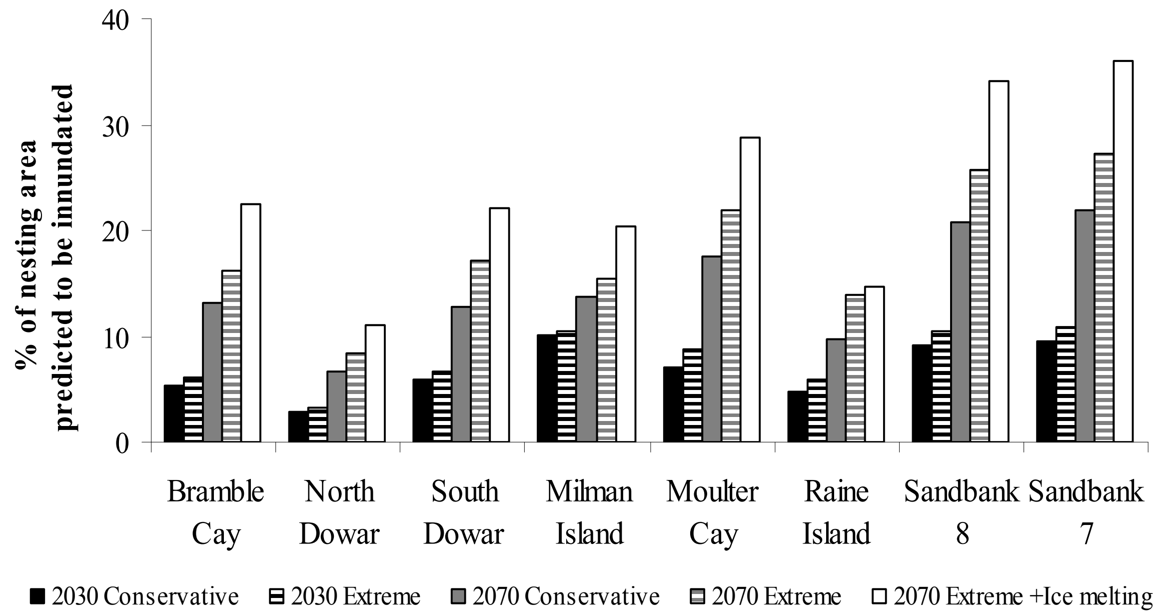

Figure 4.1. Area predicted to be inundated at each nesting grounds by 2030 and 2070 under a conservative and extreme scenario of sea level rise.

Beaches with lower elevation were, not surprisingly, found to be more susceptible to SLR as inundation was significantly and negatively correlated with maximum elevation under all sea level rise scenarios (Scenario 1, $r^2 = -0.62$, n = 10, P < 0.000; scenario 2, $r^2 = -0.75$, n = 8, P < 0.000; scenario 3, $r^2 = -0.88$, n = 8, P = 0.001;scenario 4, $r^2 = -0.92$, n = 8, P < 0.000; and scenario 5, $r^2 = -0.87$, n = 8, P = 0.001) (Figure 4.2).

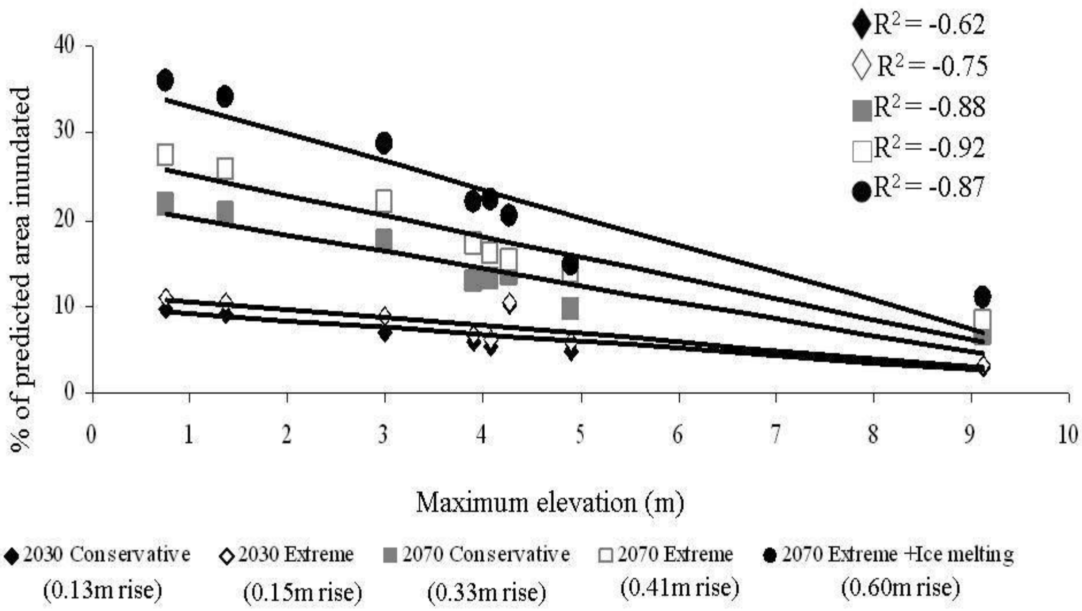

Figure 4.2. Relationship between maximum elevation at each nesting ground and area predicted to be inundated after each scenario of sea level rise for 2030 and 2070.

4.4.2.3. Threat during storm events

During storm events the nesting habitat at west Dowar is predicted to be under the greatest threat, with up to 75% of available nesting habitat inundated, potentially affecting 90% of nests laid. Milman Island, Moulter Cay, Bramble Cay, Sandbank 8, and Sandbank 7 are also predicted to have large amounts (>50%) of their nesting area inundated during storm events, with Bramble Cay and Milman Island potentially having up to 30% of their nests inundated. Raine Island is expected to have up to 30% of the available nesting area inundated during storm events (Figure 4.3).

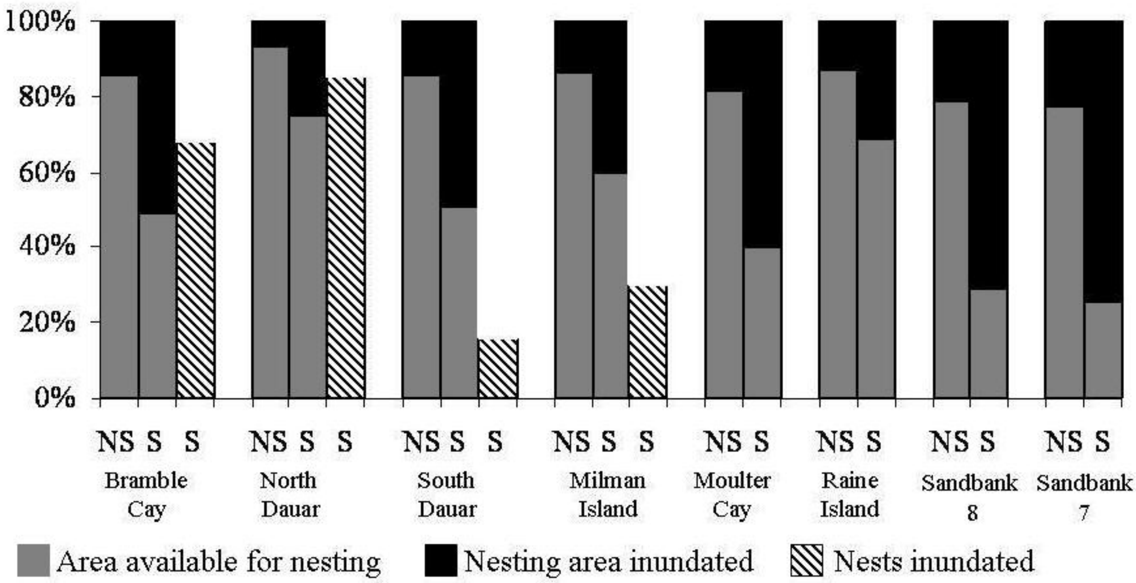

Figure 4.3. Percentage of nesting area and nests inundated, at nesting grounds for the nGBR green turtle population, under an intermediate sea level rise of 0.33 m both during storms (S) and when storms events are not occurring (NS). Information on nest inundated is only available for nesting grounds where I conducted nesting monitoring.

4.5. Discussion

4.5.1. Threat of sea level rise

To successfully conserve and manage sea turtles as climate change progresses managers will need to identify, understand, predict and mitigate any future impact to these endangered species (Hamann et al. 2007). This study quantified the area of the selected nesting grounds that will potentially be susceptible to projected SLR scenarios. It is predicted that under an extreme scenario of sea level rise with ice melting - a 0.60 m rise - 34% of the total nesting area available for the nGBR green turtle population could be inundated. The extent of inundation of individual beaches ranges from 11% to 36%, with the beaches that support the highest levels of nesting being the least vulnerable to inundation. Similar results are predicted for sea turtle nesting grounds in the Caribbean region where 26% and 32% of the nesting area in Barbados and Bonaire, respectively, are predicted to be inundated with a 0.5 m sea level rise (Fish et al. 2005, 2008).

Reduction of available nesting area will amplify density-dependent issues at nesting grounds, potentially increasing nest infection (Tiwari et al. 2006; Fish et al. 2008) and destruction of nests by co-specifics (Bustard and Tognetti 1969; Girondot et al. 2002; Limpus et al. 2003). This already occurs at Raine Island, Moulter Cay, Dowar and Bramble Cay during high density nesting years. Higher nesting density at a particular nesting ground may also reduce the total reproductive output as increased disturbance by nesting co-specifics could result in premature use of somatic energy stores and resorption of ovarian follicles (Hamann et al. 2002; Limpus et al. 2003). Another outcome of SLR is increased impact of storm events, causing periodic beach erosion and washing away and flooding of nests (Gornitz 1991; Fletcher III 1992; Church et al. 2006). This will increase egg mortality affecting the overall reproductive success of the nGBR green turtle population.

Further flooding of sea turtle nests and impacts to the reproductive output of sea turtles can occur through a raised water table as a result of SLR (Titus et al. 1991; Ross et al. 1994). Raine Island, in particular, is more susceptible to this as it already experiences water level problems (Hamann et al. 2007). On occasion, groundwater level has been so high at Raine Island that pooled water has been observed in depressions and body pits made by turtles (Limpus et al. 2006). A recent study by Guard et al. (2008) has initiated exploration of the water table dynamics at Raine Island in order to provide models of water table response to tidal oscillations. Further investigation and expansion of this study may provide more quantitative insights into the impacts of sea level rise on groundwater dynamics and therefore the impact of SLR on the reproductive output at Raine Island.

4.5.2. Possible responses by turtles and consequences of sea level rise

Sea turtles may be able to adapt to sea level rise by shifting nesting up the beach, away from the high tide (Fish et al. 2005; Limpus 2006). However, such a shift is constrained at small low-lying islands and where urban development restrains landward beach recession (Fish et al. 2008). As the nGBR green turtle population nests on beaches where little urban development exists, a landward shift in nesting is a potential response for this population. This is not the situation, however, for populations nesting at beaches developed for tourism in the Caribbean region (e.g. Fish et al. 2005, 2008). Some nesting beaches may become fully inundated as sea level continues to rise above 1 m beyond 2100 (Turner and Batianoff 2007). Turtles nesting at these or at beaches that have no more elevated nesting habitat, as may occur at west Dowar and Sandbank 7 will need to seek out new nesting sites (Limpus 2006; Hamann et al. 2007). For example, if nesting is no longer possible at west Dowar, higher density nesting may occur at the southern and northern beaches (which provides more suitable habitat) or turtles may shift to nest at nearby Mer or Waer Islands. There is also the possibility that turtles will shift their nesting to new beaches that may develop/or stabilise in the region as a result of SLR (Hamann et al. 2007).

Nest placement has been shown to affect hatchling success and sex ratio in the nGBR green turtle population (Miller and Limpus 1981; Morreale et al. 1982) and any shift in their nesting grounds may influence this. Changes in nesting locations may also have severe implications and cause further conservation challenges if they are forced to nest where even fewer conservation measures are in place or management is logistically difficult. Conversely, changes may result in improved population performance as turtles may start nesting in areas with more favourable nesting and incubating condition and/or areas with less anthropogenic threats, such as traditional hunting of turtle meat and eggs as it occurs at the nesting grounds in Torres Strait. Longer- term consequences associated with changes in nesting distribution include the development of new genetic stocks and thus differentiation in biological parameters (e.g. turtle stocks with different breeding phenology and different size adult females) (Limpus 2008 a). Although at a different time frame, this has been suggested to have occurred with the historical (Pleistocene) population of flatbacks, *Natator depressus*, which developed into two distinct current (Holocene) populations (Limpus 2008 a).

4.5.3. Further impacts of sea level rise and uncertainties

Turtle nesting beaches may be further affected by SLR through shoreline erosion, which is dependent on a series of factors such as wave energy, tidal currents, island and reef morphology, sediment type and sediment supply, among others (Cooper and Pilkey 2004; Woodroffe 2008). Developing appropriate models to successfully predict shoreline response to sea level rise is challenging (Cooper and Pilkey 2004; Fish et al. 2005). The most common and widely used model is the “Bruun rule” (Bruun 1962) (see Cooper and Pilkey 2004 for a compiled list of studies), which assumes a continuous equilibrium of sand transport between beach and nearshore (Woodroffe 2008) and therefore it is not applicable for the systems studied here. In addition, this model has been criticised for its restrictive assumptions, omission of important variables and erroneous concepts (Cooper and Pilkey 2004). To overcome some of the issues Cowell et al. (2006) recently suggested incorporating probabilistic components to model outputs to allow greater freedom in quantifying some of the input parameters; however, due to lack of specific data, in particular on the coastal processes and changes in beach profiles at each nesting ground this model could not be applied.

As assessing the quantitative impacts of shoreline erosion, rise of water table and potential accretionary events was beyond the scope of this study and therefore not incorporated into the results presented here, it is important to consider that influences from these factors could lead to greater or lesser habitat loss. Several other studies (e.g. Daniels et al. 1993; Fish et al. 2005; LaFever et al. 2007) have used a similar approach, as to this study, and only quantified the impact of SLR caused by inundation. As with many other predictions of beach response to sea level rise, the current approaches include uncertainties (Cowell et al. 2006). In this study uncertainties arise from (1) predicted sea level rise scenarios, (2) assumptions of how beaches will respond to sea level rise (in terms of their sea level and wave climate), and (3) the models used to quantify the impacts and response of SLR to selected beaches (Cowell et al. 2006). Possible errors from these uncertainties were minimised by (1) utilizing a range of sea level rise scenarios consistent with

IPCC 2007 as well as incorporating possible increases in SLR through ice/glacier melting and increase in wave-run up and (2) by using similar assumptions and methodology as other studies that address comparable questions. Nevertheless the results presented here, provide the first insights and the best current available assessment of the potential effects of sea level rise to the nGBR green turtle nesting grounds. Studies of this nature, which assess the potential impacts of sea level rise to endangered megafauna, are extremely important, as they can potentially aid managers to prioritise management efforts and to use realistic measures to mitigate potential SLR threats to these ecologically important species. Some potential management measures to mitigate the impacts of inundation and erosion from sea level rise include (1) “hard engineering structures” (e.g. seawalls, groynes), (2) “soft methods” (e.g. beach nourishment, dune building) and (3) retreat and setback regulations (Nicholls and Tol 2006; Fish et al. 2008). In order to determine the most realistic and efficient solution to use a cost benefit analysis of each strategy will be necessary as well as information on any ethical, ecological and practical issues associated with implementing them (see Chapter 8 for further discussion on this).

4.6. Chapter summary

Knowledge of how the morphology of nesting grounds will respond to predicted sea level rise scenarios is crucial for management of sea turtles in the face of climate change. This study predicted that under an extreme scenario of sea level rise with ice melting - a 0.60 m rise - 34% of the total nesting area available for the nGBR green turtle population could be inundated. Loss of nesting areas will: (1) amplify density-dependent issues at nesting grounds, potentially increasing nest infection and destruction of nests by co-specifics, and (2) increase egg mortality affecting the overall reproductive success of the northern Great Barrier Reef (nGBR) green turtle population. Sea turtles may be able to adapt to sea level rise by shifting nesting up the beach, away from the high tide. Changes in nesting locations may have severe implications and cause further conservation challenges for sea turtles as they may be forced to nest where even fewer conservation measures are in place or management is logistically difficult. Special attention should be taken to the management strategies that are in place in these areas and how distributional changes may affect population dynamics.

Although this study only accounted for the impacts of inundation from SLR it provided the first insights and the best current available assessment of the potential effects of sea level rise to the nGBR green turtle nesting grounds. Further, by using similar assumptions and methodology as other studies I was able to compare results and identify the relative impact that each nesting ground will experience in comparison to other studies. Future, studies of this nature should aim to also assess how the impacts of shoreline erosion, rise of the water table and potential accretionary events will affect sea turtle's nesting grounds.

Chapter 5.

The effects of projected changes in cyclonic frequency on the nGBR green turtle population [1,2]

[1] **Fuentes MMPB**, and Abbs D (in review) Sea turtles and climate change: the effects of projected changes in cyclonic frequency on sea turtles. Journal of Marine Ecology Progress Series

[2] **Fuentes MMPB,** Moloney, J, Limpus CJ, and Hamann M (in prep.) Historical disturbance of cyclones to sea turtles in eastern Australia. To be submitted to Marine Biology

5.1. Abstract

Given the potential vulnerability of sea turtles to climate change, a growing number of studies are attempting to predict how specific climatic processes will affect them. However, most of the studies conducted to date have focused on potential impacts from increased temperature or sea level rise, with only a few investigating the impacts of future cyclonic activity on sea turtles. From these, none has investigated how the projected changes in frequency and distribution of cyclonic activity may impact sea turtle populations. However, tropical cyclones are amongst the world's most destructive natural hazards and can negatively affect sea turtles. Thus, knowledge of how future changes in cyclone activity will affect sea turtle populations is of great value in further understanding the impact of climate change on sea turtles. Here I address this issue by investigating how the frequency of cyclones at the selected nesting grounds used by the northern Great Barrier Reef green turtle population will alter as climate change progresses. To account for known variability in model projections of cyclonic activity, I used 11 regional climate model simulations for an A2 emission scenario for 2055 and 2090. The model projections indicate a tendency for a reduction in cyclonic activity in the future and a decrease in the impacts that the nGBR green turtle population will experience from cyclones. This indicates that particular changes in climate have the potential to be beneficial to sea turtles.

5.2. Introduction

Tropical cyclones (TC) are severe atmospheric disturbances that are usually accompanied by increased wave heights, heavy rainfall and storm surges (Brokaw and Walker 1991; Waide 1991; Pimm et al. 1994; Van Bloem et al. 2005). These processes affect a diverse range of terrestrial and marine habitats, which negatively affect the animal communities that rely on them. For example, cyclones often cause extensive damage to low-lying coastal islands through rapid erosion by storm surges. This affects animal communities, such as birds and sea turtles, that depend on these environments for nesting, roosting and for food resources (Reef 1986; King et al. 1992; Coyne 2000; Rathcke 2000; Ross 2005). Furthermore, cyclones may directly affect animal communities by reducing and displacing populations (Rogers et al. 1991; Waide 1991; Puotinen 2004) inducing behavioural changes or increasing mortality through depletion of resources or destruction of incubating eggs (Grant et al. 1997; McConkey et al. 2004).

Animals particularly vulnerable to cyclones are those that rely on seashore habitats, which are more prone to cyclonic activity, for a critical period of their life cycle and have an immobile lifecycle phase (e.g. incubation of eggs), which hinders any escape from these events (Pike and Stiner 2007). Sea turtles lay their eggs in sandy ocean-exposed beaches frequented by cyclones and therefore may be impacted by them in the long term (over several generations) by removal/ alteration of nesting habitat (e.g. through beach erosion) and in the short term (the incubation period of 6-8 weeks) by increased localised (temporal and spatial) mortality of eggs (Limpus 1985; Milton et al. 1994; Martin 1996; Pike and Stiner 2007). In addition, because both incubation length and gender of sea turtle hatchlings are affected by the sand temperature during incubation (Miller and Limpus 1981; Morreale et al. 1982; Limpus et al. 1985), cooling from increased rainfall and cloud cover during cyclonic events can play a role in dictating hatchling phenotype and/or sex ratios from beaches (Reed 1980). A further and less frequently documented impact of cyclones on turtles is the increased probability of stranding events (see Limpus and Reed 1985).

Climate change is expected to alter the frequency, intensity and distribution of cyclones (Walsh and Ryan 2000, Webster et al. 2005, Abbs et al. 2007, Leslie et al. 2007) and potentially change the impact that sea turtle populations experience from cyclonic activity. Recent studies indicate that intensification of cyclones will reduce hatchling success at sea turtle nesting grounds (Van Houtan and Bass 2007). However, no study before 2009 has investigated how projected changes in the frequency and distribution of cyclones due to climate change will affect sea turtles.

Consequently, in this Chapter I address this issue by investigating how the frequency of cyclones will alter, by 2055 and 2090, at the selected nesting grounds used by the nGBR green turtle population. To do this I used a Conformal-Cubic Atmospheric Model (CCAM) from an ensemble of 11 regional climate model simulations for an A2 emission scenario. For comparative purposes, the historical frequency of cyclonic activity at each of the selected nesting grounds was also investigated.

5.3. Methods

5.3.1. Potential changes in the frequency of cyclone activity at each nesting grounds

Two steps were undertaken to investigate if there will be changes in the frequency of cyclones at the selected nesting grounds as climate change progresses. First I explored the historical (1969-2007) frequency of cyclonic activity at each of the selected nesting grounds. Then, I investigated how the frequency of cyclones that cross the nesting grounds will change by 2055 and 2090. I was unable to investigate how cyclonic activity will change by 2030 and 2070 (the timeframe used for the remaining of the thesis), since no predictive model of cyclonic activity exits, at this stage, for the study region. Therefore, I used the timeframe 2055 and 2090, which are the years for which the Australian commonwealth Scientific and Research Organisation (CSIRO) had the necessary modelling available.

5.3.1.1. Historical frequency of cyclones

Individual cyclone tracks, which crossed the eastern Queensland coast and adjacent islands, from 1969- 2007 were obtained from the Australian Bureau of Meteorology (BOM- http://www.bom.gov.au/weather/cyclone/tc-history.shtml). Data prior to the 1969/1970 season were not used due to lack of observations in earlier periods resulting in positional inaccuracies of up to 250 km (Holland 1981). Radar observations were introduced in the 1950s and 1960s resulting in improved detection of cyclones within 500 km of the coast. Further improvements in the origin and track of tropical cyclones accompanied the advent of regular satellite observations in the 1960s. Cyclone intensity is measured by either the maximum wind speed near the centre of the cyclone, or the central pressure. Practical difficulties in measuring the intensity of tropical cyclones has lead to the development of objective techniques based on satellite imagery. However, continual improvements in these techniques have resulted in biases being introduced into the intensity estimates, thus rendering them unsuitable for further analysis at this time, or until a consistent dataset becomes available. Thus only information on the location of cyclones from the BOM dataset has been used in this study.

To determine the cumulative frequency of cyclone within the study region the following steps were undertaken; (1) First, each vector cyclone track from 1969 to 2007 was buffered by 40km (which represents the average cyclone eye and an area that would be severely affected by winds) (Australia

Bureau of Meteorology 2008), (2) the vector cyclone layers were then converted into a raster layer with a resolution of 0.25 deg, (3) each raster (representing a single cyclone path) was reclassified into 1 for the buffered cyclone track and 0 for the remaining area, (4) all the raster layers were added together using the Raster Calculator in ArcGIS. After these steps were conducted I obtained a raster layer with 0.25 degree grid cells with values of the frequency of cyclones during the study period.

I then determined the frequency of cyclones that occurred for each nesting ground (using zonal statistics) as well as the frequency of cyclones that occurred within 300 km of each nesting ground (using great circle distance calculations). To compare frequency of cyclones between the different nesting grounds I conducted One way-ANOVA. Layers with monthly cyclone tracks were overlaid with nesting distribution and nesting phenology data to explore disturbance in accordance to temporal nesting patterns.

Boot Strapping was conducted to explore if the nGBR green turtle nesting sites are located in areas with lower or higher cyclonic frequency than areas where turtles are not nesting. For this a subset of 70 random points (approximate number of nesting sites used by the nGBR green turtle population) were projected 1000 times in areas where turtles are not currently nesting. The study area for this analysis encompassed the distributional range of the nGBR green turtle population (-9˚00, 147˚50’, -19˚00’, 140˚50’). The sum value of frequency hits for each subset of points was averaged and compared with the sum value of frequency hits for all the nesting sites. All spatial analyses were performed using ArcGIS 9.1 (Esri, Redlands, California).

5.3.1.2. Projected frequency of cyclones

To investigate potential changes in the frequency of cyclones that crosses the selected nesting grounds used by the northern Great Barrier Reef green turtle population, I used simulations based on the A2 emissions scenarios, for 2055 and 2090, generated using the Australian Commonwealth Scientific and Research Organisation (CSIRO) Conformal-Cubic Atmospheric Models (CCAM). The A2 emissions scenario describes a highly heterogeneous world, with continuously increasing human populations. In this simulation, economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slower than other scenarios (IPCC 2007). CCAM is a global model that uses a stretched grid, formed by projecting the panels of a cube onto the surface of the earth. The cube is then stretched so that the area of interest is simulated using a high resolution, while the remainder of the globe is simulated with increasingly lower resolution away from the region of interest. The CCAM simulations in this study had the highest resolution centred on Australia (on an area of approximately 65 km^2).

The CCAM simulations were derived from 11 general circulation models (GCM) (Table 5.1) sourced from the Intergovernmental Panel on Climate Change (IPCC) CMIP3 archive (provided to me by the Australian commonwealth Scientific and Research Organisation, CSIRO), and were nudged using two different models: bias-corrected sea surface temperature (SST) and large-scale forcing (or forced) (e.g. winds, temperatures, pressures). The bias-corrected SST nudging has the advantage in that the cold sea surface temperature bias in the central equatorial Pacific (characteristic of many GCMs) is not included in these simulations. Thus, the CCAM simulations develop large-scale circulations that are not affected by these biases. This technique also has the advantage of allowing long (e.g. 140-year) simulations to be conducted. The major disadvantage of this technique is that this method may not account for the intermodel variability seen between the host models (Abbs 2009). Simulations nudged towards the large-scale fields from the host model use ‘uncorrected’ SSTs from the host model. This means that the resulting simulations may develop large-scale circulations that are a response to the SST biases of the host model. Another disadvantage is that simulations nudged with forced nudging can only use 20-year time-slice experiments for 2046–2065 and 2081–2100 due to the lack of atmospheric-forcing data for other periods. However, the simulations nudged in large-scale forcing have the advantage that they account for the intermodel variability seen between the host models (Abbs 2009).

Table 5.1. Models used to investigate cyclonic activity for 2055 and 2090 at the selected nesting sites used by the northern Great Barrier Reef green turtle population.

Model	Institution	Downscaling method
ECHAM5 (SST)	Max Planck Institution	Bias-corrected SST
GFDL 2.0 (SST)	NOAA Geophysical Fluid Dynamics Laboratory	Bias-corrected SST
GFDL 2.1 (SST)	NOAA Geophysical Fluid Dynamics Laboratory	Bias-corrected SST
MIROC 3.2 – medres (SST)	CCSR/NIES/FRCGC, Japan	Bias-corrected SST
Mk3.5 - A2 - B35 (SST)	Australian Commonwealth Scientific and Research Organization	Bias-corrected SST
UK HADCM3 (SST)	Hadley Centre in the United Kingdom	Bias-corrected SST
ECHAM5 (forced)	Max Planck Institution	Large scale forcing (forced)
GFDL 2.1 (forced)	NOAA Geophysical Fluid Dynamics Laboratory	Large scale forcing (forced)
MIROC 3.2 – medres (forced)	CCSR/NIES/FRCGC, Japan	Large scale forcing (forced)
Mk3.5 - A2 - B35 (forced)	Australian Commonwealth Scientific and Research Organization	Large scale forcing (forced)
Mk3.0_A2_M20th (forced)	Australian Commonwealth Scientific and Research Organization	Large scale forcing (forced)

Twice-daily outputs from the CCAM were analysed, and tropical cyclone-like vortices (TCLVs) were detected. The TCLV detection and tracking scheme used here is modified from that of Nguyen and Walsh (2001). The scheme searches for low-pressure systems that have the physical characteristics of TCs (e.g. high wind speeds, rotation of winds and a warm core). These TCLVs are 'tracked' in subsequent outputs and the results collated to yield a population of modelled TCLVs, which are subsequently analysed to identify possible changes in their frequency. This is a novel approach that enables us to model TC directly from windspeed, while most GCMs only use course indices, such as temperature and precipitation. However, a downside to using the CCAM model is that it could only be run under one emission scenario (A2) due to lack of appropriate data for other emissions.

Projected changes in TCLV frequency are calculated for future climates (representative of approximately 2055 and 2090) using TCLV detections for 2046–2065 and 2081–2100, respectively. To quantify the climatological accuracy of each of the 11 simulations, I created a scale factor by comparing what past occurrences (1961-2000) each model would predict, with what was actually observed in the past. A scale factor of 1 is ideal, meaning that the model accurately predicted the observed frequency of cyclones in the past; a scale value of 0.5 over-represents past cyclone occurrence by two times; and a scale value of 2 under-represents past cyclone occurrence by half.

5.4. Results

5.4.1. Cyclone activity

A total of 172 cyclones passed through the study area between 1969 and 2007 (38 cyclone seasons) with an average of 4.52 (SE ± 1.78; range 2 to 9) cyclones each year (Figure 5.1). The frequency of hits per year decreased with time (Regression, $P = 0.054$, $r = -0.3236$, $F = 258\ 3.978$, $df = 1$). Cyclone occurrences were higher from Bowen northwards to Cardwell and into the Gulf of Carpentaria, whereas the frequency of cyclones was lower in the Torres Strait region (Figure 5.1).

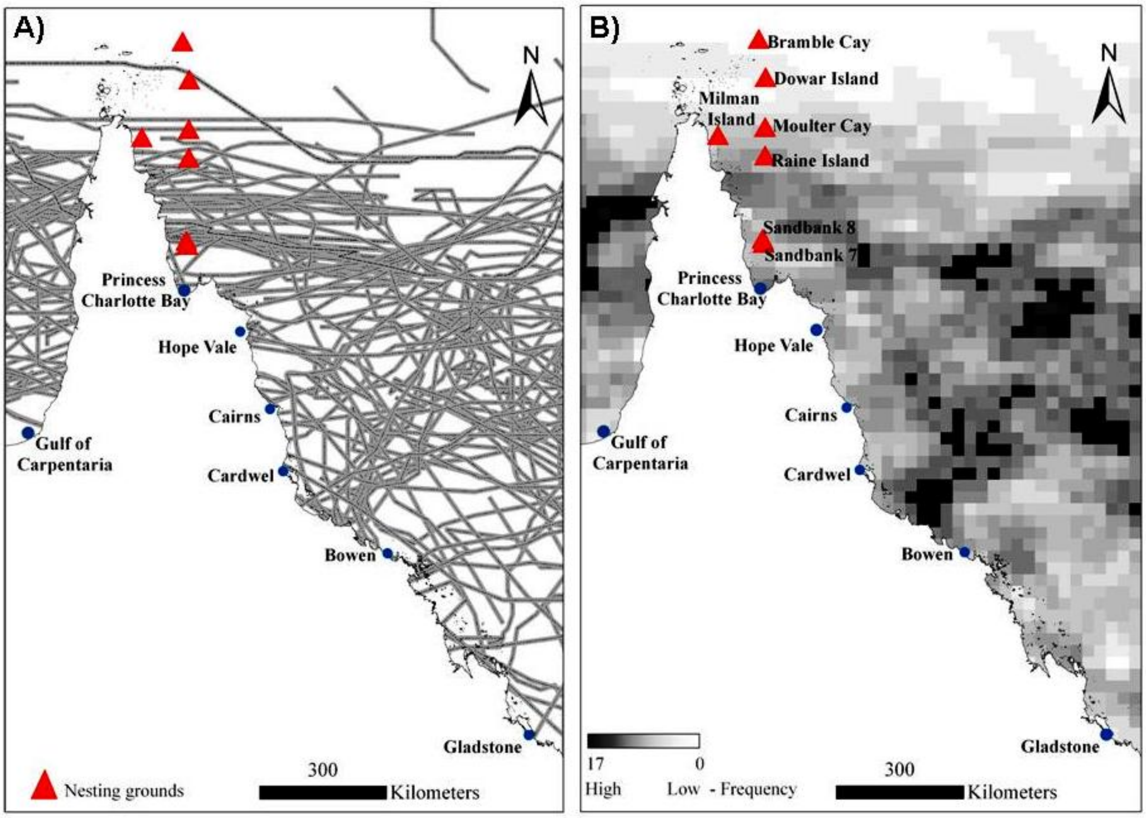

Figure 5.1. Cyclonic activities in eastern Queensland from 1969/70 to the 2006/07; A) cyclone tracks that crossed the study region, B) cumulative frequency of cyclones at the study region.

Cyclones occurred between November and May, with peak cyclone activity occurring during February (30.8% of cyclones; 1.2 hits per year) and January (23.8% of cyclones; 0.9 hits per year) (Figure 5.2).

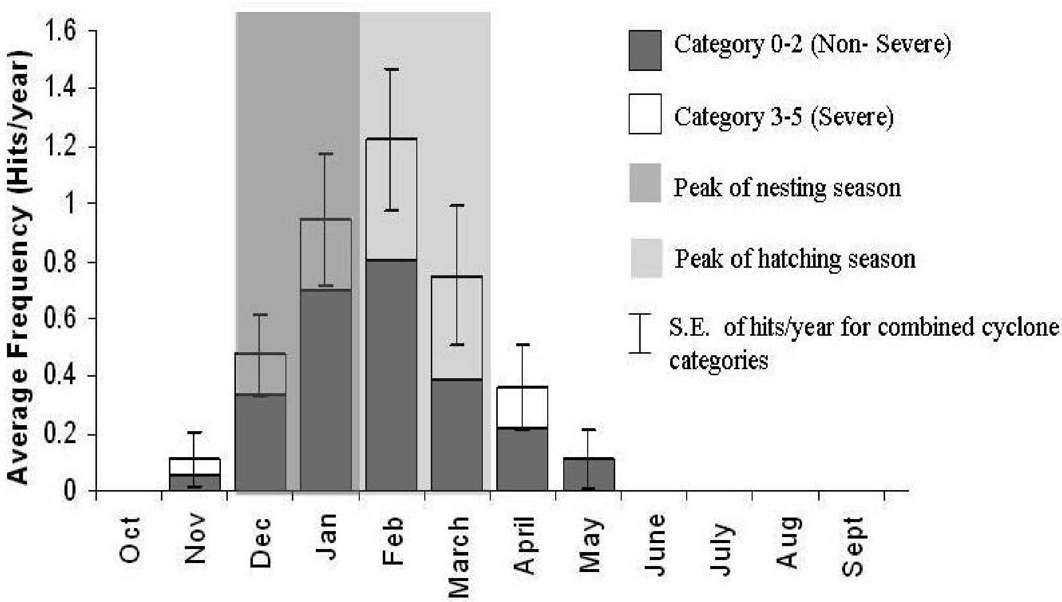

Figure 5.2. Average monthly activity of tropical cyclones in eastern Queensland and nesting phenology for the northern Great Barrier Reef green turtle population.

5.4.1.1. Historical frequency of cyclones at nesting grounds

Based on cyclone data from 1969 the selected nesting grounds used by the nGBR green turtle populations were directly hit by 0.08 (SE ± 0.005) cyclones a year. The frequency of cyclones that crossed each nesting ground varied between the different nesting grounds (ANOVA, P = 0.00, df = 4, F = 1044) (Figure 5.1 and Table 5.2); with the nesting grounds in the northern Great Barrier Reef region being most hit by cyclones while the nesting grounds in the Torres Strait region were the least hit by cyclones during the 38 year study period (Figure 5.1). Disturbance by cyclones occurred mostly in February- March which coincides with the peak of nesting for the northern Great Barrier Reef green turtle population (December – January) and while their eggs are incubating in the beach (January- February) (Figure 5.2)

Table 5.2. Average cyclonic activity a year at each of the selected nesting grounds used by the northern Great Barrier Reef green turtle population during the study period.

Nesting ground	Average frequency of direct cyclone hits a year	Average frequency of cyclone within 300km a year
Bramble Cay	0	0.125
Dowar Island	0.02	0.300
Milman Island	0.08	0.525
Moulter Cay	0.10	0.450
Raine Island	0.15	0.575
Sandbank 8	0.13	0.825
Sandbank 7	0.08	0.825

Boot strapping indicated that the northern Great Barrier Reef green turtle population is nesting in sites with lower cyclonic activity than other areas available for nesting. Mean cyclone frequency at nesting sites (3.04) was significantly lower (One- way ANOVA, P = 0.00, df = 999, F = 251.545, Post- Hoc turkey HSD, P =0.00 with all groups) than the mean frequency for the random subset of points generated (4.79 mean, range from 3.50 to 5.86).

5.3.2. Changes in cyclone frequency

5.3.2.1. Global climate models

According to the scale factor developed there is no 'best' model for the study region (Table 5.3). However, some model simulations are better than others; with GFDL 2.0, 2.1 best simulating the observed cyclonic activity and the forced Mk3.5 simulation generating the worst simulations for the study region (Tables 5.3 to 5.5).

Table 5.3. Scale factor developed to investigate the efficiency of each climate model; 1 = model accurately predicts observed cyclonic activity; 0.5 = model over represents cyclone occurrence by two times; and 2 = model under represents cyclone occurrence by half.

Nesting ground Model	Bramble Cay	Dowar Island	Milman Island	Moulter Cay	Raine Island	Sand. 8	Sand. 7	Average
Mk3.0_A2_M20th (Forced)	0.33	0.60	1.05	0.90	0.88	1.10	1.10	0.9
ECHAM5 (SST)	5.00	6.00	3.50	3.60	2.56	2.06	2.06	3.5
GFDL 2.0 (SST)	0.56	1.09	1.11	0.95	1.15	1.50	1.50	1.1
GFDL 2.1 (SST)	0.83	1.20	1.31	0.95	1.00	1.18	1.18	1.1
MIROC 3.2 – medres (SST)	2.50	4.00	3.00	2.00	2.09	1.94	1.94	2.5
Mk3.5 - A2 - B35 (SST)	0.83	1.71	3.50	2.25	2.30	2.20	2.20	2.1
UK HADCM3 (SST)	5.00	6.00	2.10	2.25	1.92	1.65	1.65	2.9
Mk3.5 - A2 - B35 (Forced)	12.00	6.00	10.50	9.00	11.50	8.25	8.25	9.4
ECHAM 5 (Forced)	0.42	0.60	0.95	0.75	0.96	1.38	1.38	0.9
GFDL 2.1 (Forced	0.36	0.60	0.88	0.69	0.82	1.00	1.00	0.8
MIROC 3.2 – medres (Forced)	0.83	0.92	1.24	1.00	1.10	1.83	1.83	1.3

5.3.2.2. Projected frequency of cyclones

I found a great variability in the regional predictions among the various climate models for both 2055 and 2090. Nevertheless, while there is a wide variation in the results most model simulations, except Mk3.5 - A2 - B35 (Forced), indicate a future decrease in cyclonic activity for the study region (Table 5.4 and 5.5).

Table 5.4. Percentage of predicted change in cyclone frequency at each nesting ground under different simulation models for 2055. Positive numbers indicate a positive increase in frequency of cyclones; negative numbers indicate a decrease in cyclonic activity; NC, indicates no cyclone activity for that site; SAME, indicates no change in cyclonic activity; and DOUBLE, indicates a prediction of two times the current cyclonic activity for that site.

Nesting ground Model	Bramble Cay	Dowar Island	Milman Island	Moulter Cay	Raine Island	Sand. 8	Sand. 7
Mk3.0_A2_M20th (Forced)	-40.0	-58.3	-19.0	-22.2	-21.7	-21.2	-21.2
ECHAM5 (SST)	DOUBLE	SAME	-66.7	-61.1	-78.3	-36.4	-36.4
GFDL 2.0 (SST)	NC	-66.7	-81.0	-66.7	-69.6	-81.8	-81.8
GFDL 2.1 (SST)	-60.0	-83.3	-61.9	-66.7	-56.5	-51.5	-51.5
MIROC 3.2 – medres (SST)	NC	NC	NC	NC	-82.6	-75.8	-75.8
Mk3.5 - A2 - B35 (SST)	NC	-41.7	-33.3	-50.0	-60.9	-60.6	-60.6
UK HADCM3 (SST)	NC	NC	NC	NC	NC	-90.9	-90.9
Mk3.5 - A2 - B35 (Forced)	NC	DOUBLE	DOUBLE	DOUBLE	DOUBLE	SAME	SAME
ECHAM 5 (Forced)	-40.0	-41.7	-47.6	-33.3	-34.8	-24.2	-24.2
GFDL 2.1 (Forced	-60.0	-50.0	-47.6	-44.4	-43.5	-15.2	-15.2
MIROC 3.2 – medres (Forced)	-60.0	-83.3	-90.5	-88.9	-91.3	-78.8	-78.8

Table 5.5. Percentage of predicted change in cyclone frequency at each nesting ground under different simulation models for 2090. Positive numbers indicate a positive increase in frequency of cyclones; negative numbers indicate a decrease in cyclonic activity; NC, indicates no cyclone activity for that site; SAME, indicates no change in cyclonic activity; and DOUBLE, indicates a prediction of two times the current cyclonic activity for that site.

Nesting ground Model	Bramble Cay	Dowar Island	Milman Island	Moulter Cay	Raine Island	Sand. 8	Sand. 7
Mk3.0_A2_M20th (Forced)	-17.4	-20.0	-16.7	SAME	SAME	SAME	SAM
ECHAM5 (SST)	NC	NC	NC	NC	NC	NC	-66.7
GFDL 2.0 (SST)	-91.3	NC	NC	-81.8	-81.8	-88.9	-90.5
GFDL 2.1 (SST)	-82.6	NC	-83.3	-78.8	-78.8	-77.8	-85.7
MIROC 3.2 – medres (SST)	NC	NC	NC	NC	NC	NC	NC
Mk3.5 - A2 - B35 (SST)	SAME	-40.0	-41.7	-6.1	-6.1	NC	NC
UK HADCM3 (SST)	NC	NC	NC	NC	NC	NC	NC
Mk3.5 - A2 - B35 (Forced)	DOUBLE	NC	DOUBLE	NC	NC	DOUB	300.0
ECHAM 5 (Forced)	-65.2	NC	-91.7	-33.3	-33.3	-72.2	-71.4
GFDL 2.1 (Forced	-78.3	-60.0	-66.7	-75.8	-75.8	-77.8	-66.7
MIROC 3.2 – medres (Forced)	NC	NC	NC	NC	NC	NC	NC

5.5. Discussion

5.5.1. Past and current cyclonic activity at the nesting grounds

All of the studied nesting grounds were affected by cyclonic activity during the study period (1969-2007). The frequency of cyclones that crossed each nesting ground varied greatly as a function of that nesting ground's location. Nesting grounds in the northern Great Barrier Reef have, in average, historically been hit by cyclones every nine years, whereas nesting grounds in Torres Strait have only been hit by cyclones one time during the thirty-eight years study period. This is relatively low when compared to other nesting grounds globally. For example, Canaveral National Seashore, a green turtle nesting ground in Florida, experienced an average of 1.2 cyclones/year from 1989-2005 (Pike and Stiner 2007). However, even though the overall disturbance of cyclones to the nGBR green turtle population is low, it is important to note that disturbance by cyclones has occurred mainly while their eggs are incubating in the beach.

Cyclonic activity can impact nesting grounds in several ways. Cyclones can cause beach erosion and thus alterations to the beach morphology (see Taylor 1924 and Hopley 1978). This will expose egg clutches to the elements and predators causing substantial loss of eggs (Limpus 1971, 1985; Eckert 1987). If nesting beaches are substantially altered turtles may have to change nesting location (Shanker 1999). If this is the case, resilience of sea turtle populations will also rely on their ability to shift nesting locations to more functional areas. In the future it is likely that nesting areas will be scarcer as sea level rise and increased temperature will also reduce the amount of optimal nesting areas available to sea turtles in the future (Chapters 3-4). Shift in nesting location may have diverse implications for turtle populations as they may start to nest in areas with different threats, currents, incubation habitat, and/or conservation measures in place.

The degree of damage from cyclones to each nesting ground will vary depending on:
(1) Site location (e.g. cays, mainland) and its characteristics (vegetation, sedimentology and morphology) - mainland beaches are more prone to erosion and loss of eggs than reef islands and cays since they are not directly protected by reefs and are more exposed to processes associated by cyclones. As all the nesting grounds used by the nGBR green turtle population are islands or cays this population has an advantage in comparison to other sea turtle populations in Australia that have important mainland nesting grounds (e.g. eastern Australia loggerhead and flatback populations);

(2) Tidal regime during cyclone activities – during spring tide larger high energy waves reach the beach zone causing more damage to nesting sites than during neap tide, when it is hard for associated waves to reach the beach and cause erosion (Boswood and Mohoupt 2007);

(3) Direction of the generated wind - North/ northeast winds cause more damage than winds from the south/southwest, as the former originates from the open ocean and creates high winds and generates big seas;

(4) Angle and direction that a cyclone track passes over each site - for the region studied here, cyclones that pass in a northern direction usually cause more damage than cyclones in a southern direction because northern cyclones are accompanied by wave activity originating from the Coral Sea while wave activity from southern cyclones are associated with coastal seas, which usually do not allow as large swells to build up;

(5) Characteristics of cyclones, such as central pressure, speed and intensity (Flood 1986).

The overall impact from cyclonic activity to the nGBR green turtle population will be a result of the importance of the nesting sites (in terms of the number of turtles nesting a year) which are most severely and frequently hit. For example, disturbance to Raine Island and Moulter Cay, where the majority of nesting for the nGBR green turtle population occurs, as opposed to any other minor nesting ground will have a disproportional impact on this green turtle population. The results from this study indicate that the nesting grounds that are most frequently hit by cyclones (Sandbank 7 and 8) have lower importance to the overall nGBR green turtle population in relation to the nesting sites that are least frequently hit by cyclones (e.g. Bramble Cay and Moulter Cay).

The overall impacts to the nGBR green turtle population will also depend on the size of the nesting season during a particular cyclonic event. The number of green turtles nesting each year correlates with the Southern Oscillation index 18 months before the breeding season (Limpus and Nicholls 2000; Limpus et al. 2003). Consequently, summers with fewer cyclones may actually have a greater impact if they fall during a year with a higher reproductive effort compared with a year during which several cyclones occur during a low nesting year. The most destructive years are those with a high frequency of cyclones coinciding with a year with high nesting density (Pike and Stiner 2007). This was the case in Queensland in 1984–1985, 1989–1990, 1995–1996 and 1997–1998 when green turtle nesting (Limpus et al. 2003) and cyclone frequencies (Australian Bureau of Meteorology 2008) were both high. The overall impact of cyclones to the nGBR green turtle population was probably very high during the 1984/1985 season as Raine Island was directly hit by one cyclone.

5.5.2. Future cyclonic activity at the nesting grounds

The number of cyclones that will disturb the nesting grounds used by the nGBR green turtle population is predicted to decrease. However, determining the exact extent of this reduction has proven to be challenging due to the large amount of variation in projections among the various models used. Variability in the results from the various model simulations reflects the high uncertainty in future projections of cyclonic activity. This is a result of TCs not being well resolved by global or regional climate models (e.g. Walsh and Pittock 1998). Variation in model predictions may be a result of each model's thermodynamic constant, assumptions, and convection schemes (Emanuel et al. 2008).

Indeed, several studies have highlighted the uncertainties and variability regarding future cyclonic activities (e.g. Hughes 2003; Emanuel et al. 2008). Although predictions of cyclonic activity in a warming climate do vary, most studies predict an intensification of cyclones (Knutson et al. 1998; Walsh and Ryan 2000; Oouchi et al. 2006; Elsner et al. 2008), and a decrease in the global frequency of cyclones (Bengtsson et al. 1996; McDonald et al. 2005; Sugi et al. 2002; Oouchi et al. 2006; Bengtsoon et al. 2007; Yoshimura et al. 2006; Vecchi and Soden 2007; Zhao et al. 2009). Thus, the results from this study are broadly consistent with the literature and current models.

Projected cyclonic intensification is likely to occur as a result of future increases in temperature and the amount of water vapour, both of which provide more energy for storms (Bengtsson et al. 2007). Projected decreases in cyclonic activity are likely to occur as a result from an increase in the static stability and a reduction of tropical vertical atmospheric circulation, caused by large increases in atmospheric water vapour (Bengtsson et al. 2007).

Projected changes in cyclonic intensity and activity will alter the impact that this sea turtle population will experience. Projected intensification of cyclones will likely cause a reduction of hatching success at nesting grounds, as nest inundation is higher in years where cyclone intensities are stronger (Pike and Stiner 2007; Van Houtan and Bass 2007). This will negatively affect the reproductive output at each nesting site. Nevertheless, a reduction in the frequency of cyclonic activity, as predicted here, will provide nesting grounds with more chance to recover and return to pre-threat conditions. This will result in a reduction of the temporal scale that each nesting ground will be negatively affected, and thus the long-term disturbance that turtles may experience.

The disturbance that the nGBR green turtle population will experience, in the future, from cyclones may also be altered as other factors change with climate change. For example, if the nGBR green turtle population starts to nest earlier as a result of warmer SST, as has been observed for loggerhead turtles in Florida (see Pike et al. 2006), the level of disturbance that they will experience in the future will change. Similarly, if this population shifts their nesting to more southern beaches, to adapt to sea level rise or increased sand temperature (Chapter 3-4), and therefore start to nest in regions with more cyclonic activity, the impacts that they will experience from cyclone may also change.

5.6. Chapter summary

Sea turtles lay their eggs in sandy ocean-exposed beaches frequented by cyclones and therefore may be impacted by them in the long term through beach erosion and in the short term, during egg incubation, by increased localised mortality of eggs and changes in sand temperature. Historically, the selected nesting grounds, especially the ones in the Torres Strait region, have experienced little disturbance from cyclonic activity, with nesting grounds being hit on average every nine years and thirty-eight years in the northern Great Barrier Reef and Torres Strait region respectively. Climate change is expected to alter the frequency, intensity and distribution of cyclones. This study indicates that as climate change progresses it is likely that impacts from cyclones to the nGBR green turtle population will be even lower as a reduction in cyclonic activity is predicted for the studied region.

However, a reduction in future cyclonic frequency may not have significant effects on the nGBR green turtle population as historically, they have experienced very low disturbance by cyclones. Nevertheless, changes in cyclone frequency may have a more positive affect on the population stability and reproductive output of turtle populations that are hit more often by cyclone activity, such as sea turtle nesting grounds in Florida.

Chapter 6.

Relative impact of various climatic processes on sea turtle nesting grounds: Using experts' opinions to inform management [1]

[1] **Fuentes MMPB**, and Cinner JE (in review) Impact of climate change to sea turtle nesting grounds: using experts' opinions to inform management. Journal of Environmental Management

6.1. Abstract

The terrestrial life stage of sea turtles and thus their reproductive output can be impacted by various climatic processes at different temporal and geographical scales. In the context of limited resources, managers will likely need to prioritise their resources and time. In order to do this efficiently, managers will need to know which climatic process will cause the most impact on sea turtles and the relative impact of each process. However, no study to date has systematically investigated the relative impact of different climatic processes, such as sea level rise, cyclonic activity, and increased sand temperatures on sea turtles. This makes the prioritization of decisions challenging. Expert knowledge has been widely used to obtain information on how a threatening process affects an ecosystem and their relative impact compared to other threats. Therefore, in this Chapter I used expert opinion, from managers and scientists, to gather information on the relative impact of key climatic processes on the nesting grounds utilised by the nGBR green population. I was also able to investigate whether there were differences in how managers and scientists perceive the impacts and consequences of different climatic processes on sea turtles.

Both scientists and managers agreed ,that from the main climatic processes investigated in this thesis (increased temperature, sea level rise, and cyclonic activity), increased sand temperature is the greatest climate related threat to the terrestrial reproductive phase of the nGBR green turtle population as climate change progresses followed by sea level rise, then cyclonic activity. Experts were in wide agreement about many of the likely consequences of these threats, although managers viewed the possibility of more intense and more frequent cyclones as more severe than scientists. Both scientists and managers perceived high levels of uncertainty about many of the potential consequences of climate change on sea turtles. Thus, further research on this topic is warranted, especially with regards to the adaptive capacity of turtles.

6.2. Introduction

As explored in the previous Chapters (2-5) the terrestrial life stage of sea turtles and thus their reproductive output can be impacted by various climatic processes (e.g. sea level rise, cyclonic activity, and increased sand temperatures) at different temporal and geographical scales. The reproductive output of the nGBR green turtle population may be impacted in two broad ways: (1) increased sand temperature will skew their sex ratios towards a predominantly female output and expose sea turtle eggs to temperatures that can exceed the upper thermal threshold for embryo development (Chapter 3); and (2) sea level rise and cyclonic activity can cause erosion and increased inundation of nesting beaches impacting the stability of nesting areas and hatching success (Chapter 4-5). In the context of limited resources for management implementation, managers will likely need to prioritise which threats to mitigate and where to focus their resource and time.

A number of research and management agencies have developed threat-ranking processes to aid the prioritization of conservation actions (e.g. Kappel 2005; Halpern et al. 2007; Kleypas and Eakin 2007; Selkoe et al. 2008; Brooks et al. 2009). A variety of approaches have been suggested to aid managers in allocating their resources, which include: (1) prioritizing threats with the greatest impact first (Pressey et al. 2003, Kappel 2005; Halpern et al. 2007; Higgason and Brown 2009; Mazaris et al. 2009 b), or (2) allocating resources to areas where the impact of threat is low and successful implementation of actions are considered likely (Jameson et al. 2002). Despite the priorities and goals (e.g. protect the most threatened versus the least threatened site) of different agencies, to implement any of these management strategies efficiently managers require information on: (1) the magnitude and relative impact of each threat, (2) knowledge gaps, (3) different management options, and (4) the likelihood of these options providing the desired conservation outcomes (Wilson et al. 2005; Joseph et al. 2008).

In the case of sea turtles and impacts from climate change no study has systematically investigated the relative impact of different climatic processes to sea turtle nesting grounds, making it challenging for managers to prioritise their decisions and to focus management. The studies conducted to date have either investigated how a particular climatic process (e.g. sea level rise) will affect sea turtles (e.g. Fish et al. 2005; Hawkes et al. 2007 b) or generally reviewed how sea turtles will be impacted by climate change (e.g. Hamann et al. 2007; Hawkes et al. 2009; Poloczanska et al. 2009). Consequently, there is a clear need to investigate the relative impact and magnitude of various climatic processes on sea turtles at a population level to aid prioritization of management decisions.

Expert knowledge has been used widely to compensate for unavailable data and uncertainty on how a threatening process affects an ecosystem and its relative impact compared to other threats (Halpern et al. 2007; Grech and Marsh 2008; McClanahan et al. 2008; Newson et al. 2009; Robinson et al. 2009). Therefore, I used expert opinion to gather information on the relative impact of key climatic processes on sea turtle nesting grounds as well as the relative impact of different levels of impact and frequency from each climatic process. Further, I also investigated the relative impact of sea turtles having different capacity to adapt to each climatic process. The expert panel for this study was comprised of scientists and managers from key agencies and with extensive knowledge of north Queensland's sea turtles. Thus, I was also able to investigate whether there were differences in how managers and scientists perceive the impacts and consequences of different climatic processes on sea turtles. In doing so, it is the first study to investigate the relative impact of different climatic processes on the terrestrial reproductive phase of sea turtles and to categorise the consequence of different impact levels from various climatic processes.

6.3. Methods

6.3.1. Expert panel

The expert panel for this study was comprised of both managers and scientists with extensive knowledge of north Queensland's sea turtles, their management, and some of the potential threats they may face in relation to climate change. I identified potential respondents for this study through (1) the Web of Science for Literature, by selecting scientists that have conducted research on sea turtles and climate change and that have extensive knowledge of Australian's sea turtles; and (2) from government agencies responsible for marine turtle management in northern Australia, by selecting managers with extensive knowledge of north Queensland's sea turtles, their management, and some of the potential threats they may face in relation to climate change. Thirty potential respondents were identified and 22 experts (11 managers and 11 scientists) responded to the survey. Although the number of respondents may seen low, it represents a high percentage (73%) of the potential respondents that had the adequate knowledge to answer the survey. Respondents were from 10 different agencies including the Great Barrier Reef Marine Park Authority, Torres Strait Regional Authority, Queensland Department of Environment and Resource Management, James Cook University, University of Queensland, University of Sydney, University of Melbourne, Charles Darwin University, and Southern Cross University.

6.3.2. Surveys

For this aspect of my thesis, I only investigated the relative impact of increased temperature, sea level rise and cyclonic activities on sea turtles. The relative impact from changes in sediment traits (as per Chapter 2) was not considered as there are still a lot of uncertainties on how changes in sediment traits will affect sea turtles and this may mask and influence the answers provided by the respondents.

To determine weights (W) for the relative impact of increased temperature, sea level rise and cyclonic activity I asked experts to complete a series of pair-wise comparison matrixes and to indicate scores for their perception of the relative severity of each climatic process. Respondents could assign 17 different scores to each comparison; scores ranged from extremely less impact to extremely more impact (see Appendix A for survey). Weights were calculated from the scores given in the matrices using Analytic Hierarchy Process (AHP) (Saaty 1980) calculation software available at http://www.isc.senshu-u.ac.jp/~thc0456/EAHP/AHPweb.html. After each pair-wise comparison, I asked respondents to indicate how certain they were about their answers in order to identify knowledge gaps. Certainty values ranged from no certainty to very high certainty (Table 6.1).

Table 6.1. Certainty category used by expert groups to assess their certainty in completing each pair-wise comparison matrixes.

Certainty category	Description	Value
None	No certainty	0
Low	Very little or no empirical work exists or expert has limited personal experience	1
Medium	Some empirical work exists or expert has some personal experience	2
High	Empirical work exists and the expert has direct personal experience	3
Very high	Extensive empirical work exists and /or the expert has extensive personal experience	4

A similar process was conducted to investigate the relative impact of different levels/magnitude of sensitivity (level that each nesting ground will be impacted by each climatic process) and exposure (frequency that each of the selected nesting ground will be exposed to each climatic process) of each climatic process as well as the relative impact of sea turtles having different capacity to adapt to each climatic process. For this I assigned different levels of sensitivity, exposure and adaptive capacity to each of the climatic processes; levels were assigned based on the results from Chapters 3-5 (Table 6.2).

Table 6.2. Different levels of sensitivity, exposure and adaptive capacity assigned to each climatic process.

Climatic process	Sensitivity (impact level)	Exposure (frequency)	Adaptive Capacity
Increased sand temperature	Temperatures above pivotal temperature	No increase in temperature	Ability to adapt within a nesting season
	Temperature above upper transient range	Occasionally – increase in temperature during only one nesting season	Ability to adapt after a turtle generation
	Temperatures near the upper thermal threshold	Often- during one turtle generation (40 years)	No ability to adapt
	Temperature above upper thermal threshold	Increase in temperature is constant	
Sea level rise	Loss of up to 10% of current nesting area	Sea level rise never occurs	Ability to adapt within a nesting season
	Loss of 10% to 35% of current nesting area	Occasionally – discrete events of sea level rise, storm surges	Ability to adapt after a turtle generation
	Loss of 35% to 60% of current nesting area	Often- sea level rise over one turtle generation (40 years)	No ability to adapt
	Loss of 60% to 85% of current nesting area	Sea level rise is constant	
	Loss of 85% to 100 % of current nesting area		
Cyclonic activity	Decrease in frequency of cyclones	No cyclonic activity	Ability to adapt within a nesting season
	Decrease in frequency and increase in more intense	Occasionally – 1 cyclone every 30 years	Ability to adapt after a turtle generation
	Increase in frequency of cyclones	Often- 1 cyclone every 5 years	No ability to adapt
	Increase in frequency and more intense cyclones	Constant – one cyclone every nesting season	

Experts were also asked to assign a consequence category to different levels of sensitivity for each climatic process. The consequence categories are based on the environment risk management framework used by the Great Barrier Reef Marine Park Authority (Great Barrier Reef Marine Park Authority 2009) (Table 6.3).

Table 6.3. Description of consequence categories that respondents were asked to assign to different levels of climatic impact.

Consequence categories	Definition	Category value
Catastrophic	Impact is clearly affecting the species over a wide area or impact is irreversible over a small area (nesting ground level) or a sensitive part of the ecosystem is irretrievably compromised.	1
Major	Impact is significant at either a local or population level to the species or nesting habitat.	2
Moderate	Impact is present either at a local or population level. Recovery period within one generation (40 years) are likely.	3
Minor	Impact is present but not to the extent that it would impair the overall condition of the species or population.	4
Insignificant	No impact on the overall condition of the species or population.	5

6.3.3. Analyses

The Mann-Whitney U test was used to examine whether the weightings and the consequence categories given by the managers were different from the scientists. Because my sample size was small (n = 22) I conducted a power analysis to determine whether there was statistical power to detect any significant difference between the two expert groups (managers and scientists). I also calculated Cohen's d effect size (d) to measure the magnitude of differences between groups (Cohen 1988; Vaske et al. 2002).

6.4. Results

6.4.1. Relative impact of each climatic process

Both managers and scientists perceive increased sand temperature to be the largest threat to the terrestrial reproductive phase of the nGBR green turtle population followed by sea level rise and cyclonic activity (Table 6.4).

Table 6.4. Relative weights assigned to each climatic process. Bold indicates a moderate relationship ($d \geq 0.5$) between expert groups.

Climatic Process	Averaged weights	Weights (managers)	Weights (scientists)	P	d	Power
Increased sand temperature	0.55	0.60	0.50	0.53	**0.50**	0.19
Sea level rise	0.27	0.21	0.33	0.57	**0.62**	0.28
Cyclonic activity	0.18	0.19	0.17	0.62	-0.08	0.05

Moderate effect sizes (d) suggest that managers perceived the relative impact of increased sand temperature to be higher and the relative impact of sea level rise to be lower than what scientists perceived (Table 6.4). These differences were not statistically significant, but the power to detect differences was low.

6.4.2. Relative impact from different levels of sensitivity

Managers and scientists generally perceived the impact of different sensitivity levels from each climatic process to be similar. A significant difference in perception was only found in relation to the impact of temperatures being above the upper transient range (30.8 ˚C- for the nGBR green turtles- see Chapter 3), that is only female turtles being produced, with managers perceiving the impacts from temperatures above the upper transient range to be higher than what scientists perceived (Table 6.5).

6.5. Relative weights assigned to different levels of sensitivity (impact) from each climatic process. Bold indicates a significant difference and a moderate relationship (d $\geq$ 0.5) between expert groups. M stands for managers and S for scientists.

Impact level (sensitivity)	Averaged weights	Weights (M)	Weights (S)	P	d	Power
Increased sand temperature						
Temperatures above pivotal temperature	0.04	0.05	0.04	0.46	**0.70**	1.00
Temperature above upper transient range	0.10	0.12	0.08	**0.02**	**0.84**	0.79
Temperatures near the upper thermal threshold	0.24	0.24	0.23	0.42	0.06	0.71
Temperature above upper thermal threshold	0.62	0.59	0.65	0.08	**-1.06**	0.06
Sea level rise						
Loss of up to 10% of current nesting area	0.03	0.03	0.04	0.62	0.29	0.10
Loss of 10% to 35% of current nesting area	0.05	0.06	0.05	0.53	-0.50	0.19
Loss of 35% to 60% of current nesting area	0.11	0.12	0.11	0.21	**-0.73**	0.13
Loss of 60% to 85% of current nesting area	0.25	0.25	0.24	0.36	-0.33	0.14
Loss of 85% to 100 % of current nesting area	0.55	0.54	0.57	0.23	0.47	0.18
Cyclonic activity						
Decrease in frequency of cyclones	0.06	0.07	0.06	1.00	0.49	0.20
Decrease in frequency and more intense cyclones	0.14	0.16	0.11	0.62	0.34	0.12
Increase in frequency of cyclones	0.22	0.22	0.23	0.94	-0.05	0.05
Increase in frequency and more intense cyclones	0.58	0.55	0.61	0.40	-0.46	0.20

6.4.3. Relative impact of different exposure of each climatic process

Both scientists and managers perceived the relative impact of different exposure levels from each climatic process to be similar (Table 6.6).

Table 6.6. Relative weights assigned to different exposure levels from each climatic process. M stands for managers and S for scientists.

Frequency of climatic processes	Averaged weights	Weights (M)	Weights (S)	P	d	Power
Increased sand temperature						
No increase in temperature	0.06	0.06	0.05	0.23	0.17	0.25
Occasionally – increase in temperature during only one nesting season	0.10	0.10	0.09	0.76	0.33	0.13
Often- during one turtle generation (40 years)	0.22	0.22	0.23	0.88	0.28	0.44
Increase in temperature is constant	0.63	0.61	0.64	0.40	-0.15	0.05
Sea level rise						
Sea level rise never occurs	0.05	0.05	0.05	0.29	-0.38	0.14
Occasionally – discrete events of sea level rise, storm surges	0.11	0.12	0.10	0.14	0.14	0.06
Often- sea level rise over one turtle generation (40 years)	0.25	0.24	0.26	0.44	-0.37	0.13
Sea level rise is constant	0.59	0.58	0.60	0.48	0.09	0.06
Cyclonic activity						
No cyclonic activity	0.07	0.08	0.06	1.00	0.49	0.20
Occasionally – 1 cyclone every 30 years	0.11	0.11	0.10	0.62	0.34	0.12
Often- 1 cyclone every 5 years	0.22	0.20	0.24	0.94	-0.05	0.05
Constant – one cyclone every nesting season	0.60	0.61	0.59	0.40	-0.46	0.20

6.4.4. Relative impact of different adaptive capacity levels to each climatic process

No statistical difference was found between managers and scientists perception on the impact of sea turtles having different ability to adapt to climate change. However, moderate effect size and low power suggests that there may potentially be a difference on how each expert group perceives the impact from sea turtles adapting to increased temperature and sea level rise (Table 6.7).

Table 6.7. Relative weights assigned to different levels of adaptive capacity from each climatic process. Bold indicates a moderate relationship ($d \geq 0.5$) between expert groups and potentially a difference between how managers and scientists perceive impacts. M stands for managers and S for scientists.

Adaptive capacity	Averaged weights	Weights (M)	Weights (S)	P	d	Power
Increased sand temperature						
Ability to adapt within a nesting season	0.08	0.40	0.20	0.15	**-0.66**	0.20
Ability to adapt after a turtle generation	0.21	0.25	0.16	0.07	**-0.84**	0.12
No ability to adapt	0.71	0.35	0.63	0.05	**0.92**	0.08
Sea level rise						
Ability to adapt within a nesting season	0.10	0.19	0.14	0.56	-0.26	0.44
Ability to adapt after a turtle generation	0.25	0.29	0.20	0.15	**-0.64**	0.20
No ability to adapt	0.65	0.52	0.66	0.21	**0.57**	0.20
Cyclonic activity						
Ability to adapt within a nesting season	0.11	0.21	0.14	0.48	-0.30	0.11
Ability to adapt after a turtle generation	0.22	0.26	0.22	0.53	-0.27	0.14
No ability to adapt	0.68	0.53	0.64	0.38	0.39	0.22

6.4.5. Perceived consequences

No significant difference was found between the consequence categories assigned by the managers and scientists to the different levels of sensitivity from each climatic process (Table 6.8). However, moderate effect size and low power suggests that there may potentially be a difference on how each expert group perceives the consequences of decrease in frequency of cyclones (Table 6.8).

Table 6.8. Differences in the mean consequence category assigned, by managers and scientists, to each level of sensitivity for each climatic process. Bold indicates a moderate relationship (d $\geq$0.5) between expert groups and potentially a difference between the consequences assigned by the managers and scientists. M stands for managers and S for scientists.

Climatic process	Impact level	Mean category (M)	Mean category (S)	P	Standardised effect size (d)	Power
Increased sand temperature	Temperatures above pivotal temperature	1.5	1.9	0.74	-0.19	0.07
	Temperature above upper transient range temperature	2.1	2.6	0.45	-0.44	0.16
	Temperatures near the upper thermal threshold	2.9	3.0	0.48	0.17	0.07
	Temperature above upper thermal threshold	2.9	3.5	1.00	-0.11	0.06
Sea level rise	Loss of up to 10% of current nesting area	0.9	0.9	0.70	-0.26	0.09
	Loss of 10% to 35% of current nesting area	1.6	1.9	1.00	-0.12	0.05
	Loss of 35% to 60% of current nesting area	2.3	2.6	0.94	0.07	0.05
	Loss of 60% to 85% of current nesting area	3.1	3.5	0.51	-0.31	0.31
	Loss of 85% to 100 % of current nesting area	3.3	3.7	0.60	0.41	0.14
Cyclonic activity	Decrease in frequency of cyclones	0.4	0.2	0.11	**0.73**	0.34
	Decrease in frequency and increase in more intense clones	1.1	1.4	0.91	-0.06	0.05
	Increase in frequency of cyclones	1.6	2.0	0.79	-0.13	0.06
	Increase in frequency and more intense cyclones	2.5	2.3	0.11	**0.74**	0.34

6.4.5.1. Increased sand temperature

Temperatures above the pivotal temperature, where a higher percentage of females are produced, was perceived to cause minor to moderate impact to sea turtles. However, more than 50% of the expert panel considered temperatures above the upper thermal threshold (above 33 ˚C) to be catastrophic to sea turtles (Figure 6.1).

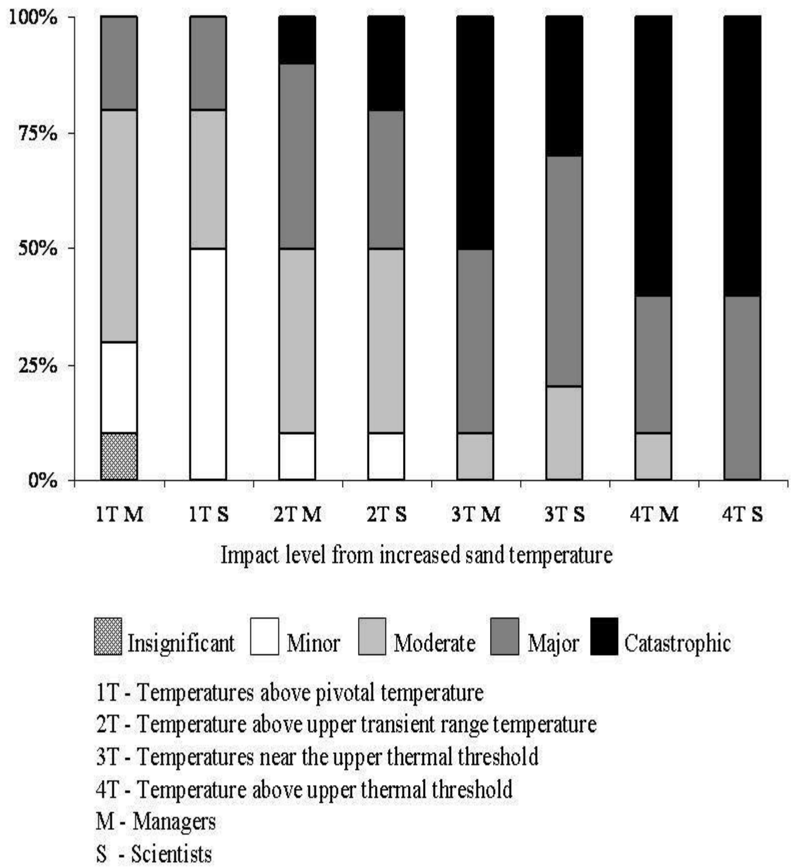

Figure 6.1. Consequences attributed by the expert panel to various level of increased sand temperature.

6.4.5.2. Sea level rise

The consequence levels assigned to the different levels of sea level rise augmented as the percentage of nesting ground inundated increased. However, some managers indicated that 85 to 100% of nesting ground loss would cause minor impact to sea turtles, as by that stage sea turtles would already have adapted and selected different nesting grounds (Figure 6.2 and Table 6.8).

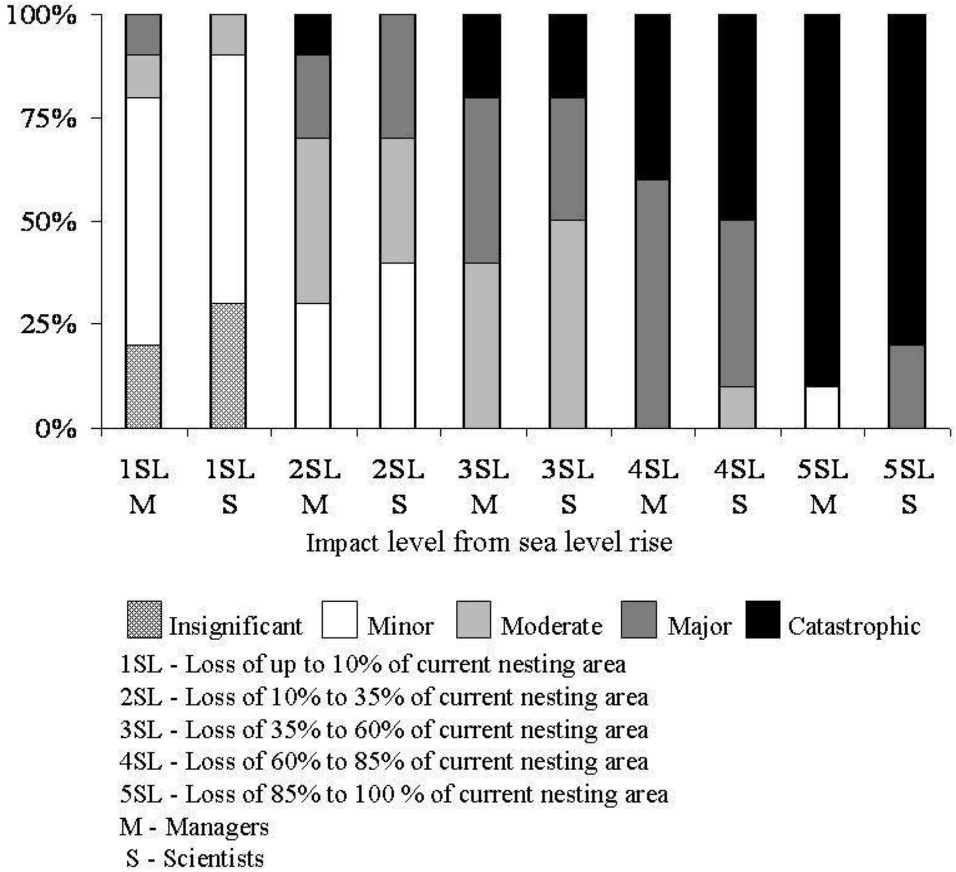

Figure 6.2. Consequences attributed by the expert panel to various level of sea level rise.

6.4.5.3. Cyclonic activity

Two moderate effect size relationships suggest that there may be some differences in how managers and scientists perceive the consequences from cyclonic activity (Table 6.8, Figure 6.3). These relationships are not statistically significant, but there was low power to detect differences (Table 6.8). In both occasions managers perceived the consequences to be higher than what scientists perceived (Figure 6.3). At least one fourth of managers considered an increase in frequency and more intense cyclones to be catastrophic while no scientists assigned this consequence category to this impact level.

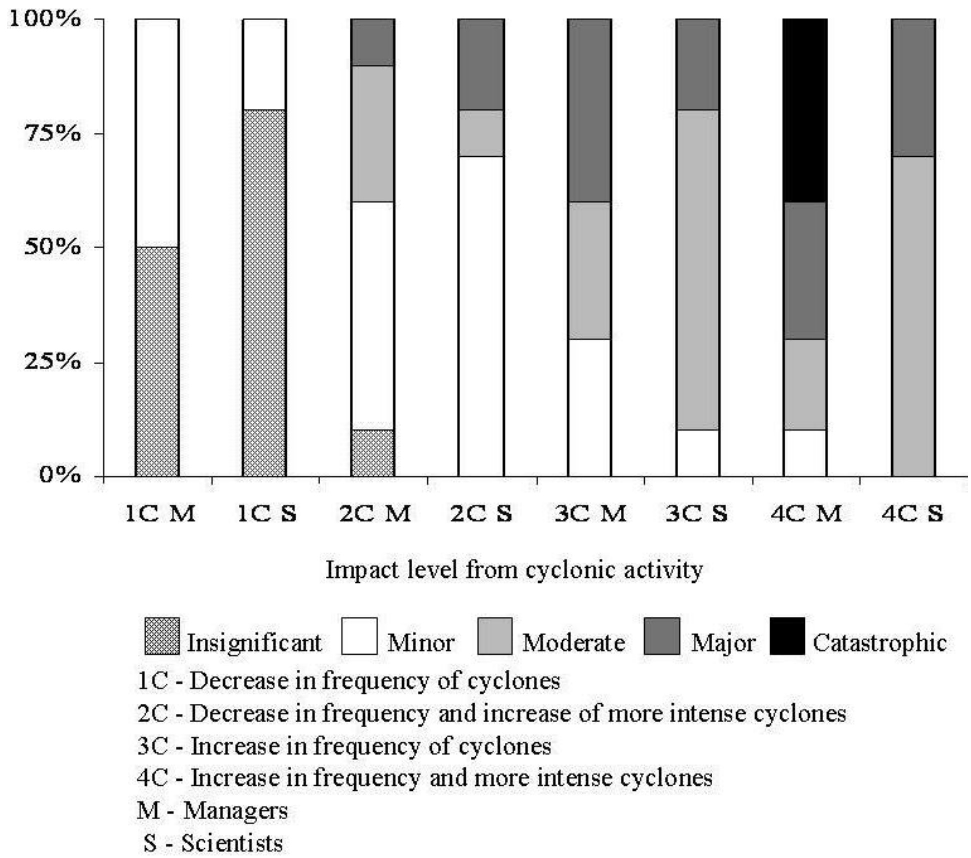

Figure 6.3. Consequences attributed by the expert panel to various levels of cyclonic activity.

6.4.6. Gaps in knowledge

Certainty scores were used to assess the current knowledge on the threats of climate change to the reproductive output of sea turtles and the ability of sea turtles to adapt to climate change. The relative impact of each climatic process, the impact from increased sand temperature, and the potential for nesting grounds to recover from increased temperature stand out as the most understood processes. All the other processes scored low certainty levels (Table 6.9).

Table 6.9. Certainty of both expert groups to questions asked. Maximum = 4 and low certainty values (≤ 2) are indicated in bold. M stands for managers and S for scientists.

Impact level	M	S	Mean of both groups
Relative impact from each climatic process	2.09	2.40	2.24
Impact from different levels of increase in temperature	**1.91**	2.20	2.04
Impact from different levels of sea level rise	**1.91**	**1.60**	**1.80**
Impact from different levels of cyclonic activity	**1.82**	2.00	**1.91**
Potential for nesting ground to recover from increased sand temperature	2.09	**1.95**	2.02
Potential for nesting ground to recover from sea level rise (0.5m rise)	**1.36**	**1.50**	**1.43**
Potential for nesting ground to recover from cyclonic activity (medium strength)	**1.73**	**1.80**	**1.77**

6.5. Discussion

According to the experts' rankings, increased sand temperature will cause two times more impact to the terrestrial reproductive phase of the nGBR green turtle population than sea level rise and three times more impacts than cyclonic activity. Although this information provides valuable insights into the relative impact of each climatic factor it has to be interpreted with care. The low degree of impact attributed to sea level rise and cyclonic activity may reflect the expert's high uncertainty on the impacts that these climatic processes have on sea turtles (see Table 6.9). Indeed, even though the expert group indicated that increased temperature will cause more impact than sea level rise, a higher proportion of experts indicated that the most extreme level of sea level rise (loss of 85% to 100% of current nesting area) will have catastrophic consequences in comparison to the most extreme level of increased temperature (temperature above upper thermal threshold). Therefore, it would be interesting to explore how expert's perceptions of the consequence of each climatic process changes as more knowledge and insights are gathered on the impacts of sea level rise and cyclonic activity on sea turtles.

Nevertheless, the consequence categories assigned by the experts can still be useful to guide and prioritise management of sea turtles in the face of climate change. If the consequence categories attributed to the different levels of impact (sensitivity) from each climatic process is used together with predictions of the likely impact from each climatic process, to each of the nesting grounds (as generated in Chapters 2-5), in a risk management framework it can guide determining the risk (consequence by likelihood, see table 6.10) of each climatic process at each nesting ground and the urgency of a mitigation strategy.

Table 6.10. Risk assessment framework; categories (low - extreme) indicate the level of risk according to the Great Barrier Reef Marine Park Authority's risk management framework (GBRMPA 2009).

	Consequence category				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Catastrophic**
Almost certain	Medium	Medium	High	Extreme	Extreme
Likely	Medium	Medium	High	High	Extreme
Possible	Low	Medium	High	High	Extreme
Unlikely	Low	Low	Medium	Medium	High
Rare	Low	Low	Medium	Medium	Medium

For example, in Chapter 3 I modelled sand temperature for 2070 and found that nesting grounds used by the northern Great Barrier Reef green turtle population will experience temperatures near the upper thermal threshold. According to our experts' categorizations, the consequence of this level of increased temperature to sea turtles will be 'major' to 'catastrophic'. If this information, on the consequence of increased temperature, is used together with the likelihood of it occurring in a risk management framework, such as the one used by the Great Barrier Reef Marine Park Authority (GBRMPA 2009), a "risk level" (likelihood X consequence, see Table 6.10) for increased temperature can be obtained. A risk level will determine the acceptability of the threat and the urgency of a mitigation strategy (Table 6.11). According to the risk management framework used by GBRMPA (Tables 6.10 and 6.11), a catastrophic threat, such as increased temperature, with a "possible" likelihood of occurring (31 to 70% chance of occurring) has a high or extreme risk (Table 6.11), hence it is an area that managers should prioritise and concentrate their management efforts. Consequently, increased temperature is classified as a high to extreme risk and should be managed straight away. Similarly, following the same rationale, impacts from sea level rise have a high risk and should be mitigated and impacts from cyclones are considered to have a low/medium risk and thus only require monitoring (Tables 6.10 and 6.11).

Table 6.11. Acceptability of risk according to Great Barrier Reef Marine Park Authority's risk management framework (GBRMPA 2009).

Risk level - acquired from Table 6.10.	**Risk mitigation action**
Low	Risk should be recorded, monitored and controlled by the responsible manager.
Medium	Mitigation actions to reduce the likelihood and consequences need to be identified.
High	Mitigating actions need to be put in place.
Extreme	Risk events graded at this level have the potential to cause serious and ongoing damage to the environment thus mitigation action needs to be put in place and activities that generate this risk need to be terminated.

Even though managers may address each climatic process individually, they need to consider synergetic and cumulative interactions between the climatic threats and between climatic processes and other anthropogenic threats (Brook et al. 2008). However, limited knowledge exists on the interactions between processes and the consequent magnitude of impacts (Emily and Isabelle 2008). Consequently, an emerging aim of conservation scientists and managers is to understand how multiple threats will interact with or exacerbate global environmental changes (Harley et al. 2006; Sutherland et al. 2006; Mora et al. 2007- see Chapter 7 for further discussion on this). This is understandable because, as I have demonstrated in my thesis there are still substantial uncertainties about how climatic processes will operate at a species level - let alone across taxa, habitats and in conjunction with other threats. Once we have a better understanding of this issues we can have more insights into the synergies that may occur and better design cost effective management initiatives.

Another important factor that can aid effective management in a data poor field is for managers and planners to remain informed about emerging climate science as well as potential impacts on the ecosystem they manage (Millar et al. 2007; Tribbia and Moser 2008). This does not seem to be a current issue in my study region with regards to sea turtles because there was a high similarity in the answers from both groups. Often, this is not the case and a disconnect between science and policy-makers is common (Tribbia and Moser 2008; Gelcich et al. 2009). Nevertheless to ensure that this does not become a future issue scientists should ensure that their information is delivered in a “management friendly” way, so that science knowledge leads to practical management (Tribbia and Moser 2008). Similarly, scientists are advised to work closely with stakeholders to ensure that they are producing relevant information for policy-makers (Mcnie 2007). By using useful and relevant scientific knowledge managers will be able to enhance their decision making response and the probability of management succeeding. Thus, the management of sea turtles as climate change progresses can only benefit from the existing and future collaboration between scientists and managers in the region

6.6. Chapter summary

Expert knowledge proved useful to explore the relative impacts of climate-related threat to the terrestrial reproductive phase of the nGBR green turtle population and to identify knowledge gaps with regards to the impacts of climate change on sea turtles reproductive output. Out of the three climatic processes investigated here (increased temperature, sea level rise, and cyclonic activity) increased temperature was perceived as the biggest threat to the terrestrial reproductive phase of the nGBR green turtle population, followed by sea level rise and cyclonic activity. The consequence categories attributed by the expert panel to each level of impact from each climatic process can be incorporated into risk management frameworks to aid the prioritisation of management options as climate change progresses.

Chapter 7.

Vulnerability of sea turtle nesting grounds to climate change: implications for management [(1)]

[1] **Fuentes MMPB**, Hamann M. and Limpus CJ (in press) Vulnerability of sea turtle nesting grounds to climate change. Global Change Biology

7.1. Abstract

Given the potential vulnerability of sea turtles to climate change, a growing number of studies are predicting how various climatic processes will affect their nesting grounds. However, these studies are limited by scale, because they predict how a single climatic process will affect sea turtles at a time, but processes are likely to occur simultaneously and cause cumulative effects. In this Chapter, I address the need for a structured approach to investigate how multiple climatic processes may affect a turtle population by using a vulnerability assessment framework to assess the cumulative impact of various climatic processes on sea turtle nesting grounds. Thus, in this Chapter I describe the assessment process and demonstrate its application to the nGBR green turtle population. Further, I manipulate the variables from this framework to allow users to investigate how mitigating different climatic factors individually or simultaneously can influence the vulnerability of the nesting grounds.

My assessment indicates that nesting grounds closer to the equator, such as Bramble Cay and Milman Island, are the most vulnerable to climate change. In the short term (by 2030), sea level rise will cause the most impact on the nesting grounds used by the nGBR green turtle population. However, in the longer term, by 2070 sand temperatures will reach levels above the upper transient range and the upper thermal threshold and cause relatively more impact on the nGBR green turtle population. Thus, in the long term, a reduction of impacts from sea level rise may not be sufficient, as nesting grounds will start to experience high vulnerability values from increased temperature. Thus, in the long term, reducing the threats from increased temperature may provide a greater return in conservation investment than mitigating the impacts from other climatic processes. Indeed, our results indicate that if the impacts from increased temperature are mitigated, the vulnerability values of almost all nesting grounds will be reduced to low levels.

7.2. Introduction

As discussed in the previous Chapters the terrestrial reproductive phase (egg laying, egg incubation and hatchling success) of sea turtles will be particularly vulnerable to climate change because there are clear and relatively straightforward effects of increased temperature, sea level rise and cyclonic activity on sea turtle nesting sites and reproductive output. Indeed, given sea turtles' potential vulnerability to climate change and the future scenarios of global warming, there has been recent concern over the potential impacts and implications of climate change on them (McMahon and Hays 2006; Hamann et al. 2007; Hawkes et al. 2009; Poloczanska et al. 2009).

Consequently, a growing number of studies are investigating and predicting how climatic processes will affect sea turtles and their nesting grounds (for review see Hawkes et al. 2009 and Poloczanska et al. 2009). Most studies predict how increased sand temperature (Hays et al. 1999, 2003; Glen & Mrosovsky 2004; Hawkes et al. 2007 b- as per Chapter 3), or sea level rise (Fish et al. 2005, 2008; Baker et al. 2006 – as per Chapter 4) will affect sea turtle's terrestrial reproductive phase. Although these studies provide valuable information and insights into how each climatic process can or will affect sea turtles, they are limited by scale because processes are likely to occur simultaneously across a population and cause cumulative and synergistic effects – as discussed in Chapter 6. Consequently, there is a need for a structured approach to investigate how multiple climatic processes may affect the full range of nesting grounds used by a turtle population.

To address this, I conducted my PhD in a systematic way to collect the necessary information to conduct an assessment of the multiple threats of climate change on the terrestrial reproductive phase of sea turtles. The first step to conduct this assessment was to determine the impact of key climatic processes to sea turtles (Chapters 2-5); I then determined the relative impact of each climatic process and the relative impact from different levels of disturbance from these processes (Chapter 6). In this Chapter I incorporate this information into a vulnerability assessment framework to allow assessment of the cumulative impact of multiple climatic processes on sea turtle nesting grounds. The variables from this framework can be manipulated to allow users to investigate how addressing different climatic processes individually or simultaneously can mitigate the vulnerability of the nesting grounds. By using this framework, managers and scientists will be able to determine which nesting grounds will be the most vulnerable to climate change, which climatic process will cause the most impact to each nesting ground, and how the vulnerability of nesting grounds will change if impacts from specific climatic factors are mitigated. With this information, managers will be better placed to direct and focus management and conservation actions to protect turtle populations.

7.3. Methods

7.3.1. The framework

The framework used here is based on the environmental vulnerability assessment framework for climate change provided by the International Panel of Climate Change (IPCC 2007) and recent studies (Turner et al. 2003; Metzger et al. 2005; Schroter et al. 2005). The vulnerability assessment was conducted in nine steps; the first three steps were carried out prior to conducting the modeling and the last six steps were part of the assessment (Figure 7.1). Below I describe each step.

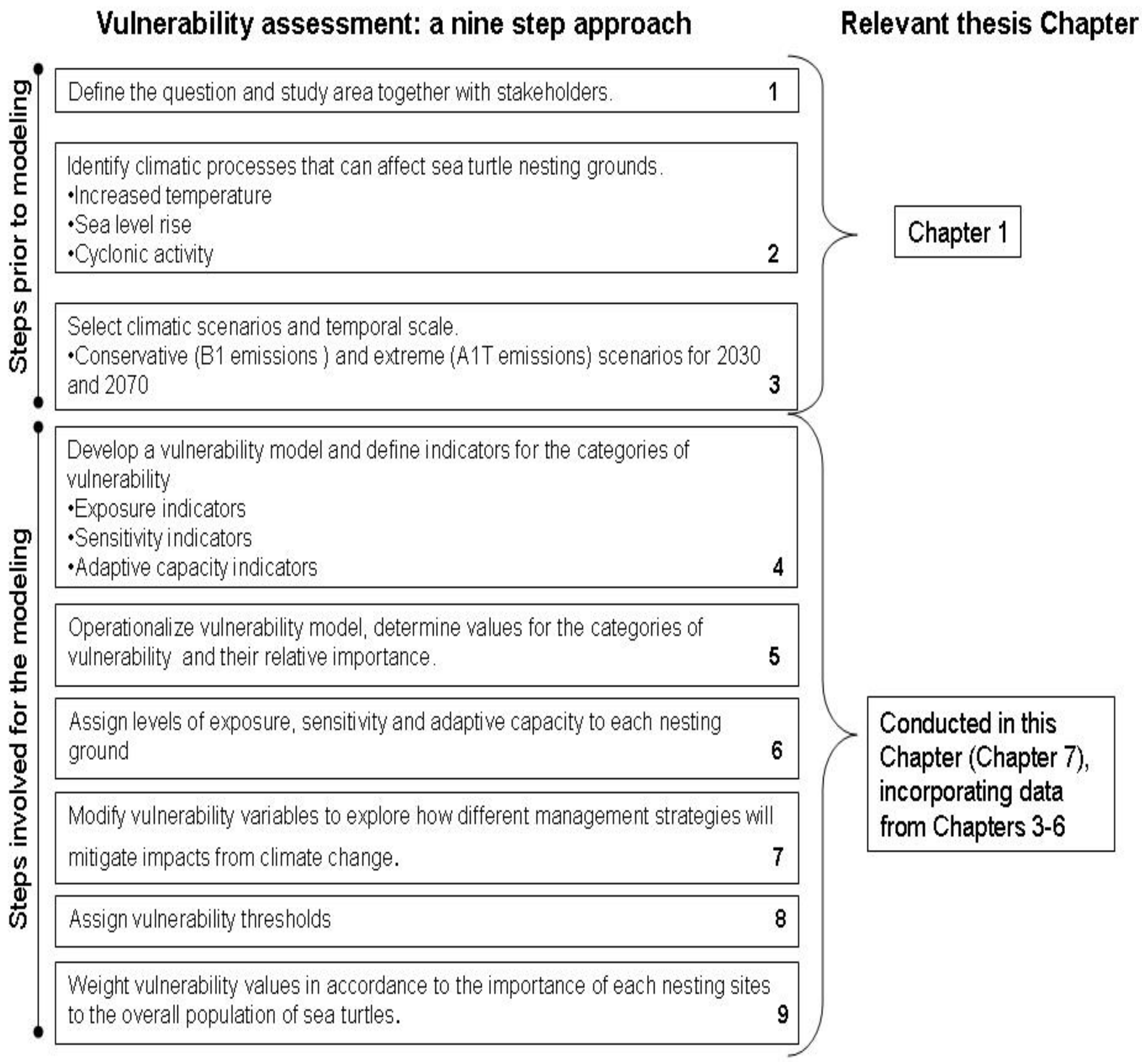

Figure 7.1.A nine step method for assessing the vulnerability of sea turtle nesting grounds to climate change.

7.3.1.1. Steps prior to assessment

Step 1: Define the question and study area together with stakeholders

As discussed in Chapter 1 data from the past 10 years have revealed that the northern Great Barrier Reef green turtle population may be in the early stages of decline, probably as a result of poor hatchling production resulting from low nesting success (percentage of females able to successfully lay eggs each night) and low hatching success. Concern about climate change exacerbating current trends and causing further impacts to this population has been expressed and the need to investigate the impacts of climate change to the reproductive output of this population has identified as a priority policy issue for several Queensland agencies (e.g. Great Barrier Reef Marine Park Authority, Environment Protection Agency and Queensland Parks and Wildlife Service).

Step 2: Identify climatic processes that can affect sea turtle nesting grounds

As mentioned in Chapter 1, as part of objective 1 from this study, I conducted a literature review to identify the main climatic process that can affect sea turtle's terrestrial reproductive phase and thus their reproductive output. Change in sediment traits, increased sand temperature (ST), sea level rise (SLR), and cyclonic activity (CA) were identified as the main climatic processes that will potentially affect sea turtle nesting grounds as climate change progresses (Hawkes et al. 2009; Poloczanska et al. 2009). However, in Chapter 2, I found it difficult to determine how sediments at sea turtle nesting grounds will change as their adjacent reef platform and reef-building organisms are affected by climatic changes, and thus how this may affect sea turtles. Consequently, I did not incorporate the potential impacts of changes in sediment traits on sea turtles to the vulnerability assessment conducted in this Chapter. However, as more knowledge of the impacts of changes in sediment trait to sea turtles is acquired it can be easily added to the framework.

Step 3: Select climatic scenarios and temporal scale

As described in Chapter 1 (section 1.3.2) all the analysis and predictions for this study were conducted for a conservative and extreme scenario of climate change for both 2030 and 2070.

7.3.1.2. Steps as part of the assessment

Step 4: Develop the vulnerability model and define indicators for the categories of vulnerability.

The first step to calculate the cumulative vulnerability (CV) of each nesting ground to climate change was to determine the vulnerability of each of the selected nesting grounds to each climatic process (Vc) (increased temperature, sea level rise, and cyclonic activity). The vulnerability model for each climatic process was described as a function of exposure (E), sensitivity (S), and adaptive capacity (AC) (as per Turner et al. 2003; Metzger et al. 2005; Schroter et al. 2005) (Figure 7.2).

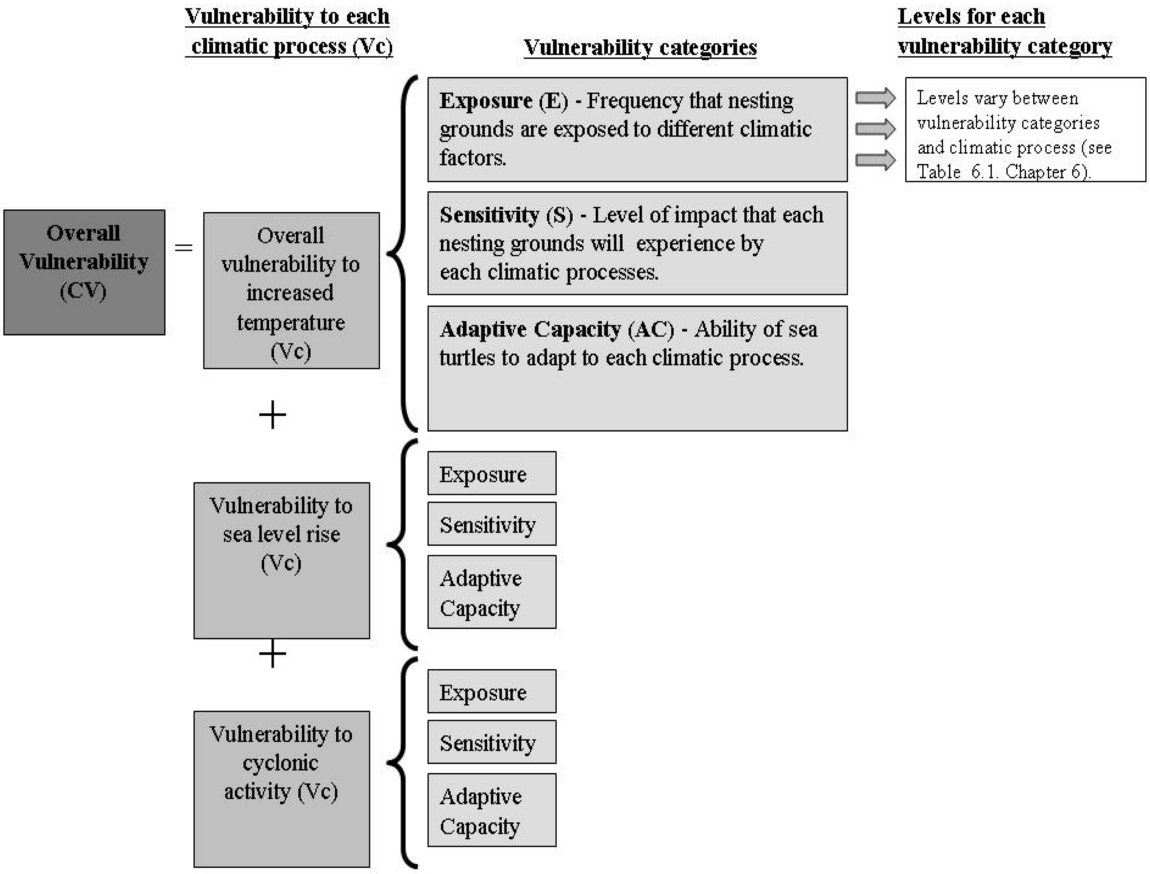

Figure 7.2. Cumulative vulnerability model and the relevant vulnerability categories used to assess the vulnerability of nesting grounds to climate change.

Exposure

Exposure was defined as the frequency that each of the selected nesting grounds would be exposed to each climatic factor. Four levels of exposure were identified for each climatic process, ranging from "never occurring" to "constant", as described in Tables 6.1 and 7.1 (methodology as per Halpern et al. 2007).

Sensitivity

Sensitivity refers to the level that each nesting ground will be impacted by the three climatic processes. Sensitivity levels where also identified and ranged from minimal to severe impact and the categories varied in accordance with each climatic factor (Tables 6.1 and 7.1).

Adaptive capacity

Adaptive capacity is the ability of nesting sea turtles at each island to adapt to each climatic process. As described in Chapter 6 three levels of adaptive capacity were identified: (1) ability to adapt within a nesting season, (2) ability to adapt after a turtle generation, and (3) no ability to adapt (Tables 6.1 and 7.1).

A rank (R), with a maximum value of 4, was given to the different levels of exposure, sensitivity, and adaptive capacity (Table 7.1) relative to the impact that each level causes (e.g. the lowest value was given to the level that causes least impact and 4 was given to the level that causes the most impact) (as per Halpern et al. 2007).

Step 5: Operationalise the vulnerability model.

In the previous step I developed the vulnerability model and defined levels for each category of vulnerability (exposure, sensitivity, and adaptive capacity). The main aim of this step is to assign an overall weight (W) value for each level of the vulnerability categories, to indicate their relative impact in relation to each other. To do this I used the average weighting (w), obtained in Chapter 6 (see Tables 6.5 to 6.7 in Chapter 6), to calculate an overall weighting (W) for each level of exposure, sensitivity, and adaptive capacity. To calculate an overall weighting (W) for exposure I corrected the values from Table 6.5 so that they would range from 0 to 1 (as per Grech and Marsh 2008 and Halpern et al. 2007), this way a category of no impact receives a value of zero (see Table 7.1). I also corrected the values for sensitivity (Table 6.6) and adaptive capacity (Table 6.7) obtained from Chapter 6 so that the maximum weight value for each category would be one, as per the sensitivity category. The overall weight (W) was then multiplied by the corresponding rank value (R) to obtain the overall value (OV) for each level of the vulnerability categories (exposure, sensitivity, adaptive capacity) (Table 7.1 and Figure 7.3).

Table 7.1. Different levels of exposure, sensitivity and adaptive capacity for each climatic process and their corresponding rank, weight and overall value.* Corrected weights from Chapter 6.

Vulnerability category		Rank (R)	Weight (W)*	Overall value (OV)
Exposure	**Increased sand temperature**			
	No increase in temperature	1	0.00	0.00
	Occasionally – increase in temperature during only one nesting season	2	0.15	0.30
	Often- during one turtle generation (40 years)	3	0.36	1.08
	Increase in temperature is constant	4	1.00	4.00
	Sea level rise			
	Sea level rise never occurs	1	0.00	0.00
	Occasionally – discrete events of sea level rise, storm surges	2	0.19	0.38
	Often- sea level rise over one turtle generation (40 years)	3	0.42	1.26
	Sea level rise is constant	4	1.00	4.00
	Cyclonic activity			
	No cyclonic activity	1	0.00	0.00
	Occasionally – 1 cyclone every 30 years	2	0.18	0.36
	Often- 1 cyclone every 5 years	3	0.37	1.11
	Persistent- constant – one cyclone every nesting season	4	1.00	4.00
Sensitivity	**Increased sand temperature**			
	Temperatures above pivotal temperature (higher % of females)	1	0.07	0.07
	Temperature above upper transient range temperature	2	0.16	0.32
	Temperatures near the upper thermal threshold	3	0.38	1.14
	Temperature above upper thermal threshold	4	1.00	4.00
	Sea level rise			
	Loss of up to 10% of current nesting area	0.8	0.06	0.048
	Loss of 10% to 35% of current nesting area	1.6	0.10	0.16
	Loss of 35% to 60% of current nesting area	2.4	0.20	0.48
	Loss of 60% to 85% of current nesting area	3.2	0.44	1.40
	Loss of 85% to 100 % of current nesting area	4	1.00	4.00
	Cyclonic activity			
	Decrease in frequency of cyclones	1	0.11	0.11
	Decrease in frequency and more intense cyclones	2	0.24	0.48
	Increase in frequency of cyclones	3	0.39	1.17
	Increase in frequency and more intense cyclones	4	1.00	4.00
Adaptive Capacity	**Increased sand temperature**			
	Ability to return to adapt within a nesting season	1.33	0.11	0.14
	Ability to adapt after a turtle generation	2.66	0.30	0.80
	No ability to adapt	4.00	1.00	4.00
	Sea level rise			
	Ability to adapt within a nesting season	1.33	0.16	0.21
	Ability to adapt after a turtle generation	2.66	0.39	1.03
	No ability to adapt	4.00	1.00	4.00
	Cyclonic activity			
	Ability to adapt within a nesting season	1.33	0.16	0.21
	Ability to adapt after a turtle generation	2.66	0.31	0.82
	No ability to adapt	4.00	1.00	4.00

Each vulnerability category (exposure, sensitivity, adaptive capacity) was then multiplied by each other to obtain the vulnerability (Vc) value for each climatic process (Figure 7.3).

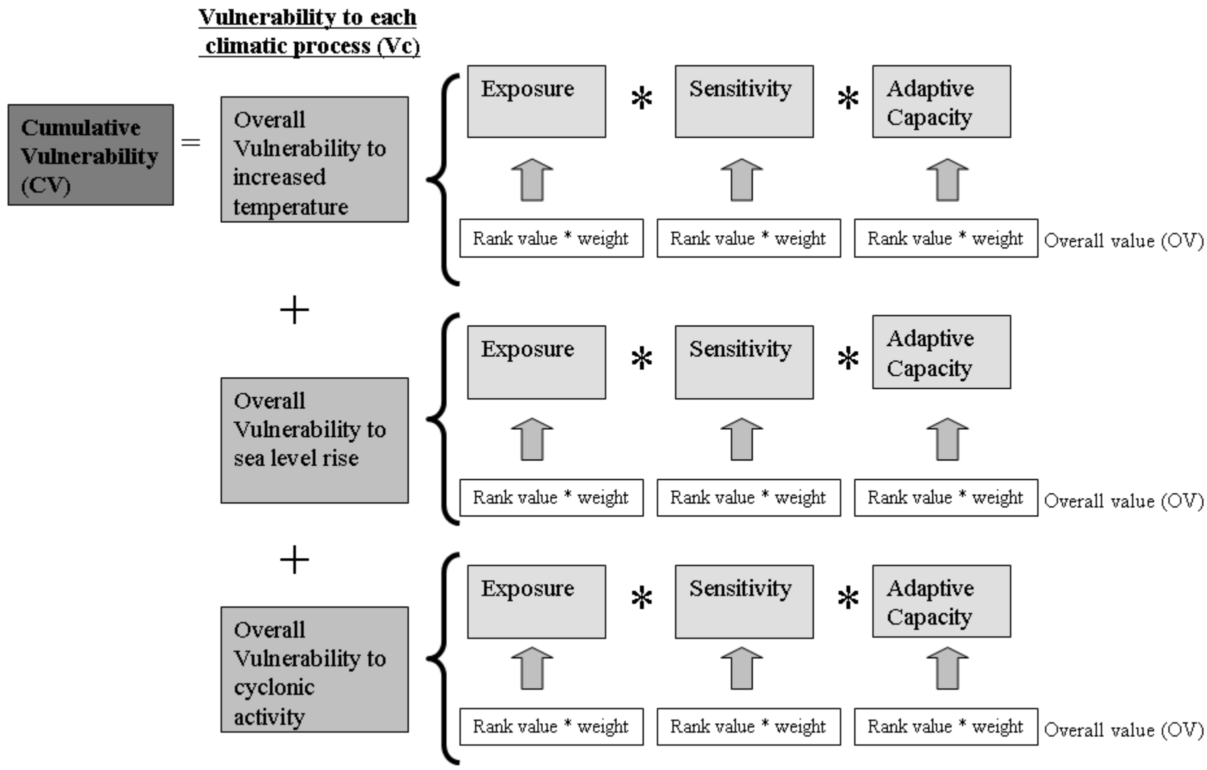

Figure 7.3. Vulnerability model, vulnerability categories and an expression of how the overall value for each vulnerability category was determined.

Step 6. Assign levels of exposure, sensitivity, and adaptive capacity to each nesting ground. In the previous steps I determined the overall value for each level of exposure, sensitivity, and adaptive capacity for each of the three climatic processes. The aim of this step is to assign one level of exposure, sensitivity, and adaptive capacity to each nesting ground. To illustrate this process, I provide a working example of how I determined Bramble Cay's overall vulnerability to increased temperature for 2030 under a conservative scenario of climate change (Figure 7.4).

Exposure

To assign an exposure value for each nesting ground I assumed that increases in temperature and sea level rise would be constant for all nesting grounds over all years and for all climatic scenarios. For example, to calculate the OV of Bramble Cay's exposure to increased temperature, I multiplied the rank of constant exposure (4) by its corresponding weight (1) (Table 7.1 and Figure 7.4). To calculate the exposure values for cyclonic activity, I assumed that cyclonic activity would occur occasionally at nesting grounds in the Torres Strait region and often at nesting grounds in the nGBR. Cyclone values were based on past cyclonic activity in the study region (information from the Australian Bureau of Meteorology 2008, and Chapter 5).

Sensitivity

Values for the sensitivity of each nesting ground to increased temperature and sea level rise were assigned based on the results from Chapters 3-5 (see summary in Table 7.2). For example, in Chapter 3 I predict that by 2030 under a conservative scenario of climate change, Bramble Cay will experience temperatures above the pivotal temperature. Consequently, to determine Bramble Cay's sensitivity value to increased temperature I multiplied 1, which is the rank for temperatures above the pivotal temperature (see Table 7.1), by 0.07, which is the corresponding weight, and obtained 0.07 as the OV of sensitivity for Bramble Cay for 2030 under a conservative scenario (Figure 7.4). In line with recent studies and the results from Chapter 5 I assumed that cyclonic activity will decrease in frequency and increase in intensity (Webster et al. 2005; IPCC 2007; Emanuel et al. 2008).

Table 7.2. Categorical values for each vulnerability category for conservative (C) and extreme (E) scenarios for 2030 and 2070. Categories for increased temperature are based on results from Chapter 3, categories for sea level rise are based on Chapter 4, and categories for cyclonic activity are based on Chapter 5.

	Increased sand temperature				**Sea level rise – loss of nesting ground**				**Cyclonic activity**
	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E	2030 and 2070 E and C
Bramble Cay north	Temperature above pivotal	Temperature above UTRT	Temperature near the UTT	Temperature above the UTT	up to 10%	up to 10%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones
Dowar north	Temperature above pivotal	Temperature above UTRT	Temperature near the UTT	Temperature near the UTT	up to 10%	up to 10%	up to 10%	10- 35%	Decrease in frequency and more intense cyclones
Dowar south	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Temperature above UTRT	up to 10%	up to 10%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones
Milman north	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Temperature above the UTT	10- 35%	10- 35%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones
Milman east	Temperature above pivotal	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	10- 35%	10- 35%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones
Milman south	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Temperature near the UTT	10- 35%	10- 35%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones
Milman west	N/A	N/A	Temperature above pivotal	Temperature above UTRT	10- 35%	10- 35%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones
Moulter Cay north	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	Temperature near the UTT	up to 10%	up to 10%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones
Raine Island	Temperature above pivotal	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	up to 10%	up to 10%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones
Sandbank 7 north	Temperature above pivotal	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	up to 10%	10- 35%	10- 35%	35% to 60%	Decrease in frequency and more intense cyclones
Sandbank 7 south	N/A	N/A	Temperature above pivotal	Temperature above pivotal	up to 10%	10- 35%	10- 35%	35% to 60%	Decrease in frequency and more intense cyclones
Sandbank 8 north	Temperature above pivotal	Temperature above pivotal	Temperature above pivotal	Temperature above UTRT	up to 10%	10- 35%	10- 35%	10- 35%	Decrease in frequency and more intense cyclones

Adaptive capacity

Assigning a value to the capacity of sea turtles to adapt to the impacts of different climate processes on their nesting grounds was more challenging as no empirical data exist. Indeed, reviews and published research on sea turtles and climate change highlight the need for further investigation of sea turtles' adaptive capacity (see Hawkes et al. 2009). Nevertheless, based on the knowledge that sea turtles have adapted to past climate changes (see Hamann et al. 2007, Limpus 2008 a; Poloczanska et al. 2009), I assumed that sea turtles would have the ability to adapt to climate change after a turtle generation. Therefore, to assign Bramble Cay an overall value of adaptive capacity to increased temperature I multiplied 2.66 (rank value) by 0.3 (weight value) (Tables 7.1 and 7.2 and Figure 7.4). As more data become available, the adaptive capacity value can be easily modified.

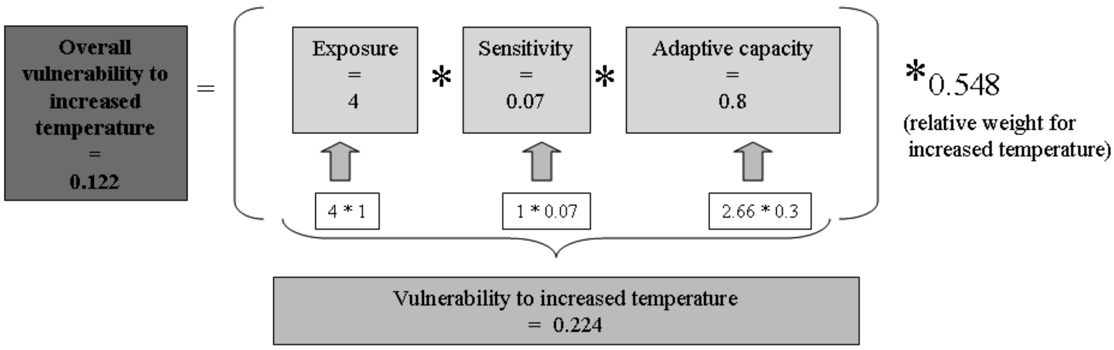

Figure 7.4. Worked example of how Bramble Cay's vulnerability to increased temperature for 2030 under a conservative scenario of climate change was determined.

Overall vulnerability

After I calculated the vulnerability of each nesting ground for each climatic process, emission scenario, and year, the next step was to calculate the overall vulnerability of each nesting ground to climate change. For this I multiplied the weights for the relative impact of each climatic process, obtained Chapter 6, Table 6.4, by the corresponding vulnerability value from each climatic process to obtain an overall vulnerability (Vc) (Equation 1). I then calculated the cumulative vulnerability (CV) for each nesting ground by adding the Vc values for each climatic process. Thus, the CV at each nesting ground is described as (also see Figures 7.3 and 7.4):

$$CV = Vc\ (ST) * 0.548 + Vc\ (SLR) * 0.269 + Vv\ (CA) * 0.183, \qquad \text{(Equation 1)}$$

where CV = cumulative vulnerability, Vc = vulnerability to a climatic process, ST = increased temperature, SLR = sea level rise, and CA = cyclonic activity.

Step 7: Modify vulnerability variables to explore how different management strategies will mitigate impacts from climate change.

To investigate how the CV of each nesting ground will alter as the impact of different climatic processes is addressed (by management strategies), I manipulated some of the vulnerability categories. To investigate the degree to which the vulnerability of the nesting grounds would change if the impacts from increased temperature are mitigated, I altered the increased temperature exposure value for all nesting grounds to "no increase in temperature" (rank 1 and weight 0.0- as per Table 7.1) and the sensitivity value to "temperatures above pivotal temperature" (category 1 and weight 0.07 -as per Table 7.1). Similarly, to investigate the changes in the vulnerability of the nesting grounds if sea level rise is addressed, I changed the sea level rise exposure value for all nesting grounds to "no sea level rise" (category 1 and weight 0.0 - as per Table 7.1) and the sensitivity value to "loss of up to 10% of the nesting area" (category 0.8 and weight 0.06 - as per Table 7.1). The reason I used this sensitivity category, even though sea level rise would be mitigated, is that loss of nesting area can still occur from either or both aperiodic cyclonic activity and storm surges.

Step 8: Assigning vulnerability thresholds.

To aid the interpretation of the results, I created four vulnerability categories (low, intermediate, high, and extreme). The categories were determined in accordance with the sensitivity values (Table 7.1) for each climatic factor. The exposure values (as per Table 7.1) and adaptive capacity values (as per Table 7.1) were kept constant - as described in Step 6. For example, a low vulnerability value was obtained by using the lowest sensitivity category for increased temperature and sea level rise and using the value for cyclonic activity as decreasing in frequency but intensifying. Similarly, for the extreme category, I used the highest values for increased temperature and sea level rise and again for cyclonic activity I used the value for activity as decreasing in frequency but intensifying. The other vulnerability categories were determined in the same way with the respective sensitivity category.

Step 9: Weight vulnerability values according to the importance of each nesting site to the overall population of sea turtles.

A particular sea turtle population uses several sites to nest, with some sites having more importance (proportional to the number of turtles nesting) than others. This is the case for the nGBR green turtle population (as discussed in Chapter 1 and illustrated in Figure 1.1), where the largest proportion of nesting (90%) occurs at Raine Island and Moulter Cay. Subsidiary nesting occurs at Bramble Cay and Dowar Island, minor nesting (on average 50–300 nesting females a year) takes place at Sandbanks 7 and 8, and trivial nesting (10–50 nesting females a year) occurs at Milman Island (Dobbs et al. 1999; Limpus et al. 2003). Occasional nesting for this population also occurs at approximately 60 other nesting grounds in northern Australia (Chapter 1, Figure 1.1). Because of the variability in the importance of each of these sites, I weighed the vulnerability scores of each nesting site according to the importance of each nesting site to the population. The weights were based on the percentage of nesting that occurs at each site in relation to the overall nesting across these sites. Consequently, the following weights were attributed: Raine Island (0.50), Moulter Cay (0.40), Dowar Island (0.025), Bramble Cay (0.03), Sandbanks 7 and 8 (0.02) and Milman Island (0.005). This will allow investigation of the relative impact on the overall population.

7.4. Results

7.4.1. Vulnerability to increased temperature

The nesting grounds studied here will start to be vulnerable to increase in temperature by 2070. Prior to that, most nesting grounds will have temperatures that are between the pivotal temperature (29.3 ˚C) and the upper transient range (30.8 ˚C), and thus in 2030 will have only low vulnerability scores (Table 7.3). However, by 2070 nesting grounds will be much more vulnerable to increased temperature and the nesting grounds will experience temperatures above the upper transient range and the upper thermal threshold (33 ˚C). Bramble Cay and the northern facing beach at Milman Island are the nesting areas most vulnerable to increased temperature (Table 7.3).

7.4.2. Vulnerability to sea level rise

In the long term (by 2070) the vulnerability to sea level rise of the nesting grounds studied here is relatively low compared to their vulnerability to increased temperature (Table 7.3). However, some nesting grounds in the nGBR will experience higher levels of vulnerability to sea level rise in the short term (by 2030) than they will to increased temperature. Nevertheless, the vulnerability of nesting grounds to sea level rise will not be exacerbated or achieve high levels by 2070. Only Sandbank 7 is likely to have high levels of vulnerability to sea level rise by 2070 (Table 7.3).

7.4.3. Vulnerability to cyclonic activity

The vulnerability of the nesting grounds to cyclonic activity was found to be low. This is a reflection of the low predicted cyclonic activity in the study region (Table 7.3).

Table 7.3. Overall vulnerability of the nesting grounds to different climatic processes under conservative (C) (based on B1 emission scenario of the IPCC b) and extreme (E) (based on A1T emission scenario of the IPCC 2007 b) scenarios of climate change by 2030 and 2070. Vulnerability values were obtained as described in steps 1-7. Threshold values for increased temperature, sea level rise and cyclonic activity, respectively are: low (> 0.13, > 0.05, and > 0.02; white), intermediate (between 0.13 to 0.56, 0.05 to 0.18, and 0.02 to 0.08; light grey), high (0.56 to 1.99, 0.18 to 1.58, and 0.08 to 0.19; dark grey), and extreme (above 7, 4.48, and 0.65; darker/black grey) (see step 6 for how vulnerability values where assigned).

	Vulnerability to increased temperature				Vulnerability to sea level rise				Vulnerability to cyclonic activity			
Nesting grounds	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E	2030 C	2030 E	2070 C	2070 E
Bramble Cay north	0.12	0.56	2.00	7.02	0.05	0.05	0.18	0.18	0.03	0.03	0.03	0.03
Dowar north	0.12	0.56	2.00	2.00	0.05	0.05	0.05	0.18	0.03	0.03	0.03	0.03
Dowar south	0.12	0.12	0.56	0.56	0.05	0.05	0.18	0.18	0.03	0.03	0.03	0.03
Milman north	0.12	0.12	0.56	7.02	0.18	0.18	0.18	0.18	0.08	0.08	0.08	0.08
Milman east	0.12	0.12	0.56	2.00	0.18	0.18	0.18	0.18	0.08	0.08	0.08	0.08
Milman south	0.00	0.00	0.12	0.56	0.18	0.18	0.18	0.18	0.08	0.08	0.08	0.08
Milman west	0.12	0.12	0.56	2.00	0.18	0.18	0.18	0.18	0.08	0.08	0.08	0.08
Moulter Cay north	0.12	0.12	0.56	2.00	0.05	0.05	0.18	0.18	0.08	0.08	0.08	0.08
Raine Island south	0.12	0.12	0.12	0.56	0.05	0.05	0.18	0.18	0.08	0.08	0.08	0.08
Sandbank 7 north	0.12	0.12	0.12	0.56	0.05	0.18	0.18	0.54	0.08	0.08	0.08	0.08
Sandbank 7 south	0.00	0.00	0.12	0.12	0.05	0.18	0.18	0.54	0.08	0.08	0.08	0.08
Sandbank 8 north	0.12	0.12	0.12	0.56	0.05	0.18	0.18	0.18	0.08	0.08	0.08	0.08

7.4.4. Cumulative vulnerability

The cumulative vulnerability of the nesting grounds studied is relatively low in the short term (2030). However, by 2070 the cumulative vulnerability of the nesting grounds will increase considerably (Table 7.4). Under a conservative scenario, all nesting grounds studied will experience at least intermediate vulnerability values by 2070, with the nesting grounds in Torres Strait, Milman Island, and Moulter Cay experiencing the highest vulnerability values (Table 7.4). Results are more drastic under an extreme scenario of climate change, as most nesting grounds are predicted to experience high vulnerability values, with Bramble Cay and the north-facing beach at Milman experiencing extreme vulnerability values (Table 7.4). It is important to note, however, that the most important nesting grounds for this population, such as Raine Island and Moulter Cay have relatively lower vulnerability levels when compared to some of the other nesting grounds, which are less important, such as Milman Island and Bramble Cay (Figure 7.5).

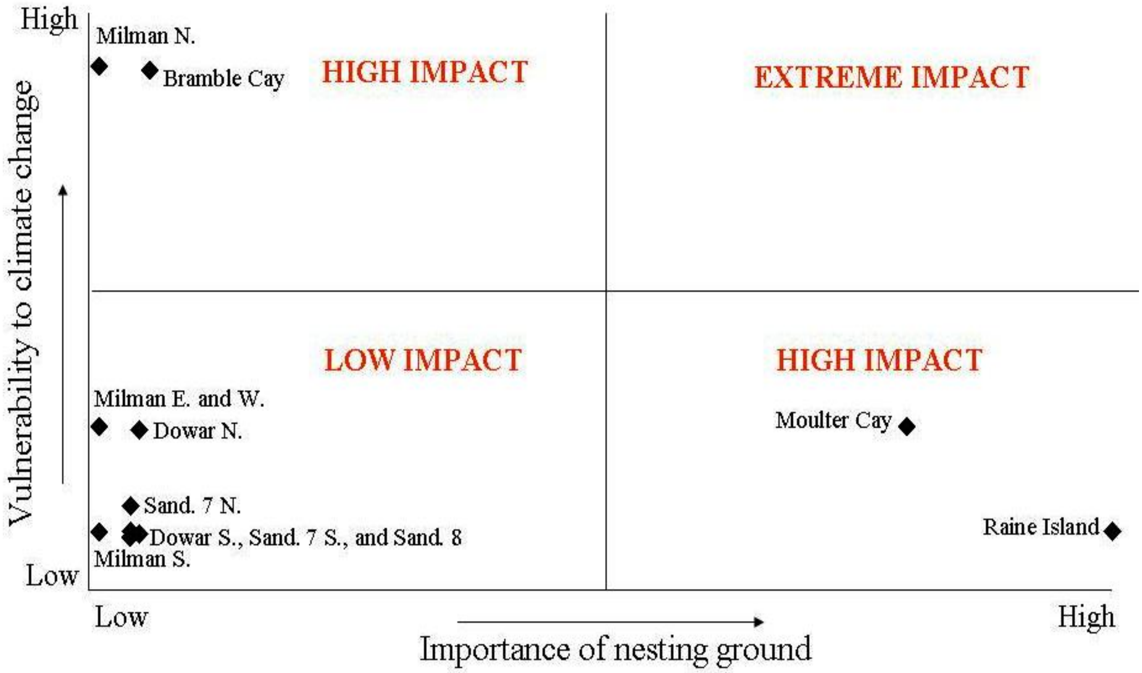

Figure 7.5. Indication of the impact that the vulnerability of each nesting ground will have to the overall nGBR green turtle population.

7.4.5. Changes in cumulative vulnerability with different management strategies

Addressing the impacts from increased temperature will cause the greatest reductions in the cumulative vulnerability of nesting grounds to climate change. If the impacts from increased temperature are mitigated, all nesting grounds will experience very low levels of cumulative vulnerability in the future, with the nesting grounds in Torres Strait experiencing the lowest level of vulnerability and Sandbank 7 experiencing the highest level of vulnerability (Table 7.4). Addressing the impacts from sea level rise will not be as effective as reducing the threats from increased temperature, especially in the long term (2070). By 2070, a reduction of the impacts from sea level rise may not be sufficient, as nesting grounds will still experience high cumulative vulnerability levels resultant from increased temperature (Table 7.4).

Table 7.4. Cumulative vulnerability of nesting grounds to climate change with different management responses under conservative (C) (based on B1 emission scenario of the IPCC b) and extreme (E) (based on A1T emission scenario of the IPCC 2007 b) scenarios by 2030 and 2070. Low vulnerability is highlighted in white (> 0.19), intermediate values are between 0.19 and 0.82 (light grey), high values are between 0.82 and 3.76 (dark grey) and extreme values between 3.76 and 12.13 (in darker grey). * Vulnerability values were weighted in accordance to the percentage of nesting that occurs at each site in relation to the overall nesting for the nGBR green turtle population (Step 9).

	Cumulative vulnerability with no management response				Cumulative vulnerability with management of temperature				Cumulative vulnerability with management of sea level rise				Cumulative vulnerability, in relation to overall population*, with no management response			
Nesting grounds	**2030 C**	**2030 E**	**2070 C**	**2070 E**	**2030 C**	**2030 E**	**2070 C**	**2070 E**	**2030 C**	**2030 E**	**2070 C**	**2070 E**	**2030 C**	**2030 E**	**2070 C**	**2070 E**
Bramble Cay north	0.20	0.64	2.21	7.23	0.08	0.08	0.20	0.20	0.15	0.59	2.03	7.05	0.006	0.019	0.066	0.216
Dowar north	0.20	0.64	2.08	2.21	0.08	0.08	0.08	0.20	0.15	0.59	2.03	2.03	0.005	0.016	0.052	0.055
Dowar south	0.20	0.20	0.77	0.77	0.08	0.08	0.20	0.20	0.15	0.15	0.59	0.59	0.005	0.005	0.019	0.019
Milman north	0.38	0.38	0.82	7.28	0.26	0.26	0.26	0.26	0.20	0.20	0.64	7.10	0.001	0.001	0.004	0.036
Milman east	0.38	0.38	0.82	2.26	0.26	0.26	0.26	0.26	0.20	0.20	0.64	2.09	0.001	0.001	0.004	0.011
Milman south	0.26	0.26	0.38	0.82	0.26	0.26	0.26	0.26	0.08	0.08	0.20	0.64	0.001	0.001	0.001	0.004
Milman west	0.38	0.38	0.82	2.26	0.26	0.26	0.26	0.26	0.20	0.20	0.64	2.08	0.001	0.001	0.004	0.011
Moulter Cay north	0.26	0.26	0.82	2.26	0.13	0.13	0.26	0.26	0.20	0.20	0.64	2.08	0.104	0.104	0.320	0.904
Raine Island south	0.26	0.26	0.38	0.82	0.13	0.13	0.26	0.26	0.20	0.20	0.20	0.64	0.130	0.130	0.190	0.410
Sandbank 7 north	0.26	0.38	0.38	1.18	0.13	0.26	0.26	0.62	0.20	0.20	0.20	0.64	0.005	0.007	0.007	0.023
Sandbank 7 south	0.13	0.26	0.38	0.74	0.13	0.26	0.26	0.62	0.08	0.08	0.20	0.20	0.002	0.005	0.007	0.014
Sandbank 8 north	0.26	0.38	0.38	0.82	0.13	0.26	0.26	0.26	0.20	0.20	0.20	0.64	0.005	0.007	0.007	0.016

7.4.6. Cumulative vulnerability of nesting grounds in relation to importance to the overall population

If the importance of each nesting ground is taken into account, Raine Island, Moulter Cay, and Bramble Cay will be the nesting sites with the highest cumulative vulnerability scores (Table 7.4). In fact, these sites are the only sites that will have significant cumulative vulnerability values by 2030 (Table 7.4).

7.4. Discussion

Multiple climatic processes (e.g. increased temperature, sea level rise, and cyclonic activity) will impact sea turtle nesting grounds at different intensities and geographical scales. Knowledge of which climatic process will cause the most impact, and which regions will be most impacted, can aid management strategies and responses (Pressey et al. 2003; Kappel 2005; Halpern et al. 2007; Higgason and Brown 2009; Mazaris et al. 2009 b). The most vulnerable nesting grounds to climate change are Bramble Cay and the northern beaches at Milman Island. However, as these nesting grounds have relatively lower importance to the overall population (in terms of percentage of nesting turtles) the impacts from climate change on these islands will not be as high as if Raine Island or Moulter Cay had higher levels of vulnerability (Figure 7.5). My study also indicates that in the long term (by 2070), increased temperature will cause the most impact to the nesting grounds used by the nGBR green turtle population. Therefore, if sea turtles continue to use the same nesting grounds in the future, reducing the threats from increased temperature may provide a greater return in conservation investment than mitigating the impacts from sea level rise or cyclonic activity. Indeed, my results indicate that if the impacts from increased temperature are mitigated, the vulnerability values of almost all nesting grounds will be reduced to low levels.

Some of the potential options to mitigate the impacts of increased temperature include changing the thermal gradient at beaches (e.g. nest shading, re-vegetation programs, sand coloring, and habitat modification), nest relocation, and artificial incubation (Naro-Maciel et al. 1999; Hawkes et al. 2007 b, 2009). The best management options will be site specific and dependent on a series of factors, including feasibility, risk (interaction and impact on other species and ecosystems), cost, constraints to implementation (both cultural and social), and probability of success in relation to selected sites (Pressey and Bottrill 2009) (see Chapter 8 for further discussion on management options). Thus, a “toolbox” with various strategies may be needed to address the impacts of increased temperature across the nesting sites used by the nGBR green turtle population. For example, the best management strategy at Dowar Island might be to relocate nests to cooler areas, as periodic monitoring of the beaches is conducted by turtle and dugong rangers. However, this strategy is not feasible for other nesting grounds, such as Bramble Cay, that are remote and have no constant monitoring.

Implementing any strategy, even at small spatial scales, will be costly and time intensive. Hence, if we consider the limited resources available, managers may also need to prioritise the nesting grounds on which they focus their management and resources. Thus, knowledge of the extent that nesting grounds will be affected is essential to guide management decisions. According to my results, impacts from climatic changes to Raine Island, Moulter Cay, and Bramble Cay will cause the most impact to the overall nGBR green turtle population. Consequently, managers may decide to focus their management in these regions. From a governance perspective, both Raine Island and Moulter Cay are protected (the Environmental Protection Agency manages the islands and surrounding intertidal areas and the Great Barrier Reef Marine Park Authority has jurisdiction over the waters below mean low water), but Bramble Cay is not protected by any legislation. However, considering the ecological importance of Bramble Cay, there might be scope to protect it as an Indigenous Protected Area (an area of Indigenous-owned land or sea where traditional owners have entered into an agreement with the Australian Government to promote biodiversity and cultural resource conservation) another option may be to declare Bramble Cay a nature refuge (where land owners -traditional owners in this case- can enter in a formal agreement with the Australian Government).

Protection of nesting grounds that are currently less important than these three sites and that will be less impacted has also been suggested as a strategy. Regardless of the priorities and goals (e.g. protect the most threatened versus the most ecologically important site) of different agencies and groups, the framework used here can provide valuable guidance for management decisions. My method provides the first systematic and comprehensive framework to assess how sea turtle nesting grounds will be affected by climate change. The framework used here can easily be adapted if new information is obtained, and can be transferable to different sea turtle populations and sea turtle life cycle phases (e.g. adult sea turtles, foraging) provided the necessary data exist. The framework is not meant to be a rigid prescription of a specific technique, but rather an approach for managers and scientists to address the impacts of climate change to sea turtles. However, I strongly suggest that the framework is applied to multiple areas (e.g. nesting areas) used by a single population, so that an understanding of a population level (management unit) can be obtained. It is also important that the models are updated as new information becomes available and the experts' knowledge changes. For example, as further understanding of sea turtles' adaptive capacity is gained and the experts' opinions potentially change, the new scores should be altered and incorporated into the model.

Indeed, our understanding of sea turtles' adaptive capacity to climate change is likely to increase, since several studies have highlighted the need for further research on this topic (see Hamann et al. 2007; Hawkes et al. 2009). A way to move forward may be to develop a method to measure sea turtles' adaptive capacity to climate change and acquire further understanding of the geomorphology processes at each nesting ground and their capacity to adapt. Some indication of sea turtles' ability to adapt to climate change at each nesting site may be provided by information on their current status, trend, the threats they face (e.g. predation, harvest), the awareness and legislative compliance at a local level, and the morphological stability of their nesting sites. Including these additional parameters in the framework has the potential to refine and add ecologically important information to vulnerability assessments. Similarly, if an understanding of how sea turtles may potentially shift their nesting ground as climate change progresses, as an adaptation response, is gained the vulnerability assessment conducted here should be conducted at the identified areas that may serve as potential nesting grounds to sea turtles in the future. This will provide insights into areas that managers may need to focus their resources and management strategies.

Another important thing to incorporate in future studies is the impacts of synergetic (amplifying) effects and interactions from different climatic processes (Brook et al. 2008; Brooks et al. 2009). Climate processes will not act in isolation and they may produce unexpected changes to ecosystems when combined with local conditions and other threats (Harley et al. 2006; Emily and Isabelle 2008). For example, sea level rise may reduce the area available for sea turtles to nest; this will amplify density-dependent issues at nesting grounds, potentially increasing nest infection and destruction of nests by cospecifics (Bustard and Tognetti, 1969; Limpus et al. 2003). It is likely that most threat interactions will amplify their impacts; however, the nature and magnitude of these synergies are unknown for most threats and ecosystems (Halpern et al. 2007) and could potentially be beneficial. For instance, increased temperature may negatively impact on the wild pigs and goannas that predate on turtle eggs and may reduce their numbers or change their distribution, resulting in a decrease in the predation of sea turtle nests. Unfortunately, the prevalence and magnitude of these interactions remain one of the largest uncertainties in projections of future ecological change (Emily and Isabelle 2008). Thus, further research on this issue is warranted.

As more data becomes available on synergetic effects and the adaptive capacity of sea turtles, the framework can be updated to include new sources of information and to refine the results from this analysis. Nevertheless, the results and methodology presented here provide guidance to global managers and scientists on a methodological approach to assess the vulnerability to climate change of sea turtle nesting grounds and gives valuable information on how and where they should focus their management.

7.6. Chapter summary

The vulnerability assessment used here proved efficient to investigate the impact of multiple climatic processes on sea turtle nesting grounds and provided valuable information for future management of the nGBR green turtle population. The main strengths of the framework used here is that it can easily be adapted when information is obtained, and it can be transferable to different sea turtle populations and sea turtle life cycle phases provided the necessary data exist.

The vulnerability assessment indicated that in the long term, by 2070 sand temperatures will reach levels above the upper transient range and the upper thermal threshold and cause relatively more impact on the nGBR green turtle population than the other climatic processes investigated. Thus, in the long term a stronger focus on mitigating the threats from increased temperature will be necessary for long term management.

Chapter 8.
General discussion [1]

[1] **Fuentes MMPB**, Grech A, Fish M, and Hamann M (in prep.) Feasibility, risks, and constraints of management options to mitigate the impacts of climate change on sea turtles. To be submitted to Biological Conservation

8.1. Sea turtles and climate change

As discussed in the previous Chapters (1-7), sea turtles are particularly vulnerable to climate change. The most detectable impacts of climate change on sea turtles will likely occur in their terrestrial reproductive phase (egg laying, egg incubation and hatchling success phase) as there are clear and relatively straightforward effects of increased temperature, sea level rise and cyclonic activity on sea turtle nesting sites and reproductive output (see Chapters 1, 3-5, and Figure 8.1). Increased sand temperature has the potential to exceed thermal mortality thresholds for eggs and to skew the sex ratio of hatchlings towards a predominantly female output (Chapter 3, and Figure 8.1). In addition, sea level rise and cyclonic activity will cause erosion and increased inundation of nesting beaches reducing the stability of nesting areas and hatching success (Chapters 4-5, and Figure 8.1). Further impacts to the reproductive output of sea turtles may occur through changes in the sediment traits of their nesting grounds as reef-flats adjacent to nesting grounds are impacted by ocean acidification and increases in sea surface temperature (Chapter 2, and Figure 8.1).

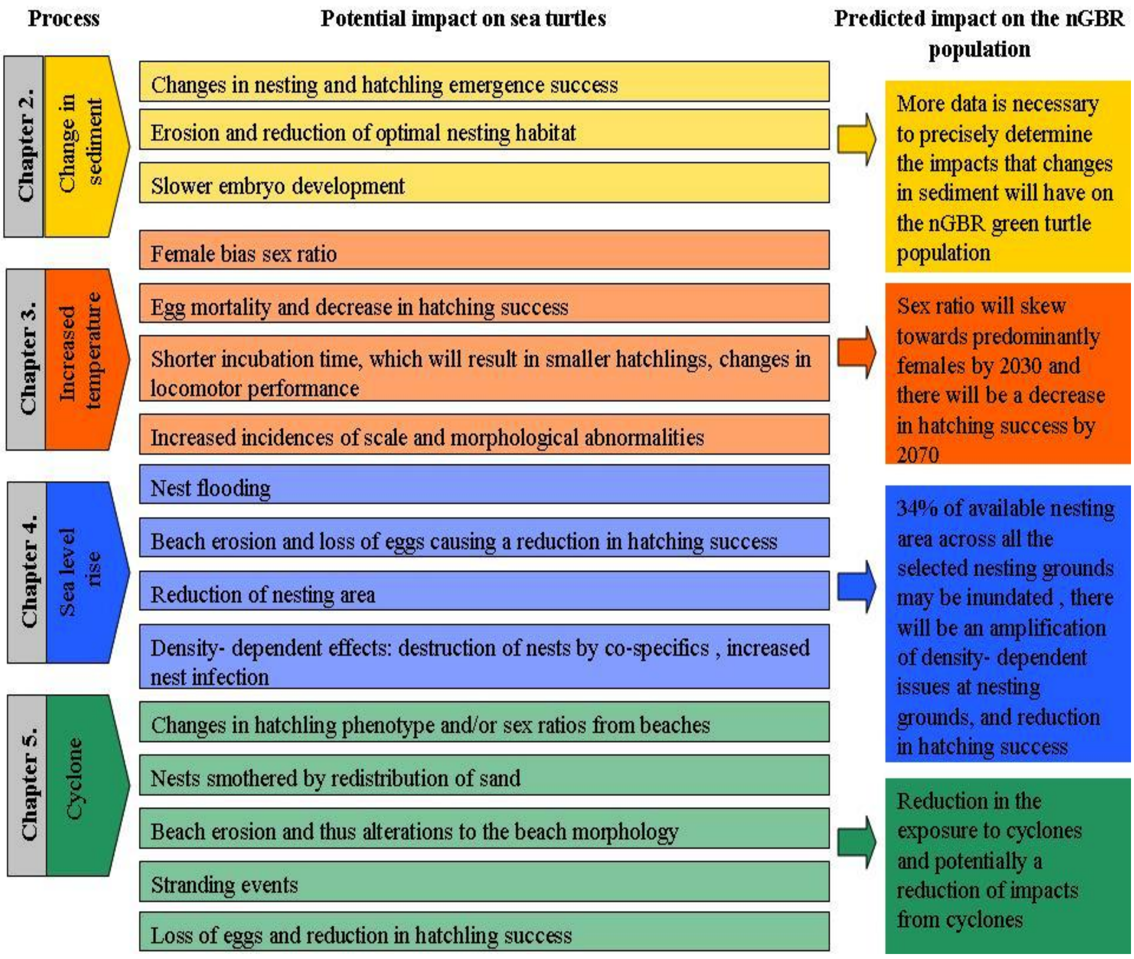

Figure 8.1. Summary of the impacts that each climatic processes will have on the terrestrial reproductive phase of sea turtle and a description of how the nGBR green turtle population is predicted to be affected by climate change.

Sea turtles have demonstrated to have a biological capacity to adapt to climate change; during the millions of years that they have existed there have been dramatic changes in climate (temperature and sea level rise) and landforms (Hamann et al. 2007; Hawkes et al. 2009). Sea turtles have undoubtedly adapted by re-distributing their nesting sites and developing new migratory routes. However, sea turtles are now faced with a variety of constraints which may impede their capacity to adapt to current and future climate change. Constraints include: accelerated rates of climate change, often declining and depleted populations, as well as cumulative impacts of anthropogenic threats and restriction of alternative habitats because of coastal development. It has been suggested that any adaptation response (e.g. shift in distribution) may be slow and insufficient to counteract the impacts of climate change on some reptiles (see Janzen 1994; Morjan 2003; Schwanz and Janzen 2008). Thus, the capacity for sea turtles to quickly adapt to rapid climate change is not well known. Given the uncertainty about sea turtles capacity to respond and adapt in time, their ecological and cultural importance, and the potential impacts that climate change may have on them, there is a need to undertake a precautionary approach and implement measures that increase their resilience as well as to conduct adaptive management and implement actions that can help mitigate the known and likely adverse impacts of climate change on sea turtles.

For managers to efficiently increase the resilience of sea turtle populations in the face of climate change and to effectively prioritise their resources and choose the best management option to mitigate the impacts of climate change on sea turtles they will require: (1) an understanding of the magnitude and relative impact of each climatic process; (2) an understanding of where gaps in knowledge exist; (3) identification of management options and information to determine the likelihood of these options providing the desired conservation outcomes, and (4) a method to prioritise adaptation measures in relation to their effectiveness, cost and feasibility (Wilson et al. 2005; Joseph et al. 2008). As these factors will likely differ between species and more specifically genetically distinct sea turtle populations it is important that this information is obtained for the specific population that is to be managed or on a regional basis when population boundaries are not clear.

Consequently, the goals of this thesis were to: (1) contribute towards a comprehensive population scale understanding of how the terrestrial reproductive phase of the nGBR green turtle population will be impacted by climate change; and (2) provide valuable information to aid the management and conservation of the nGBR green turtle population as climate change progresses. To achieve these goals I: (1) identified how key climatic processes will affect the reproductive output and nesting grounds used by the nGBR green turtle population; (2) assessed the vulnerability of nesting grounds used by the nGBR green turtle population to climate change; (3) identified various management options to increase the resilience of the nGBR green turtle population and to mitigate the impacts that they will likely experience from climate change; and (4) discussed some of the issues and challenges inherent in each of the identified management option.

8.2. Thesis summary

Objective 1: Investigate how key climatic processes will affect the reproductive output and nesting grounds used by the nGBR green turtle population (Chapters 2-5).

To investigate/predict how climate change will affect the nesting grounds used by the nGBR green turtle population, I first conducted a literature review to identify key climatic processes that can affect sea turtle nesting grounds and thus their reproductive output. I identified change in sediment traits (Chapter 2), increased temperature (Chapter 3), sea level rise (Chapter 4), and cyclonic activity (Chapter 5) as the key processes that can affect sea turtles' terrestrial reproductive phase. Thus, in Chapters 2, 3, 4 and 5, respectively, I investigated and predicted how each of these processes could affect the nGBR green turtle population.

In Chapter 2, I investigated how changes in sediment traits could affect the reproductive output of sea turtles. For this, I first described the sediment and identified the reef-building organisms of the selected nesting grounds. I then reviewed the literature on the vulnerability of each identified reef-building organism to climate change and how various sediment characteristics ecologically affect sea turtles. I found that sediment from the studied nesting grounds is predominantly composed of well-sorted medium-grained to coarse-grained sands and are either dominated by Foraminifera, molluscs or both. Dissimilarities in the contemporary sedimentology of the nesting grounds suggest that each may respond differently to projected climate change. Due to several knowledge gaps I was unable to quantify and precisely determine how the sediment at sea turtle nesting grounds will change as their adjacent reef platform and reef-building organisms are affected by climatic changes, and thus predict how sea turtles may be affected. However, I identified several knowledge gaps that need to be addressed to properly investigate this (see section 8.4).

To investigate how increased temperature will affect the reproductive output of sea turtles, I first conducted a systematic process to select the best predictive model of sand temperature. To do this, in Chapter 3, I explored the efficiency of three regression analyses and compared the fit of these three models using the Akaike Information Criterion (AIC) to select the best model. The selected model (SST + AT) was then used to predict future sand temperature under various scenarios of global warming for the selected sea turtle nesting grounds. My models predicted an almost complete feminisation of annual hatchling output into the nGBR green turtle population by 2030 and a decrease in hatching success by 2070.

The impacts of sea level rise on sea turtles were investigated in Chapter 4. For this, I developed a 3-D elevation model and quantified what proportion of each nesting ground may be inundated under a conservative and extreme scenario of sea level rise (SLR) by 2030 and 2070. Results indicate that up to 34% of available nesting area across all the nesting grounds may be inundated as a result of SLR. Flooding will increase egg mortality and loss of nesting area at these nesting grounds affecting the overall reproductive success of the northern Great Barrier Reef (nGBR) green turtle population.

Lastly, in Chapter 5, I investigated how the frequency of cyclones at the selected nesting grounds may change as climate change progresses. For this, I applied 11 regional climate model simulations for an A2 emission scenario for 2055 and 2090 to the study region. I found great variation in predictions among the various models used. Nevertheless, most of the models predicted a reduction in cyclonic activity and thus a reduction in the impacts that the nGBR green turtle population will experience from cyclonic activity in the future.

Objective 2: Assess the vulnerability of nesting grounds used by the nGBR green turtle population to climate change (Chapters 6-7).

In Chapter 6 I investigated the relative impact of different climatic processes to sea turtle nesting grounds. This information, together with the information from three of my data chapters (Chapters 3-5), was incorporated into a vulnerability assessment framework (Chapter 7) to allow assessment of the cumulative impact of multiple climatic processes on sea turtle nesting grounds. The vulnerability assessment indicated that: (1) the nesting grounds closer to the equator, such as the northern-facing beaches at Bramble Cay and Milman Island, are the most vulnerable to climate change and that these sites are also the most vulnerable to increased temperature (Chapter 7, Tables 7.3 and 7.4); (2) Sandbank 7 is the most vulnerable nesting ground to sea level rise by 2070 (Table 7.4); and, (3) the vulnerability of the nesting grounds used by the nGBR green turtle population to cyclonic activity is very low (Table 7.4). Further, I found that in the long term (by 2070), increased temperature will cause the most impact on the nesting grounds used by the nGBR green turtle.

Objective 3: Provide suggestions of management options to mitigate the impact of climate to the reproductive output of the nGBR green turtle population (Chapter 8).

In this Chapter I describe a variety of management options suggested by my expert panel and myself to mitigate the impacts of climate change to the terrestrial reproductive phase of the nGBR green turtle population and to increase their resilience to climate change (Tables 8.1 and 8.2). Further, I highlight, the fact that the best management options will be site specific and dependent on a series of factors, and evaluate the feasibility, risks, and effectiveness of each of the identified management options.

8.3. Evaluating the approach: management implications

This study used a systematic and comprehensive framework to assess how multiple climatic processes will affect sea turtle nesting grounds at a population scale. Even though sea turtles will be affected by multiple climatic processes simultaneously (Figure 8.1) studies conducted to date have not considered the cumulative and synergetic impacts from the various climatic processes in their analysis and have only investigated how a single climatic process at a time will impact a single nesting ground. Therefore, there was a clear need for a methodological approach to investigate how multiple climatic processes will impact the nesting grounds used by a specific turtle population. I addressed this by conducting this study in a systematic way; I undertook six steps (as described in Chapter 1), one of which consisted of a vulnerability assessment. This allowed me to investigate how multiple climatic processes will impact a range of nesting grounds used by the nGBR green turtle population. As described in Chapter 7, the vulnerability assessment used here allows the identification of: (1) which climatic process will cause the most impact to each nesting ground; (2) which nesting grounds will be the most vulnerable to climate change; (3) how the vulnerability of the nesting grounds will change as climate change progresses; and, (4) how the vulnerability of the nesting grounds will change as the impacts from climatic processes are mitigated.

The framework used here is based on the environmental vulnerability assessment framework for climate change provided by the International Panel of Climate Change (IPCC 2007) and recent studies (Turner et al. 2003; Metzger et al. 2005; Schroter et al. 2005) and it can be easily adapted if new information is obtained, and is transferable to different sea turtle populations and life cycle phases (e.g. adult sea turtles, foraging) provided the necessary data exist. The framework is not meant to be a rigid prescription of a specific technique, but rather a guideline for managers and scientists to address the impacts of climate change on sea turtles. However, as mentioned in Chapter 7, I strongly suggest that the framework is applied to the full range of areas (e.g. nesting areas) used by a single population, so that an understanding of a population level (management unit) can be obtained. It is also important that the vulnerability assessment is updated as new information becomes available and the experts' knowledge changes, this is particularly true for information on the adaptive capacity of sea turtles.

As it stands, the impacts predicted by the framework (Chapters 3-5) assume a static scenario without any adaptation from sea turtles and the framework assumes that sea turtles will be able to adapt to climate change similarly at all nesting grounds. However, as discussed in Chapter 7, the adaptive capacity of sea turtles and their nesting grounds will vary spatially as a result of sea turtles' current status, trend, the threats they face (e.g. predation, harvest), the awareness and legislative compliance at a local level, management effectiveness, and the morphological stability of their nesting sites. Therefore, as more understanding of sea turtles' adaptive capacity and site-specific data is acquired in relation to the parameters mentioned above it should be included in the framework to refine and add ecologically important information to vulnerability assessments. Similarly, if an understanding is gained of how sea turtles may potentially shift their nesting grounds (as an adaptation response as climate change progresses), then the vulnerability assessment conducted here should be repeated in areas that may serve as potential nesting grounds to sea turtles in the future. This will provide insights into which areas managers may need to focus their resources and management strategies.

Nevertheless, the framework used aided the identification of the climatic processes that will cause the most impact on the terrestrial reproductive phase of the nGBR green turtle population and identified how the vulnerability of this population to climate change will change as the impacts of each climatic process are mitigated. Subsequently, the next steps from this framework would be to incorporate other anthropogenic threats to the framework, and to systematically assess and prioritise specific management options (e.g. nest shading, nest relocation) to mitigate the key threats identified at each nesting ground. Consequently, as part of the surveys conducted in Chapter 6, I also asked experts to suggest management options to mitigate the impacts of climate change to the terrestrial reproductive phase of the nGBR green turtle population. Most of the management options suggested have previously been identified by other studies (e.g. Hamann et al. 2007; Hawkes et al. 2007, 2009). However, more than 60% of the respondents suggested indirect management measures, such as reduction of harvest, environmental education with locals, protection of their habitat and reduction of emissions, which will increase sea turtles resilience to climate change and enhance their future capacity to adapt.

The best management option to mitigate the impact from each climatic process will likely be site-specific and dependent on a series of factors, including: (1) feasibility (does the technology and/or expertise exist to carry out this measure? At what scale can it be implemented?); (2) constraints on implementation (both cultural and social); (3) risk (interaction and impact on other species and ecosystems); (4) effectiveness (how effective would this measure be in achieving the overall conservation goal); and (5) costs. Since the experts indicated high uncertainty about the feasibility, effectiveness, risks and benefits of most of the management options suggested, below I screen the suggested management options and discuss some of the issues and challenges inherent to each of them. The cost of the management options was not assessed as a more detailed cost-benefit analysis is necessary and this is outside the scope of this work. Therefore, it is recommended that, prior to any management option being implemented; costs and benefits should be assessed. There are three main methods to do this: (1) Cost-Benefit Analysis - analysis of the cost- effectiveness of different alternatives in order to see whether the benefits outweigh the costs; (2) Multi-Criteria Analysis - considers more than one criterion and may be used when there are non-monetary benefits; and (3) Cost-Effectiveness Analysis - is a form of economic analysis that compares the relative costs and outcomes (effects) of two or more courses of action. Cost-effectiveness analysis is distinct from cost-benefit analysis, which assigns a monetary value to the measure of effect (Boardman et al. 2006).

Table 8.1. Management options suggested by the expert panel to mitigate the impacts of climate change to the terrestrial reproductive phase of the nGBr green turtle population and their feasibility, risks and effectiveness.

Climatic processes to be managed	Management strategy	Feasibility/constraints	Risks	Effectiveness
Changes in sediment traits	Prioritise protection of reefs that have high cover of key carbonate producers	Feasibility depends on local and national support.	Risk of impacting local and national communities that rely on the reefs being protected (e.g. if reef protected provided commercial resources to community)	There are many knowledge gaps to be filled before the effectiveness of this management option can be assessed.
	Restore reef-flat areas with coral nurseries and/or artificial substrate	Technology exists; it will be more challenging to implement at a broad scale, at remote reefs or more dynamic reefs.	May interfere with other organisms and ecosystems.	There are many knowledge gaps to be filled before the effectiveness of this management option can be assessed.
Increased sand temperature	Nest shading with structure (e.g. artificial shading) to reduce sand temperature.	Technology exists; may be challenging to implement at a national scale or in remote areas. It is likely that a large area will need to be shaded to mitigate the impacts from increased sand temperature to the reproductive output of sea turtles on a particular nesting site.	Artificial shading could bias sex ratios towards males, risky when there is little knowledge of natural sex ratio.	Could be efficient (if large areas are shaded) but may reduce variability in sex ratio.
	Revegetation programs, tree planting – replant native coastal vegetation in areas where it has been removed; prevent removal of beach vegetation	Feasible – suggested to be a better option than nest shading as will keep the variability in sand temperature. However, it may not be feasible at cays and islands that have never been vegetated (e.g. Bramble Cay in Torres Strait).	Risk of introducing non-native vegetation or altering the ecosystem (e.g. casuarina trees in Florida). Could bias sex ratios towards males. Risky when there is little knowledge of natural sex ratio. Less of an option for low lying coral cays that have never been vegetated.	May be effective at local scales.

Table 8.1. Management options suggested by the expert panel to mitigate the impacts of climate change to the terrestrial reproductive phase of the nGBr green turtle population and their feasibility, risks and effectiveness.

Climatic processes to be managed	Management strategy	Feasibility/constraints	Risks	Effectiveness
Increased sand temperature	Beach sprinklers (solar)	Technology exists; however, no study to date has indicated how much water to use; may be hard to implement at a national scale or in isolated areas and /or on islands that are also seabird rookeries. Not feasible unless freshwater stores are located adjacent to the beach (then there will be water allocation issues). Seawater can not be used because of salinity issues with egg development. Not feasible at any of the studied nesting grounds for the nGBr green turtle population.	Watering could limit gas exchange and increase fungal infection. Could bias sex ratios towards males; risky when there is little knowledge of natural sex ratio and natural hydrology of islands.	There are many knowledge gaps to be filled before the effectiveness of this management option can be assessed.
	Sand colouring by adding new sediment to the nesting beach.	Technology exists; feasibility dependent on local and national support.	Risk of impacting ecosystems function, with time and sediment transportation sand colour will return to original especially in highly dynamic beaches. May alter sediment characteristics and thus affect reproductive output of sea turtles.	It has been suggested not to be an effective option.
	Nest relocation (*in situ*).	Technology exists; hard to implement at a broad scale and nearly impossible to implement at remote sites, such as the studied nesting grounds for the nGBR green turtle population, that are uninhabited and no personnel would be available. Will need to be ongoing, may not be affordable in the long term.	May be risky when there is no/ limited knowledge of the natural sex ratio and of the sex ratio being produced at re-located sites. Baseline data necessary as relocation may occur at areas that are not favourable (e.g. areas with increased risk of disease). May distort gene pools by imposing artificial selection on ‘poor’ nesters. High labour costs.	Could be efficient but may reduce variability in sex ratio.

Table 8.1. Management options suggested by the expert panel to mitigate the impacts of climate change to the terrestrial reproductive phase of the nGBr green turtle population and their feasibility, risks and effectiveness.

Climatic processes to be managed	Management strategy	Feasibility/constraints	Risks	Effectiveness
Increased temperature	Hatcheries, artificial incubation (taking eggs from the beach and artificially incubating them).	Technology exists; hard to implement at a broad scale. Will need to be ongoing, may not be affordable year after year. Specific infrastructure will be required and staff will need to be long term (whole nesting season). Thus, it is nearly impossible to implement at remote sites, such as the studied nesting grounds for the nGBR green turtle population, that are uninhabited and no personnel would be available.	May be risk when there is no/ limited knowledge of the natural sex ratio and of the sex ratio being produced at re-located hatcheries. Need sufficient baseline data prior to moving nests; working out natural sex ratios must precede artificial manipulation. May distort gene pools by imposing artificial selection on ‘poor’ nesters; would be a viable conservation strategy for populations with low repeatability in individual selection of nest sites. Expensive, high labour costs, may have other impacts on hatchling development fitness and quality.	Could be efficient but may reduce variability in sex ratio.
Sea level rise, cyclonic activity and storm surge	General habitat modification (use of engineering techniques for beach rehabilitation; beach nourishment, groins)	Technology exists; hard to implement at a broad scale. Logistically challenging in remote areas. High costs.	Risk of impacting ecosystem function and causing further impacts. Best to be carried out with full knowledge of the coastal ecosystem that it is affecting. May alter sediment characteristics and thus affect reproductive output of sea turtles.	The success of beach nourishment is currently under discussion with both increases and declines in reproductive output reported.
	Create artificial nesting beaches, floating islands	Technology exists but might be dependent on site. Feasibility will depend on local and national support. High costs.	Risk of impacting ecosystem function. Need sufficient baseline data prior to moving nests; working out natural sex ratios must precede relocation of nests.	There are many knowledge gaps to be filled before the effectiveness of this management option can be assessed.

Table 8.1. Management options suggested by the expert panel to mitigate the impacts of climate change to the terrestrial reproductive phase of the nGBr green turtle population and their feasibility, risks and effectiveness.

Climatic processes to be managed	Management strategy	Feasibility/constraints	Risks	Effectiveness
Sea level rise, cyclonic activity and storm surge	Hatcheries, artificial incubation, move nests from areas of high erosion	Technology exists; hard to implement at a broad scale. Will need to be ongoing, may not be affordable year after year. Specific infrastructure will be required and staff will need to be long term (whole nesting season). Thus, it is nearly impossible to implement at remote sites, such as the studied nesting grounds for the nGBR green turtle population, that are uninhabited and no personnel would be available.	May be risk when there is no knowledge of the natural sex ratio and of the sex ratio being produced at re-located hatcheries. Need sufficient baseline data prior to moving nests; working out natural sex ratios must precede artificial manipulation. May distort gene pools by imposing artificial selection on ‘poor’ nesters; would be a viable conservation strategy for populations with low repeatability in individual selection of nest sites.	Could be efficient but may reduce variability in sex ratio.
	Establish or enforce setback regulations	Feasibility dependent on local and national support. Does not apply to uninhabited islands in the nGBR and Torres Strait region.	Risk of impacting local and national human communities and dune systems.	There are many knowledge gaps to be filled before the effectiveness of this management option can be assessed.

Considering the feasibility, constraints, effectiveness and risks of each management option, and the uncertainties inherited in them, I suggest that until more is known about the risks and benefits of each active management option, managers should:

(1) Increase the resilience of sea turtles to climate change by reducing the current threats that they face; for the nGBR green turtle population, this includes a reduction in harvest of eggs and turtles, protection of key foraging and nesting habitat, reduction of pollution, and a reduction of incidental catch recreational and commercial fisheries gear (Table 8.2);

(2) Increase hatchling production at Raine Island. For this it will be necessary to identify the causes of poor hatchling production at Raine Island and some possible solutions. This is already underway and a coordinated interdisciplinary approach is being undertaken by sea turtle ecologists, native title holders, wildlife managers, coastal geomorphologists, coastal engineers and other stakeholders interested in the preservation of the islands biological, historical and cultural values

(3) Protect beaches that produce male hatchlings. Therefore important nesting sites to protect include Milman Island and Sandbank 7;

(4) Identify and prioritise protection of nesting grounds that have the potential to serve as functional nesting grounds as climate change progresses. To investigate this, knowledge of which islands will disappear and where new ones will be formed as climate change progresses will be necessary. After this is established it will be necessary to investigate whether these sites will have optimal incubating environments, in term of temperature, and moist as climate change progresses.

As mentioned above (option 1), there are many ways to increase the resilience of sea turtles to climate change however, in the context of limited resources, political and social costs and associated constraints it is unfeasible for managers to mitigate the impacts of all anthropogenic threats along the entire distribution of the nGBR green turtle population. Consequently, managers will need to prioritise their management actions and selectively allocate their resources and time. For conservation actions to be effective, it will be essential to target resources to individual sites that can facilitate the achievement of conservation goals at a local scale. Thus, the costs, constraints and opportunity of each management strategy and the ecological importance of each nesting site will need to be considered before any strategy is implemented (Pressey and Bottrill 2009).

Constraints and opportunities are shaped by social, economic and cultural conditions in a region, which inevitably control the implementation of conservation plans. In contrast, opportunities for conservation actions exist when the degree of impact on communities is perceived to be low and when there is a political and/or organizational will (Pressey et al. 2000) and community interest (Green et al. 2009). For example, as explained in Chapter 3, Traditional Owners can conduct Indigenous hunting of sea turtles as Indigenous hunting rights have been affirmed by the Commonwealth Government's *Native Title Act 1993*, subsequent judgments in the High Court of Australia and the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (see Havemann et al. 2005). Therefore, banning turtle harvest is culturally and socially infeasible in the Torres Strait region as it would negatively impact on the social and cultural wellbeing of Torres Strait communities and it would be interpreted as reducing the Native Title rights of Aboriginal Australians. Thus, an option might be for Traditional Owners to alter the intensity of turtle take within their communities through Sea Country management agreements with government. Similarly, for nesting sites in Torres Strait, agreements can be made for egg harvest to take place in warmer areas that have temperatures above the thermal threshold (e.g. open areas in the top dune on northern-facing beaches) and areas that are more vulnerable to storm surges and inundation, and limit harvest in regions that are cooler and produce mainly male hatchlings.

Understanding the constraints and opportunities of each management option is essential to ensure that implementation and enforcement will be successful. Thus, below I assess some of the constraints and opportunities of the different management options that were identified by myself and my expert panel to increase the resilience of the nGBR green turtle population to climate change.

Table 8.2. Constraints and opportunities of management options to increase the nGBR green turtle population's resilience to climate change. May be applied to other sea turtle populations. However, the constraints and opportunities may vary between the different turtle populations.

Threat	Action / Management options	Constraints	Options/opportunities
Unsustainable legal or illegal use (e.g. harvest, poaching)	Manage indigenous harvest (turtle meat and eggs). Note: Within the range of the nGBR green turtle population there are several nations that have different legislation regarding the use of sea turtles; ranging from permissible commercial use to total prohibition. In Australia, according to the *Native Title Act 1993*, indigenous Australians have the legal right to hunt sea turtles. Regardless, unsustainable use at an ecological scale has been mentioned as a threat for this population (Limpus 2008).	Prohibiting turtle harvest is culturally and socially infeasible in the northern Queensland region as it would negatively impact on the social and cultural wellbeing of Torres Strait communities. This would be interpreted as reducing the *Native Title* rights of Aboriginal Australians. It will be costly to build/ develop the capacity and to provide the necessary tools for people to manage and monitor sea turtle harvest throughout the whole distribution range of green turtles from the nGBR stock; this is especially true for developing areas outside Australia such as Indonesia and Papua New Guinea. Currently there is no precise information on harvest levels or indication of sustainable harvest numbers.	Allocate areas that generally have sand temperatures above the thermal threshold (e.g. open areas in the top dune on northern-facing beaches) and areas that are more vulnerable to storm surges and inundation for egg harvest, and limit egg harvest at regions that are cooler and produce males. Alter the intensity of turtle take in communities through Sea Country management agreements with traditional owners or government e.g. Traditional use of marine Resource Agreements and/ or development of a coordinated ranger program (e.g. in Torres Strait). Conduct education programs within local communities highlighting the need for a conservative and sustainable approach to harvesting and the implications of overharvesting the nGBR green turtle population. Use the best available science and local indigenous knowledge to quantify existing harvest and to determine sustainable levels of harvest. Opportunity for Australia to provide support for sea turtle management in the Asia/Pacific region and to develop new bilateral or multilateral agreements to ensure that international conservation and management of sea turtles is consistent with domestic policies and international treaty obligations (e.g. Memorandum of Understanding on the Conservation and Management of Marine Turtles and their Habitats in the Indian Ocean and South East Asia (MoU).

Table 8.2. Constraints and opportunities of management options to increase the nGBR green turtle population's resilience to climate change. May be applied to other sea turtle populations. However, the constraints and opportunities may vary between the different turtle populations.

Threat	Action / Management options	Constraints	Options/opportunities
Pollution, marine debris, poor water quality and entanglement.	Reduce pollution and sea turtle death associated with ghost nets by: - Identifying sources of marine debris, and quantifying it. This will allow a more strategic approach to any follow-up activities with polluters, who could then be the target of compliance and/or education programs; - Respond to stranding events; - Implement legislation for the prevention of garbage discharge from vessels of all sizes; - Minimise use of plastic bags.	The costs and scale associated with implementing ghost net programs may be a constrain. However, as the nGBR green turtle population is probably not greatly affected by ghost nets (few green turtles caught) the money spent may not provide a great return in conservation investment. Local and national support will be necessary to maintain water quality, decrease use of plastic bags, nutrient run-off, sedimentation and inappropriate disposal of rubbish.	Education programs with local communities, industries, and fishing groups on the impacts that marine debris and water pollution can have on sea turtles and other wildlife. Conduct beach clean ups and ghost net programs. This can provide opportunity for employment schemes (e.g. rangers, etc.) Develop national guidelines on proper ways to discard fishing line and netting. Promote compliance of laws that restrict pollution from vessels.
Coastal development and habitat alteration	Protect key foraging and nesting habitat	There is little knowledge about the locations of key foraging habitats for the nGBR green turtle population, especially in international waters. Thus, there is the need to identify key foraging and nesting habitat that currently is not protected. Local and national support and implementation of legislation may be a constrain	Protection of key habitat, that currently is not protected, through rezoning of marine protected areas and existing community based management plans (for the nGBR green turtle population, this would mean protecting nesting and foraging areas in Torres Strait and international areas, as key sea turtle habitat in the GBR is already protected by the GBRMPA). Conduct education programs with local communities on how coastal development and habitat alteration can impact sea turtles as well as provide suggestions of how the community and industries can mitigate their impacts. Opportunity for employing personnel to protect key sea turtle habitat.

Table 8.2. Constraints and opportunities of management options to increase the nGBR green turtle population's resilience to climate change. May be applied to other sea turtle populations. However, the constraints and opportunities may vary between the different turtle populations.

Threat	Action / Management options	Constraints	Options/opportunities
Fishing activities (e.g. by-catch)	Minimise incidental catch in recreational and commercial fisheries gear. Monitor foreign fishing vessels operating illegally. Regulate for mandatory use of TEDs for all vessels in international waters.	Local and national support; impacts on local communities that rely on fisheries. There is little baseline quantifying the impacts of various fisheries on the nGBR green turtle population. Challenging to monitor the whole extent of waters used by the nGBR green turtle population for activity of foreign fishing vessels. The use of TEDs imposes a small economic cost on fishers.	Boat speed restrictions; use of turtle-friendly fishing gear. Education programs within local communities intended to reduce the risk of interactions or negative outcome of interactions between turtles and fishing gears in national and international waters used by the nGBR green turtle population uses. Conduct awareness programs on the existing code of fishing ethics, which aims at minimizing the impacts of fisheries on sea turtles.
Predation	Reduce predation of eggs at nesting beaches.	Cost may be high. Eradication programs may need to be ongoing, may not be affordable year after year and will need on-ground personnel. Some of the animals that prey on turtle eggs are native species (e.g. goannas) and thus protected under the *QLD Wildlife Conservation Act 1992.* No data on the magnitude of nests predated are available.	Community education; eradication of predators (non-native ones). Control activities in remote areas offer scope for Aboriginal and Torres Strait Islander people to become involved.

Community education was identified, by my turtle expert panel, as a key strategy to mitigate the threats that the nGBR green turtle population currently face and thus to increase their resilience to climate change. Indeed education has been identified as an essential strategy to promote the conservation ethic and is an important process that empowers individuals to solve or prevent environmental problems (Delgado and Nichols 2005; Bennett and Martin 2008). Education has the power to promote environmental concerns by increasing awareness, acquiring knowledge, changing attitudes, providing skills and encouraging participation (United Nations Educational, Scientific and Cultural Organisation 1978). Therefore, community education and training was a key part of my PhD and during my field work I educated turtle and dugong officers and local community members about various aspects of sea turtle biology and ecology and the threats that sea turtles face. I also developed an educational cartoon book on sea turtles and climate change (see Appendix B for a draft) that will be published next month. The book addresses the following issues:

- The ecological and cultural values of sea turtles and the importance of conserving them;
- Current threats that sea turtles face, highlighting the fact that current populations are depleted and sensitive to additional threats;
- Ways that climate change can affect sea turtles;
- Implications of reduced turtle numbers to indigenous communities;
- What can be done – including suggestions of ways that communities can help increase sea turtles' resilience and adaptive capacity to climate change by reducing the threats sea turtles currently face and reducing greenhouse emissions.

The book will be distributed in Torres Strait this year as part of the turtle and dugong officer's environmental program that occurs on some islands. Distribution will target school children in grades 5-7 attending the local Tagai campuses (Moa, Murray, Erub, Ugar, Warraber, Poruma, Masig, Dauan, Saibai, Kubin and the Kaurareg Archipelagos region).

I also conducted education and awareness on the potential impacts of climate change on sea turtles with the broader community. This was accomplished through the media and popular articles; during my candidature I gave 2 TV interviews (ABC1 news and Seven local news), 3 radio interviews (ABC -The world today, ABC Beat and ABC science show), and several interviews for various newspapers, where I discussed the impacts of climate change on biodiversity, focusing on sea turtles.

8.4. Management outcomes

Throughout my PhD I worked closely with different management agencies, such as the Great Barrier Reef Marine Park Authority and Torres Strait Regional Authority, thus I was able to deliver my results in a manner that could be incorporated into their management practices. Consequently, information derived from my thesis has contributed to the Great Barrier Reef Outlook Report, which is a report prepared to the federal parliament every 5 years with reliable information on the overall conditions and research of the Great Barrier Reef region. Additionally, the results from my thesis were also used for the Marine Climate Change and Adaptation Report Card for Australia (lead by the Australian Commonwealth Scientific and Industrial Research Organisation). The report card provided a synopsis of impacts and potential adaptation strategies for the Australian marine region to different stakeholders. Further, the Hon. Kate Jones (current Australian Minister of Climate Change) has publicly acknowledged the value of the study conducted for this thesis, and indicated that this research has led to increased capacity for management of sea turtles in the face of climate change.

8.5. Future work and knowledge gaps

Although there has been a substantial increase in the number of studies that investigate the impacts of climate change on the terrestrial reproductive phase of sea turtles, there are many knowledge gaps that need to be addressed before a deeper understanding of the impacts of climate change on the reproductive output of sea turtle's and their nesting grounds will be possible. To better understand and mitigate the predicted impacts of climate change on the terrestrial reproductive phase of the nGBR green turtle population, and other sea turtle populations, I suggest the following research areas need to be addressed:

(1) Sustainable sex ratio

Although most of the work on the impacts of climate change on the reproductive output of sea turtles has focused on the impacts of climate change on the sex ratio of sea turtle populations, there are several issues that remain unknown and warrant further research. These include information on: (a) the sex ratio and the pivotal temperature of sea turtle populations; (b) how many males are necessary to maintain a fertile and productive population; and (c) how a modified sex ratio will affect long-term population dynamics of sea turtles.

(2) Nesting ground responses to climate change

Knowledge of how the morphology of nesting grounds will respond to predicted sea level rise scenarios is crucial for management of sea turtles in the face of climate change. To date, studies have only accounted for the impacts from inundation. Thus future studies should investigate how shoreline erosion, rise of water table and potential accretionary events will affect sea turtle nesting grounds.

(3) Changes in sediment traits at nesting grounds and implications for sea turtles

To properly investigate how sea turtles will be impacted by changes in sediment traits, information on the following research gaps need to be acquired: (a) responses/tolerance levels of the different reef-building organisms to projected climate change – at this stage, studies on the effects of increased sea surface temperature and ocean acidification have generally been confined to a few species of corals, algae and foraminiferans and, therefore, large gaps still remain in our knowledge of the physiological and ecological impacts of increased SST and ocean acidification on other reef-building organisms, such as coralline algae and *Halimeda*; (b) calcification response to ocean acidification; (c) threshold levels at which sediment production rates may change in the future; (d) how decreased calcification rates affect biological functioning or organism survival; (e) specific sediment requirements of sea turtles, especially how the compositional characteristics of sand affects their reproductive ecology; and (f) thermal properties of different sediment characteristics.

(4) Selection of nesting beach by first-time breeders

It is important to have an understanding of the processes that drive the selection of a nesting beach by female sea turtles as they commence their breeding life in order to understand selection of future nesting beaches as climate change progresses. Further research should also investigate the potential for turtles to change their breeding behaviour as an adaptation response to climate change, through: (a) shifts in timing of the breeding season; (b) shifts to use cooler beaches; or (c) selection of new breeding sites following the loss of a nesting ground and/or as climate change progresses. Similarly, the potential for sea turtles to adapt, and how fast, in case a nesting site is "lost" from sea level rise should also be investigated. This knowledge will be crucial for adaptive management decisions in the face of a changing climate. It will also be interesting to investigate whether some females lay their eggs in areas that are less prone to the impacts of climate change (e.g. cooler areas).

(5) Current and future habitat use by sea turtles

It is important to identify the thermal and morphological characteristics of key habitats (e.g. nesting areas) used by sea turtles at a population scale, and investigate their sensitivity to climatic events such as storms and sea-level rise. Future studies should also identify areas that have the potential to serve as functional habitats for sea turtles under predicted climate and sea change forecasts, and investigate distributional shifts resulting from climate change. Special attention should be taken to examine the management strategies that are in place in these areas and determine how potential distributional changes may affect population dynamics.

(6) Cumulative and synergetic impacts of climate change

Climate processes will not act in isolation and they may produce unexpected changes to ecosystems when combined with local conditions and other threats. It is likely that most threat interactions will amplify their impacts; however, the nature and magnitude of these synergies are unknown for most threats and ecosystems and could potentially be beneficial. Consequently, there is a need to understand the cumulative and synergetic impacts from climate change on sea turtles and their nesting grounds as well as the overall threats they will face from other anthropogenic stressors (e.g. hunting, coastal development).

(7) Adaptive capacity and resilience of sea turtles

There is a lack of baseline data on population demography and the spatial limits to distribution (terrestrial, marine, foraging and nesting) for most sea turtle populations. Coupled with low certainty in several climate predictions and cumulative impacts it is difficult to understand the resilience of sea turtle populations and their capacity to adapt to climate change under current conditions (e.g. elevated rates of climate change, multiple stressors, etc.). Therefore, future studies should investigate the extent to which sea turtles can or will exhibit adaptive responses and how these responses may counteract impacts of climate change. Investigation of ways to increase and facilitate adaptation is warranted. Some insights into the potential responses of sea turtles to future climate change may be obtained by further understanding how sea turtles adapted to climate change in the past, which can be obtained from advances in genetic studies.

(8) Implications of management options and most suitable management strategies

The best management strategies to mitigate the impacts of climate change on sea turtles may vary geographically and according to the magnitude and specific threats that an area may face; successful implementation will vary according to existing constraints, opportunities, costs and feasibility. However, as previously discussed, there are still many unknown factors within each of the potential management strategies, especially those promoting intervention. Consequently, further studies should explore the constraints, opportunities, costs and feasibility of various management options at key nesting grounds. Further, as management options are trialled, information about their success or failure should be made available to managers in all regions, both locally and internationally, to help develop shared knowledge and, ultimately, guidelines for management. This

shared learning will be critical to promote adaptive management, whereby managers adapt their strategies according to the best information available.
Addressing these eight knowledge gaps will increase the understanding of how sea turtle populations will be impacted by climate change and will be fundamental to inform future management and mitigation strategies. However, it is important that these studies are conducted at the appropriate scale (e.g. population scale – at the whole range of key nesting ground used by a population, rather than at one individual site) as species and nesting grounds will be affected differently by predicted climatic changes to provide the necessary information to manage the whole management unit (population) rather than just one location (e.g. nesting ground or foraging area).

8.5. Concluding remarks

To date, the assessments of the impacts of climate change on the terrestrial reproductive phase of sea turtles have only focused on the impacts of one climate process at a time on a single or a few nesting grounds, which does not encompass the full range of areas used by a sea turtle population. My study addressed this by using a systematic vulnerability assessment that assessed the cumulative impacts of climate change on the full range of nesting areas used by the nGBR green turtle population. Future studies should work to improve the framework I used by incorporating synergetic impacts and more information on adaptive capacity of sea turtles as well as addressing the eight areas of future research identified.

Management of sea turtle populations in the face of a rapidly changing climate will require a global effort, both to reduce the direct impacts of climate change and to increase resilience of turtle populations. A series of management options exist to accomplish this; however, before any management strategy is implemented its feasibility, costs, risks, constraints and opportunities need to be further explored to ensure effective implementation and that the overall conservation goals are met.

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Appendix A- Survey to determine the relative impact of each climatic process

Vulnerability of sea turtle nesting grounds to climate change survey

Identification information

Name:

Email address:

Affiliation:

☐ Researcher ☐ Manager

1. Relative importance/impact of each climatic process.

Please consider the relative impact of each climatic process to sea turtles and assign values accordingly.

1.a Please indicate below the degree to which you think either sea level rise or increased sand temperature will have more impact to sea turtles. The higher the number towards one climatic process the higher their relative impact.

← More impact from sea level rise | More impact from increase in temperature →

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

Sea level rise | Increased sand temperature

1.b Please indicate below the degree to which you think either sea level rise or cyclonic activity will have more impact to sea turtles. The higher the number towards one climatic process the higher their relative impact.

← More impact from sea level rise | More impact from cyclonic activity →

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

Sea level rise | Cyclonic activity

1.c Please indicate below the degree to which you think either increased sand temperature or cyclonic activity will have more impact to sea turtles. The higher the number towards one climatic process the higher their relative impact.

← More impact from increased sand temperature   More impact from increased cyclonic activity →

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

Increased sand temperature   Cyclonic activity

What is your level of certainty answering the questions above? (Please indicate one)

Certainty	
None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

2. Relative impact of various levels of increased sand temperature.

Please consider the relative impactof each feature within each process (A to C) in relation to increase in sand temperature.

2a. Exposure (increased sand temperature)

Please indicate below the degree to which you think the relative impact from each exposure level will have more impact to sea turtles. The higher the numbers toward one exposure level the higher their relative impact on sea turtles.

More impact process A ←   → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No increase in sand temperature at nesting ground   **B.** Occasional increase in sand- increase in temperature during only one nesting season

More impact process A ←   → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No increase in sand temperature at nesting ground   **B**. Increase in sand temperature during one turtle generation

More impact process A ←   → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No increase in sand temperature at nesting ground   **B.** Constant / persistent increase in sand temperature

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Increase in sand temperature during one turtle generation

B. Occasional increase in sand- increase in temperature during only one nesting season

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Constant / persistent increase in sand temperature

B. Occasional increase in sand- increase in temperature during only one nesting season

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Constant / persistent increase in sand temperature

B. Increase in sand temperature during one turtle generation

What is your level of certainty answering the question (2A) above? (Please indicate one)

Certainty	
None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

2b. Sensitivity level (increased sand temperature - across multiple seasons)

Please indicate below the degree to which you think the relative impact from each sensitivity (impact) level will have more impact to sea turtles. The higher the numbers toward one impact level the higher their relative impact on sea turtles.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Sand temperature above pivotal temperature transient **(higher % of females being produced)**

B. Sand temperature above upper **(only females being produced)**.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

Sand temperatures above pivotal temperature threshold **(higher %of females being produced)**

B. Sand temperatures near the upper thermal **(Deformation of hatchlings and only females being produced)**

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Sand temperatures above pivotal temperature threshold **(higher % of females being produced) being hatchling mortality)**

B. Sand temperatures above the upper thermal **(Deformation of hatchlings and only females produced, increased**

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Sand temperatures above the upper transient range threshold
(only females being produced)

B. Sand temperatures near the upper thermal
(Deformation of hatchlings and only females being produced)

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Sand temperatures above the upper transient range threshold
(only females being produced)

B. Sand temperatures above the upper thermal
(Deformation of hatchlings, only females being produced, increased hatchling mortality)

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Sand temperatures near the upper thermal threshold threshold
(Deformation of hatchlings and only females produced)

B. Sand temperatures above the upper thermal
(Deformation of hatchlings, only females produced, increased hatchling mortality)

What is your level of certainty answering the question (2b) above? (Please indicate one)

Certainty	
None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

Please asses the consequence of each impact level using the categories presented at the table below.

Categories to be used to asses the consequences of each impact level.

Consequence	Definition
Catastrophic	Impact is clearly affecting the species over a wide area or impact is irreversible over a small area (nesting ground level) or a sensitive part of the ecosystem is irretrievably compromised.
Major	Impact is significant at either a local or population level to the species or nesting habitat.
Moderate	Impact is present either at a local or population level. Recovery period within one generation (40 years) are likely.
Minor	Impact is present but not to the extent that it would impair the overall condition of the species or population.
Insignificant	No impact on the overall condition of the species or population.

Impact level - across multiple seasons	Consequence
Temperatures above pivotal temperature	
Temperature above upper Transient Range Temperature (only females produced),	
Temperatures near the upper thermal threshold	
Temperature above upper thermal threshold (deformation and mortality).	

2c. Potential for the nesting habitat to recover (increased sand temperature)

Please indicate below the degree of relative impact from each potential recovery level. The higher the numbers toward one recovery level the higher their relative impact.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Ability to return to pre-threat condition within a nesting season

B. Ability to return to pre-threat condition after a turtle generation

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Ability to return to pre-threat condition within a nesting season

B. No ability to return to pre-threat condition

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Ability to return to pre-threat condition after a turtle generation

B. No ability to return to pre-threat condition

What is your level of certainty answering the question (2D) above? (Please indicate one)

Certainty

None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

3. Relative impact from various levels of sea level rise.

Please consider the relative impact of each feature within each process (A to C) in relation to increase in sea level rise.

3a. Exposure (sea level rise)

Please indicate below the degree to which you think the relative impact from each exposure level will have more impact to sea turtles. The higher the numbers toward one exposure level the higher their relative impact on sea turtles.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No sea level rise at the nesting ground

B. Sea level rise occasionally occurs at nesting ground –discrete events from storm surge

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No sea level rise at the nesting ground

B. Sea level rise occurs often – over one generation

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No sea level rise at the nesting ground

B. Sea level rise is constant – Impacts the stability of the population

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Sea level rise occurs often – over one generation

B. Sea level rise occasionally occurs at nesting . ground –discrete events from storm surge

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Sea level rise is constant

B. Sea level rise occasionally occurs at nesting ground –discrete events from storm surge

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Sea level rise is constant generation **B.** Sea level rise occurs often – over one

What is your level of certainty answering the questions (3A) above? (Please indicate one)

Certainty

None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

3b . Sensitivity level (sea level rise)

Please indicate below the degree to which you think the relative impact from each sensitivity (impact) level will have more impact to sea turtles. The higher the numbers toward one impact level the higher their relative impact on sea turtles.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Loss of up to 10% of current nesting area **B**. Loss of 10% to 35% of current nesting area

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Impact from loss of up to 10% of current nesting area **B**. Loss of 35% to 60% of current nesting area

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Loss of up to 10% of current nesting area **B.** Loss of 60% to 85% of current nesting area

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Loss of up to 10% of current nesting area area **B.** Loss of 85% to 100 % of current nesting

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Loss of 10% to 35% of current nesting area **B.** Loss of 35% to 60% of current nesting area

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Loss of 10% to 35% of current nesting area **B.** Loss of 60% to 85% of current nesting area

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Loss of 10% to 35% of current nesting area **B**. Loss of 85% to 100% of current nesting area

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Loss of 35% to 60% of current nesting area **B.** Loss of 60% to 85% of current nesting area

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Loss of 35% to 60% of current nesting area **B.** Loss of 85% to 100% of current nesting area

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Loss of 60% to 85% of current nesting area **B.** Loss of 85% to 100% of current nesting area

What is your level of certainty answering the questions (3b) above? (Please indicate one)

Certainty	
None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

Please asses the consequence of each impact level using the categories presented below

Categories to be used to asses the consequences of each impact level.

Consequenc	Definition
Catastrophic	Impact is clearly affecting the species over a wide area or impact is irreversible over a small area (nesting ground level) or a sensitive part of the ecosystem is irretrievably compromised.
Major	Impact is significant at either a local or population level to the species or nesting habitat.
Moderate	Impact is present either at a local or population level. Recovery period within one generation (40 years) are likely.
Minor	Impact is present but not to the extent that it would impair the overall condition of the species or population.
Insignificant	No impact on the overall condition of the species or population.

Impact level	Consequence
Loss of up to 10% of current nesting area	
Loss of 10% to 35% of current nesting area	
Loss of 35% to 60% of current nesting area	
Loss of 60% to 85% of current nesting area	
Loss of 85% to 100% of current nesting area	

3c. Potential for the nesting habitat to recover (sea level rise)

Please indicate below the degree of relative impact from each potential recovery level. The higher the numbers toward one recovery level the higher their relative impact.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
Extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Ability to return to pre-threat condition within a nesting season

B. Ability to return to pre-threat condition after a turtle generation

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
Extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Ability to return to pre-threat condition within a nesting season

B. No ability to return to pre-threat condition

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Ability to return to pre-threat condition after a turtle generation

B. No ability to return to pre-threat condition

What is your level of certainty answering this? (Please indicate one)

Certainty

None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

4. Relative impact from various levels of cyclonic activity.
Please consider the relative impact from each feature within each process (a to b) in relation to cyclonic activity.

4a. Exposure (cyclonic activity)
Please indicate below the degree to which you think the relative impact from each exposure level will have more impact to sea turtles. The higher the numbers toward one frequency level the higher their relative impact on sea turtles.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No cyclonic activity at nesting ground — **B**. Cyclonic activity occasionally occurs at nesting ground (1 cyclone every 30 years)

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No cyclonic activity at nesting ground — **B**. Cyclonic activity occurs often (1 cyclone every 5 years)

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. No cyclonic activity at nesting ground cyclone every . — **B**. Cyclonic activity persistent (at least one nesting season)

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Cyclonic activity occasionally occurs at nesting ground (1 cyclone every 30 years) — **B**. Cyclonic activity occurs often (1 cyclone every 5 years)

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Cyclonic activity occasionally occurs at nesting ground (1 cyclone every 30 years) — **B**. Cyclonic activity persistent (1 cyclone every nesting season)

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Cyclonic activity occurs often (1 cyclone every 5 years)

B. Cyclonic activity persistent (1 cyclone every nesting season)

What is your level of certainty answering the questions (4A) above? (Please indicate one)

Certainty	
None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

4b. Sensitivity level (cyclonic activity - across multiple seasons)

Please indicate below the degree to which you think the relative impact from each sensitivity (impact0 level will have more impact to sea turtles. The higher the numbers toward one impact level the higher their relative impact on sea turtles.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Decrease in frequency of cyclones

B. Decrease in frequency and more intense cyclones

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Decrease in frequency of cyclones

B. Increase in frequency of cyclones

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Decrease in frequency of cyclones

B. Increase in frequency and more intense cyclones

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more		extremely more		

A. Decrease in frequency of cyclones and more intense cyclones

B. Increase in frequency of cyclones

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Decrease in frequency of cyclones and more intense cyclones

B. Increase in frequency and more intense cyclones

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Increase in frequency of cyclones

B. Increase in frequency and more intense cyclones

What is your level of certainty answering the questions (4b) above? (Please indicate one)

Certainty	
None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

Please asses the consequence of each impact level using the categories presented at the table below

Categories to be used to asses the consequences of each impact level.

Consequence	Definition
Catastrophic	Impact is clearly affecting the species over a wide area or impact is irreversible over a small area (nesting ground level) or a sensitive part of the ecosystem is irretrievably compromised.
Major	Impact is significant at either a local or population level to the species or nesting habitat.
Moderate	Impact is present either at a local or population level. Recovery period within one generation (40 years) are likely.
Minor	Impact is present but not to the extent that it would impair the overall condition of the species or population.
Insignificant	No impact on the overall condition of the species or population.

Impact level – across multiple seasons	Consequence
Decrease in frequency of cyclones	
Decrease in frequency and more intense cyclones	
Increase in frequency of cyclones	
Increase in frequency and more intense cyclones	

4c. Potential for the nesting habitat to recover (cyclonic activity)

Please indicate below the degree of relative impact from each potential recovery level. The higher the numbers toward one recovery level the higher their relative impact.

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Ability to return to pre-threat condition within a nesting season

B. Ability to return to pre-threat condition after a turtle generation

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Ability to return to pre-threat condition within a nesting season

B. No ability to return to pre-threat condition

More impact process A ← → More impact process B

8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8
extremely more			moderately more			slightly more		equal impact	slightly more			moderately more			extremely more	

A. Ability to return to pre-threat condition after a turtle generation

B. No ability to return to pre-threat condition

What is your level of certainty answering the questions (4c) above? (Please indicate one)

Certainty	
None	**0**
Very little or no empirical work exists or expert has limited personal experience	**1**
Some empirical work exists or expert has some personal experience	**2**
Empirical work exists and the expert has direct personal experience	**3**
Extensive empirical work exists of the expert has extensive personal experience	**4**

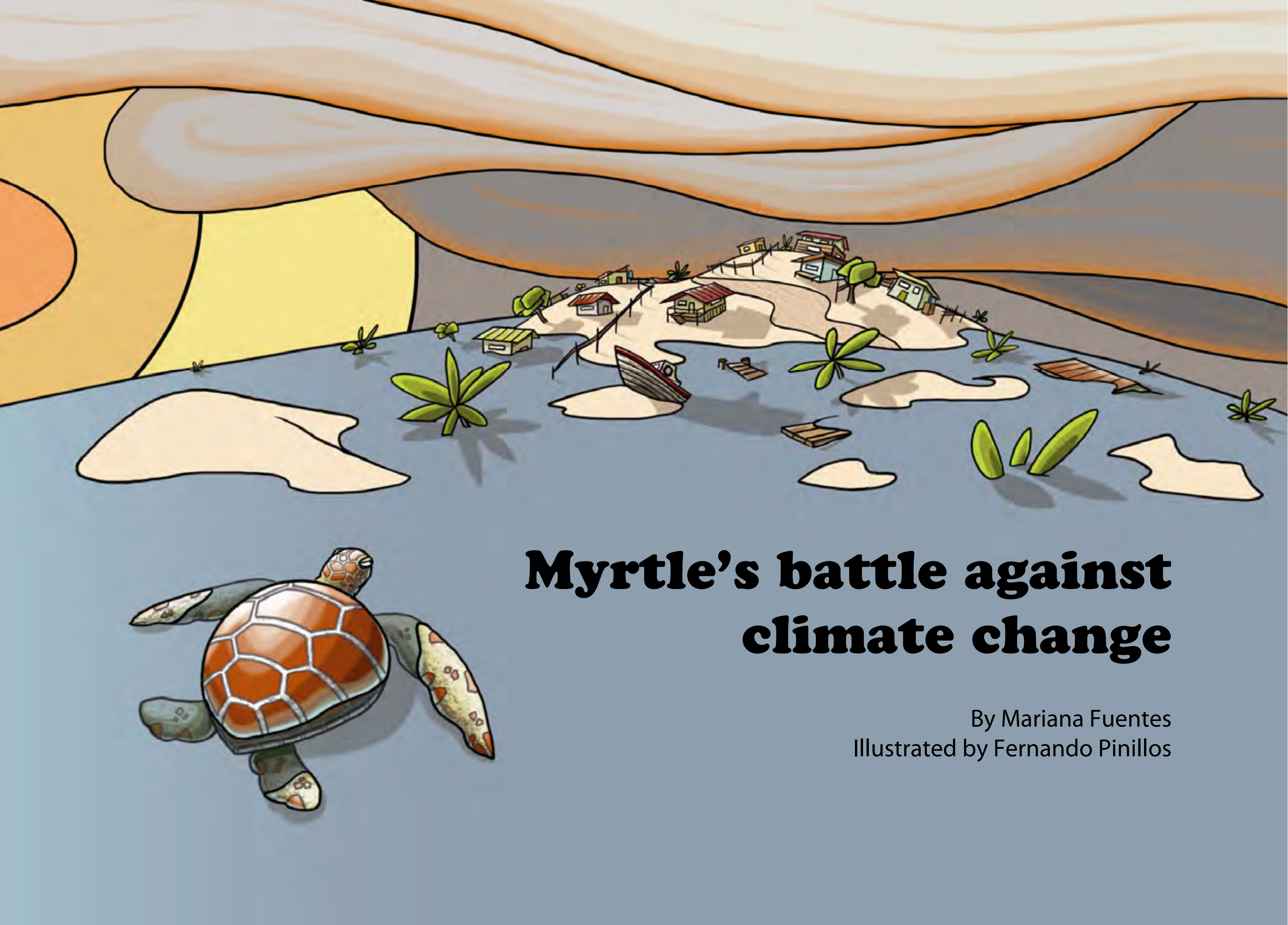
Management options – Can you suggest any management options to each of the climatic processes?

Management option	**Climatic process**

Can you suggest any research question that could aid climate related management?

Appendix B. Draft of educational material generated from this thesis

Please note: this is just a draft of the educational book that is being developed. By no means this is the last draft, it is only here to give an indication of the sort of work that has been conducted.



Myrtle's battle against climate change

By Mariana Fuentes
Illustrated by Fernando Pinillos

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Illustrated by Fernando Pinillos

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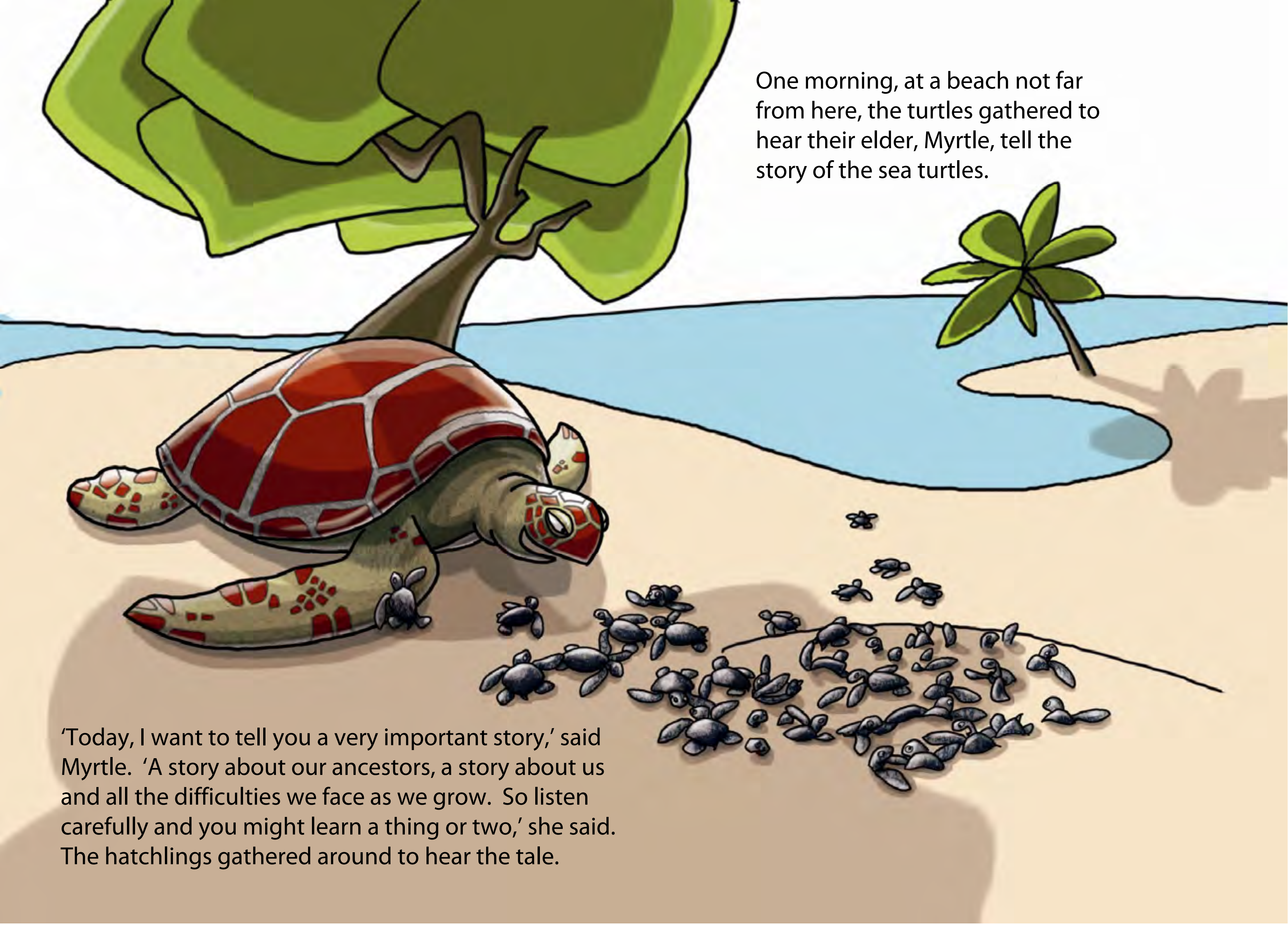
Introduction

This book is based on findings from the PhD research conducted by Mariana Fuentes on the impacts of climate change on the northern Great Barrier Reef green sea turtle population. The main character of the book, 'Myrtle', is based on a real turtle that was satellite-tagged in 2008 at Mer Island, Torres Strait. Myrtle was named by students from the local Tagai State College. This book is dedicated to the children of the Torres Strait islands with the hope that they learn about the effects of climate change on sea turtles and find a way to make a difference.

About the Author

Originally from Brazil, Mariana Fuentes moved to Australia almost a decade ago to become a marine biologist. She has been working on sea turtle conservation and management programs for the last eight years and has conducted research on many aspects of sea turtle biology and ecology. In addition to Australia, Mariana's work has taken her to Madagascar, Vanuatu, Kenya, the United States and Barbados, and more recently to the unique tropical islands of the Torres Strait where she has been studying the impacts of climate change on the northern Great Barrier Reef sea turtle population. Sea turtles have an important role to play both ecologically and, for the people of Torres Strait, culturally. Mariana's commitment to building the capacity of local communities to address the impacts of climate change led to the development of this book, which aims to educate Torres Strait children about the perils faced by sea turtles in the face of climate change, and what these challenges mean to the Torres Strait communities.



One morning, at a beach not far from here, the turtles gathered to hear their elder, Myrtle, tell the story of the sea turtles.

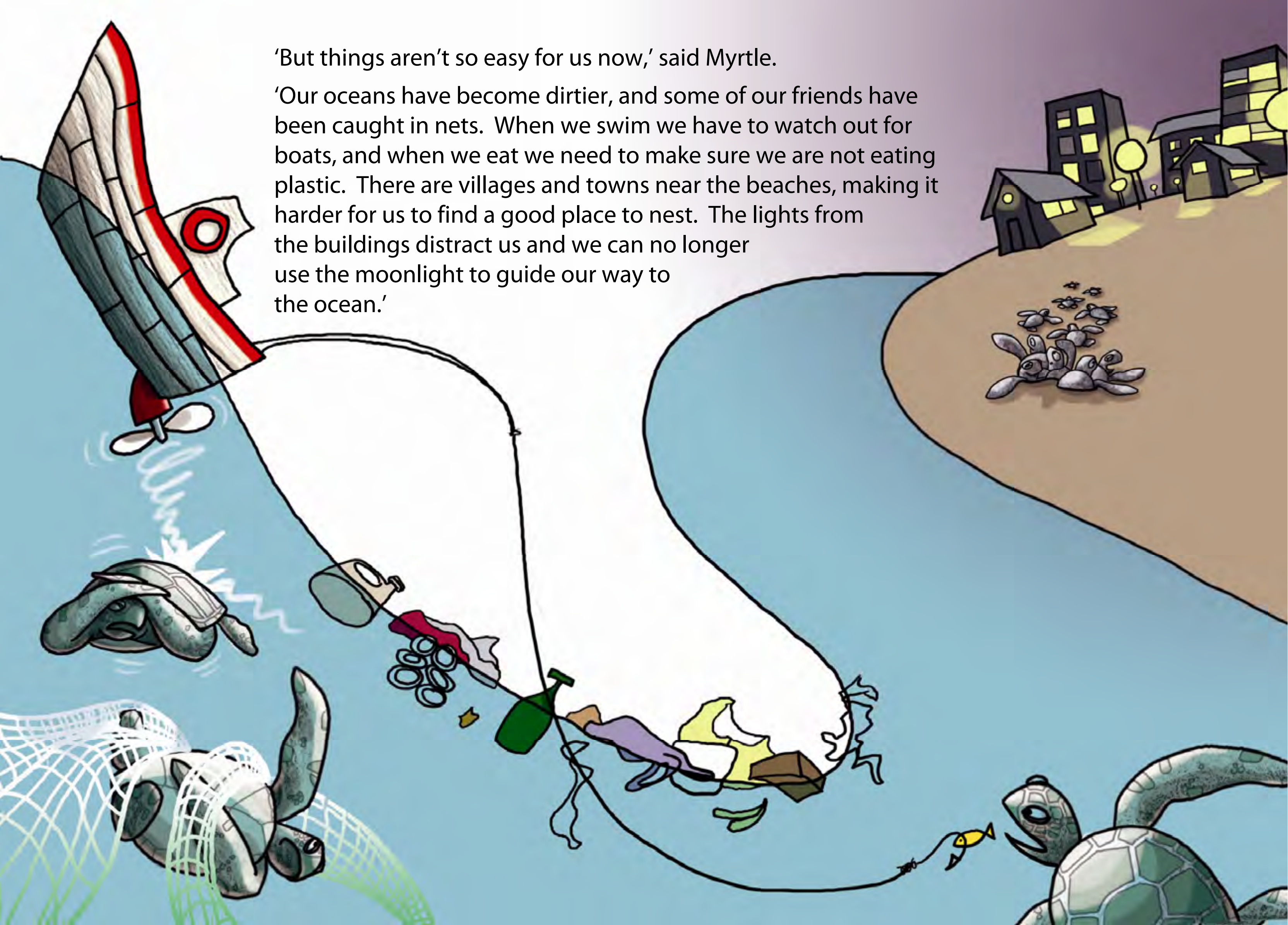
‘Today, I want to tell you a very important story,’ said Myrtle. ‘A story about our ancestors, a story about us and all the difficulties we face as we grow. So listen carefully and you might learn a thing or two,’ she said. The hatchlings gathered around to hear the tale.

'Sea turtles have existed for a long time. Back in the days, hundreds of years ago, there were many of us, so many that you wouldn't believe.'

'Life was very different then. There were lots of nice nesting beaches for us to lay our eggs, the oceans were clean, and we didn't have to worry about being hit by boats or being entangled in nets.'

'But things aren't so easy for us now,' said Myrtle.

'Our oceans have become dirtier, and some of our friends have been caught in nets. When we swim we have to watch out for boats, and when we eat we need to make sure we are not eating plastic. There are villages and towns near the beaches, making it harder for us to find a good place to nest. The lights from the buildings distract us and we can no longer use the moonlight to guide our way to the ocean.'



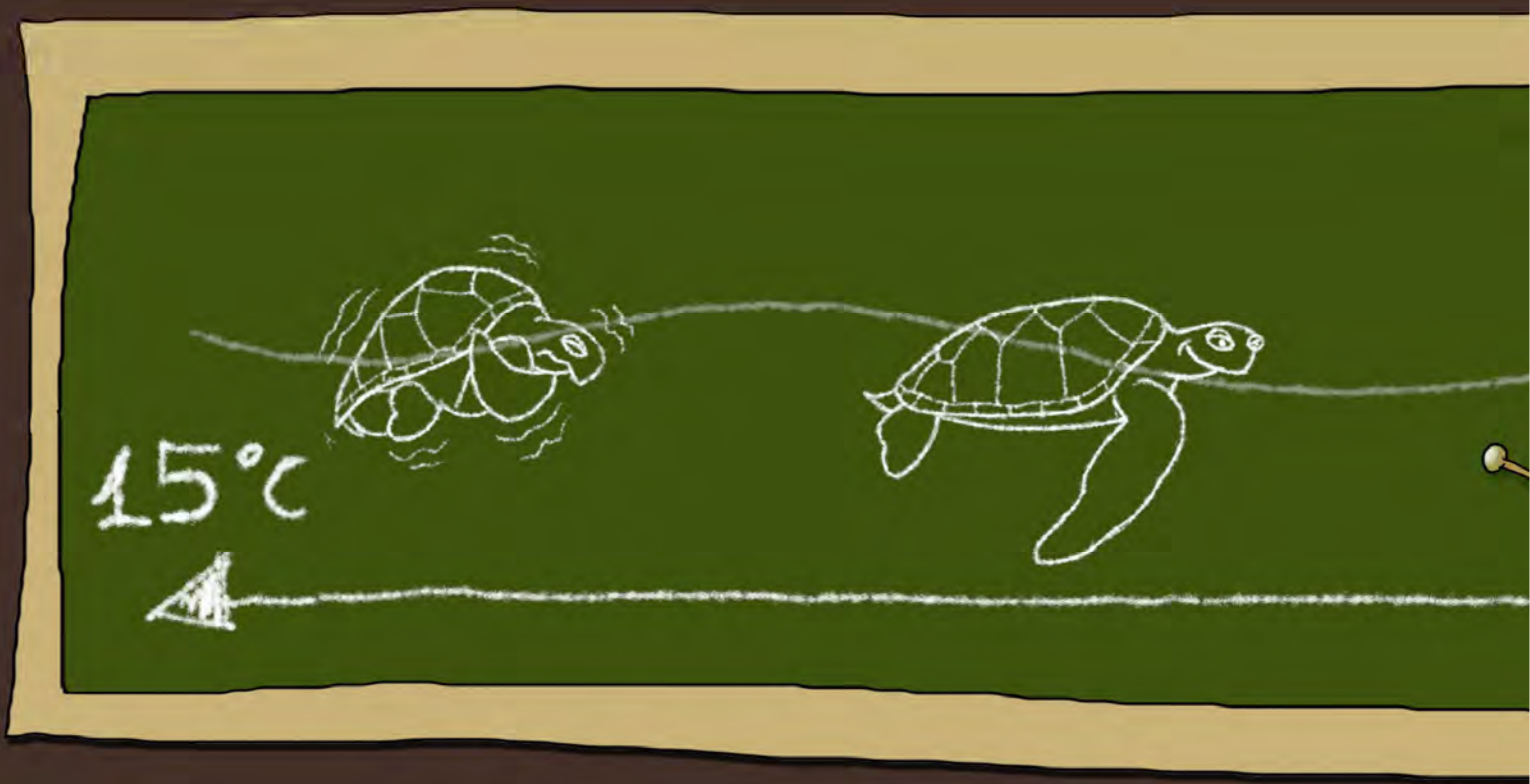
‘Because of all these changes to our habitat, many of our friends and family have died. There are less of us now than in the past and we are more sensitive to new threats such as *climate change*.’

‘Climate change is the result of an increase in the Earth’s temperature across the world,’ said Myrtle.

‘It is believed that the increase in temperature is caused by human activities, such as burning of fossil fuels like oil and coal to make electricity for our homes and fuel for our cars.’

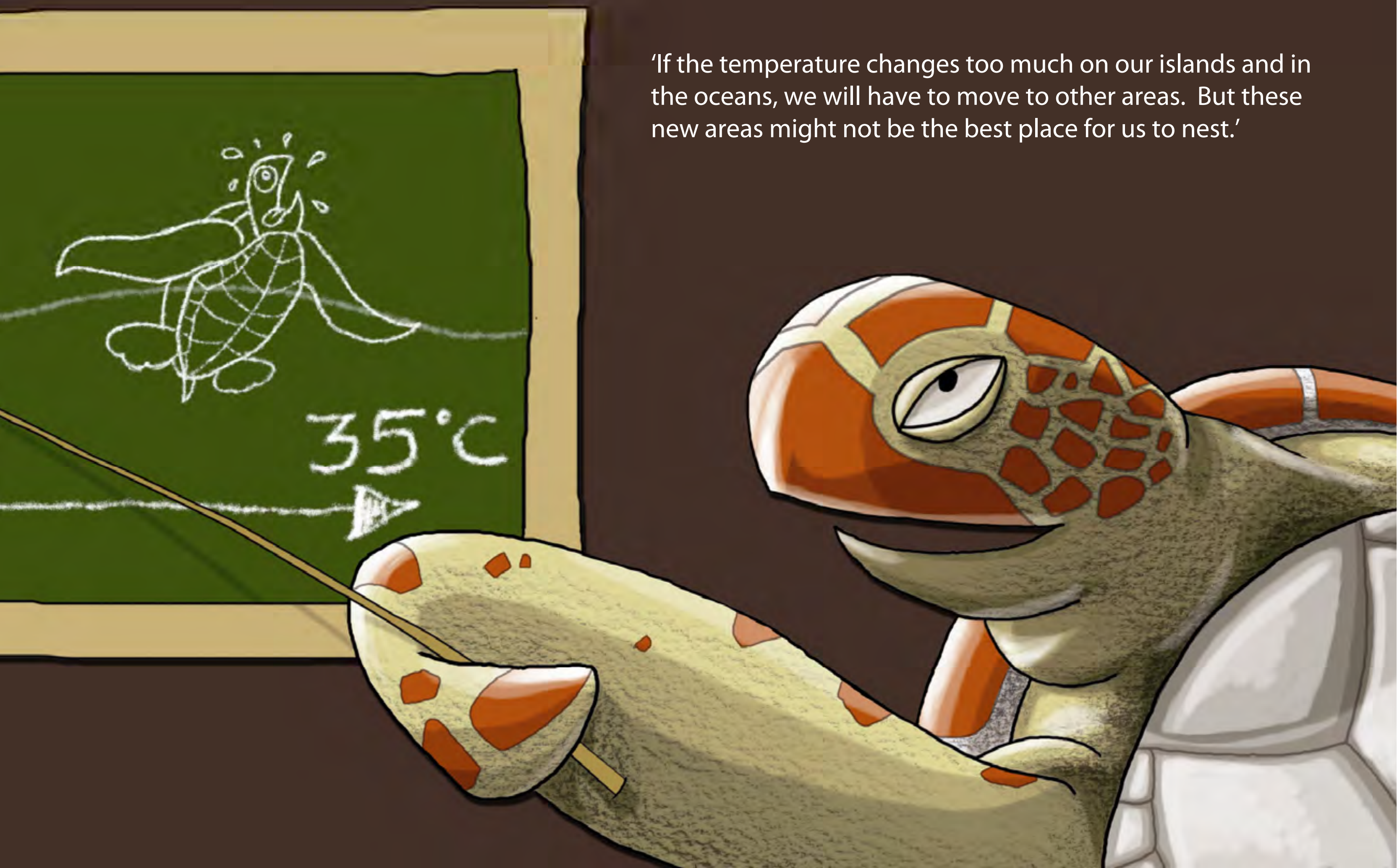
'Burning of fossil fuels creates greenhouse gases, which escape into the air. The gases cause most of the warming. A warmer Earth may lead to changes in rainfall patterns and a rise in the sea level. This may affect plants, animals and humans.'

‘An increase in Earth’s temperature will have a big impact on sea turtles,’ said Myrtle.

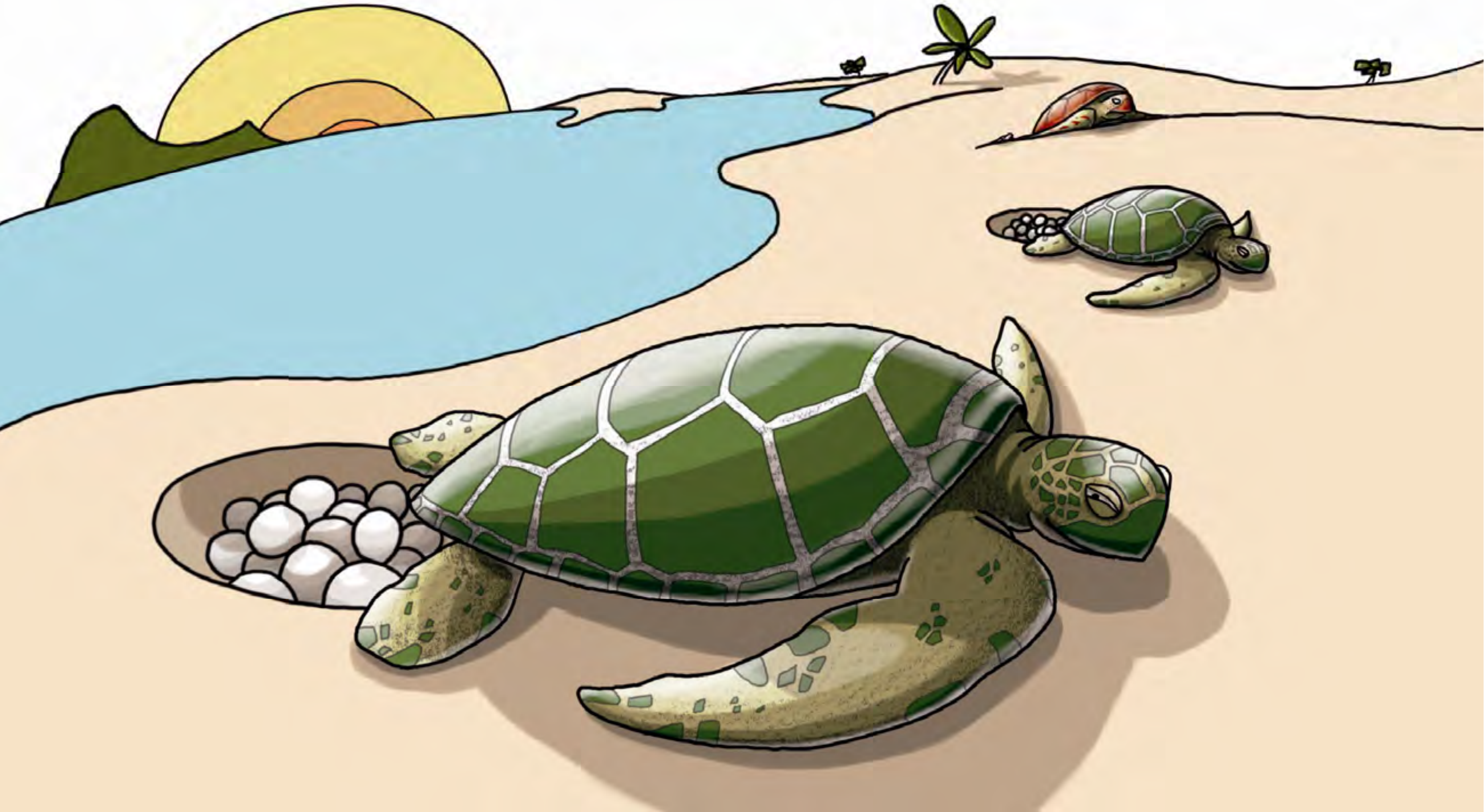


‘We are sensitive creatures. We can only tolerate ocean temperatures of between 15 and 35 degrees Celsius. When the water is too cold, it is hard for us to swim. If the water becomes too hot, we become stressed.’

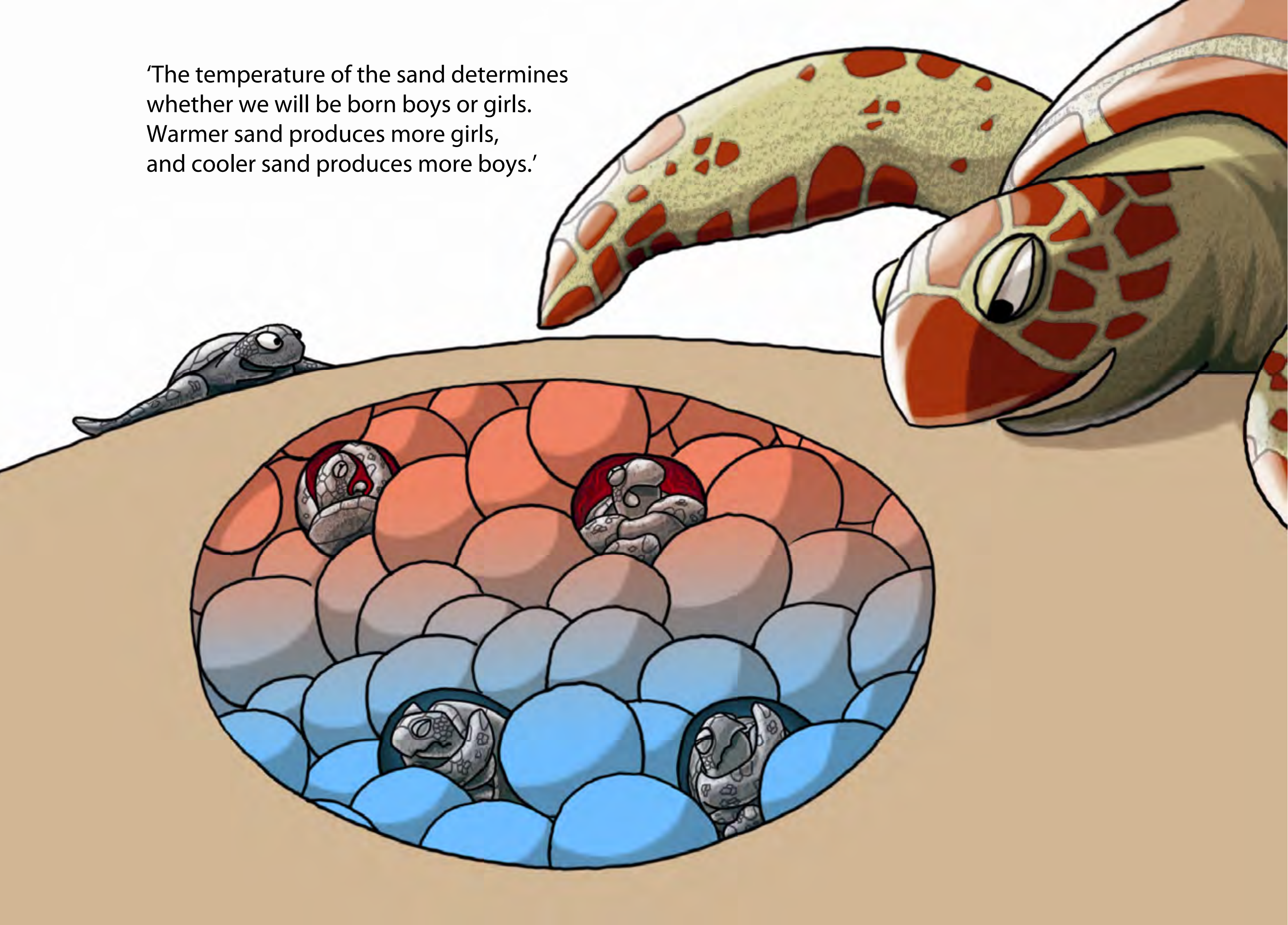
‘If the temperature changes too much on our islands and in the oceans, we will have to move to other areas. But these new areas might not be the best place for us to nest.’



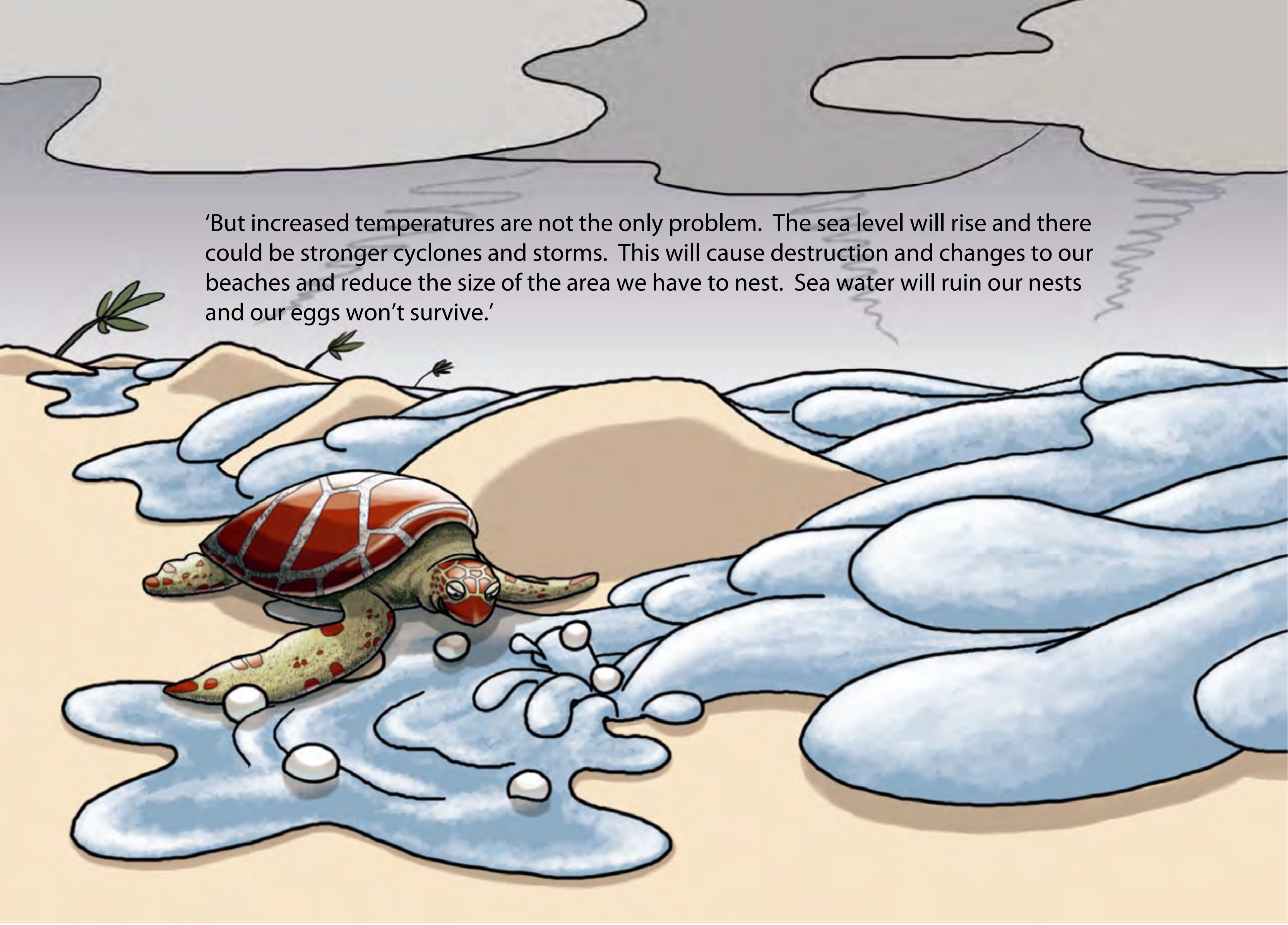
‘If the temperature on our beaches becomes too hot, the development of our eggs and babies can be affected. For turtle eggs to incubate properly, sand temperatures need to be between 25 and 33 degrees Celsius. Temperatures above and below this may affect the development of baby turtles, causing them to die before they hatch. If sand temperatures become warmer, fewer eggs will develop into hatchlings.’



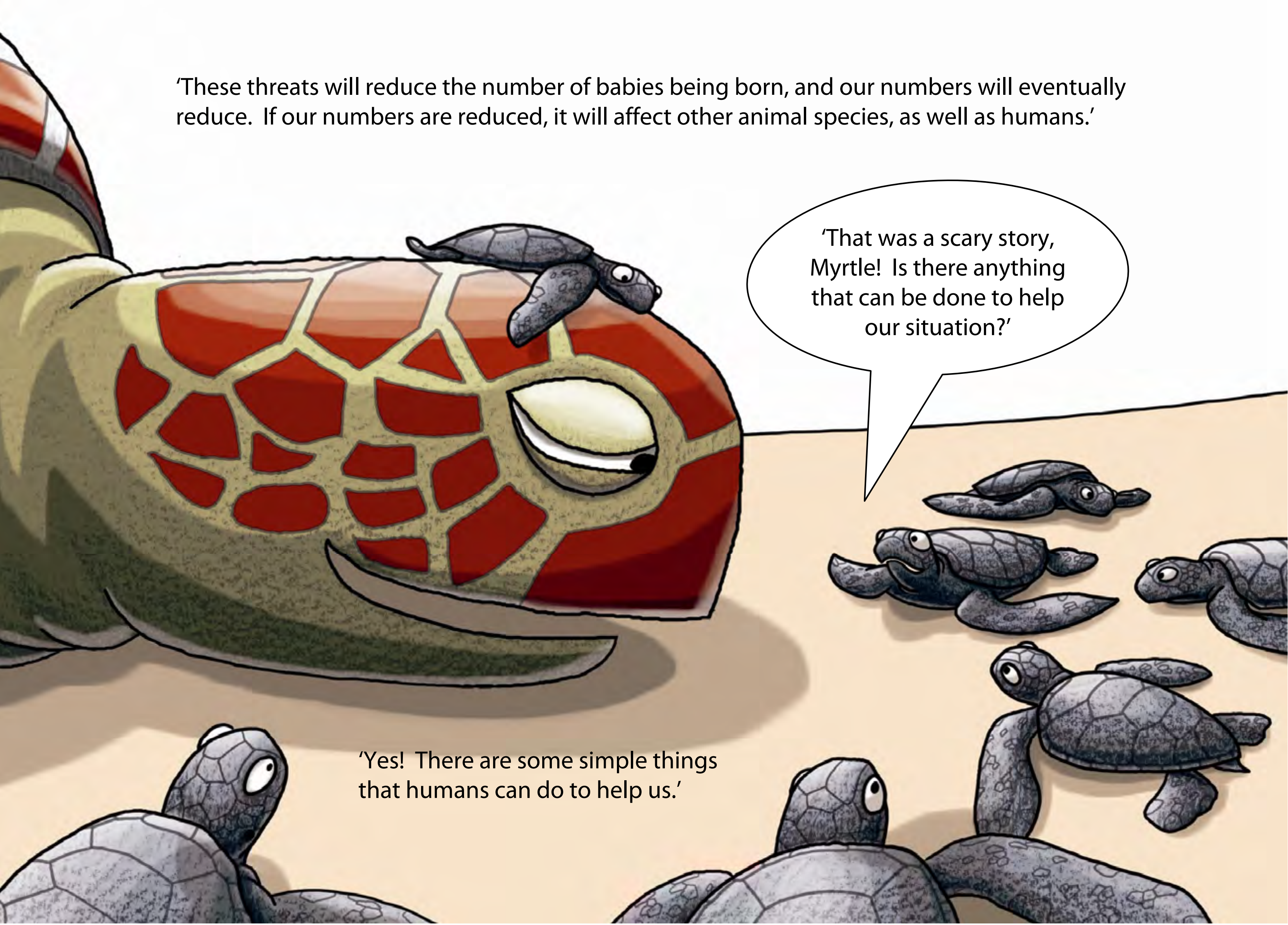
‘The temperature of the sand determines
whether we will be born boys or girls.
Warmer sand produces more girls,
and cooler sand produces more boys.’



‘But increased temperatures are not the only problem. The sea level will rise and there could be stronger cyclones and storms. This will cause destruction and changes to our beaches and reduce the size of the area we have to nest. Sea water will ruin our nests and our eggs won’t survive.’

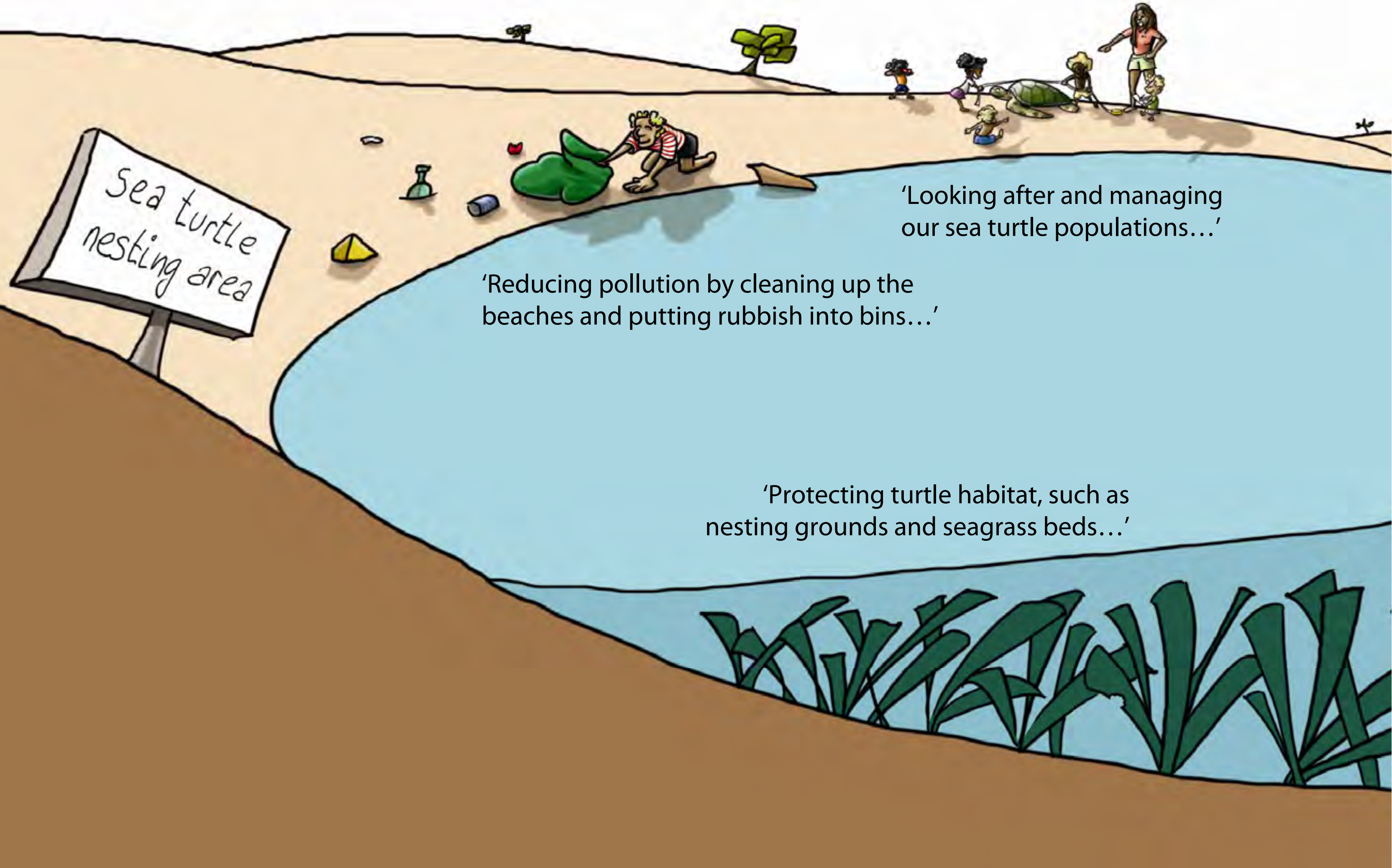


‘These threats will reduce the number of babies being born, and our numbers will eventually reduce. If our numbers are reduced, it will affect other animal species, as well as humans.’

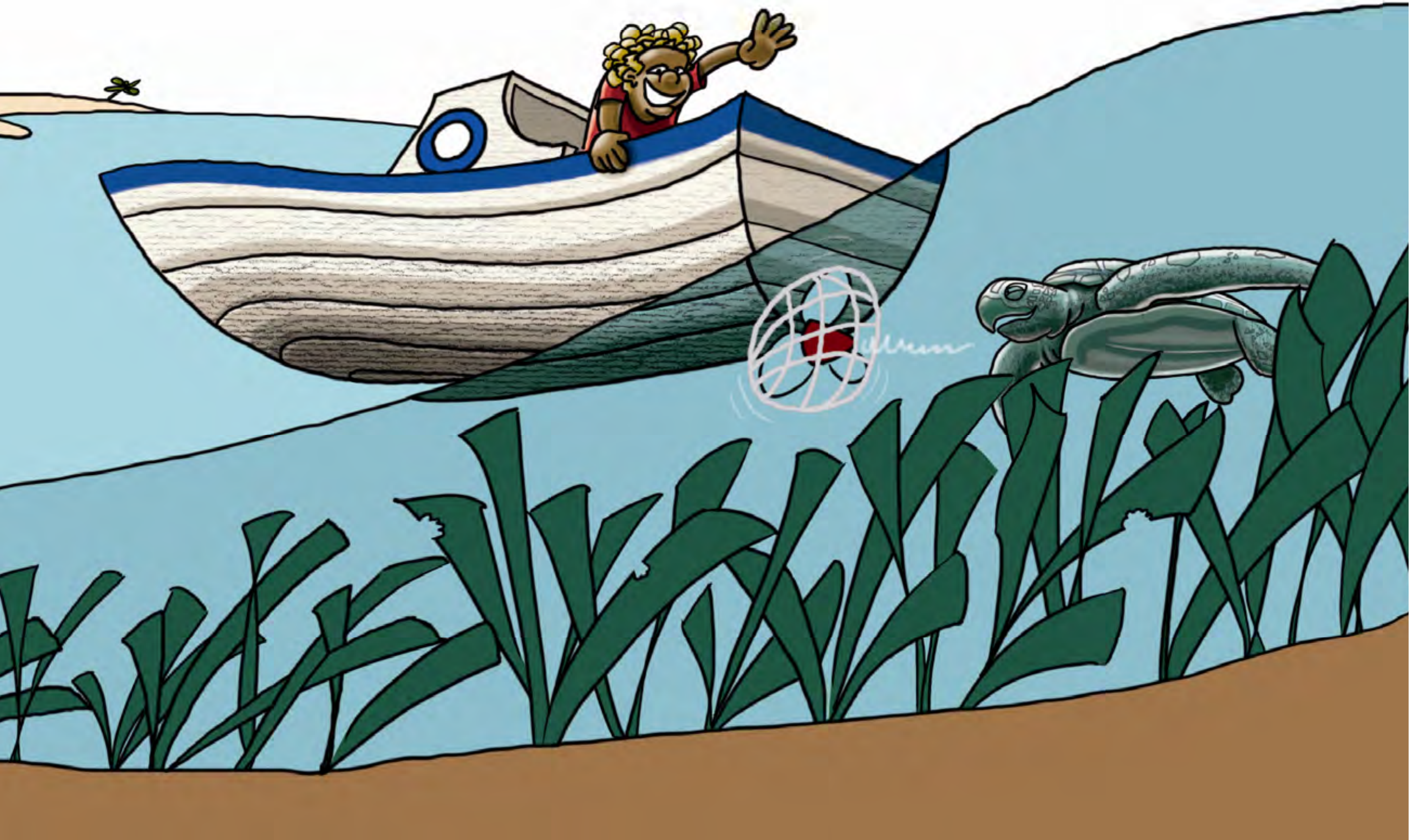


‘Yes! There are some simple things that humans can do to help us.’

‘If the types of threats we face are reduced, we will have a better chance of coping with and adapting to climate change. Some of the things that can be done include…’

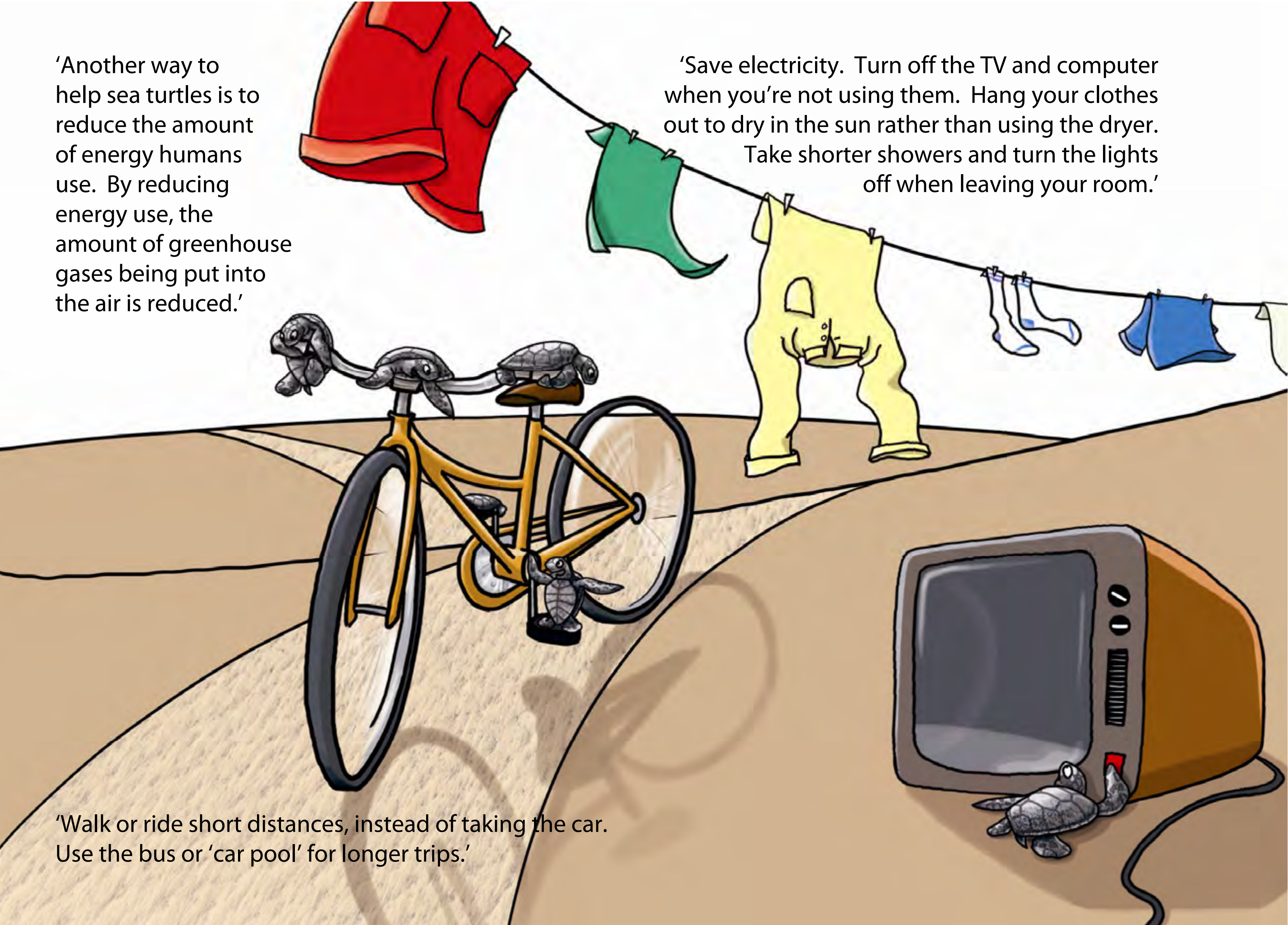


'…and using turtle-friendly boating gear.'

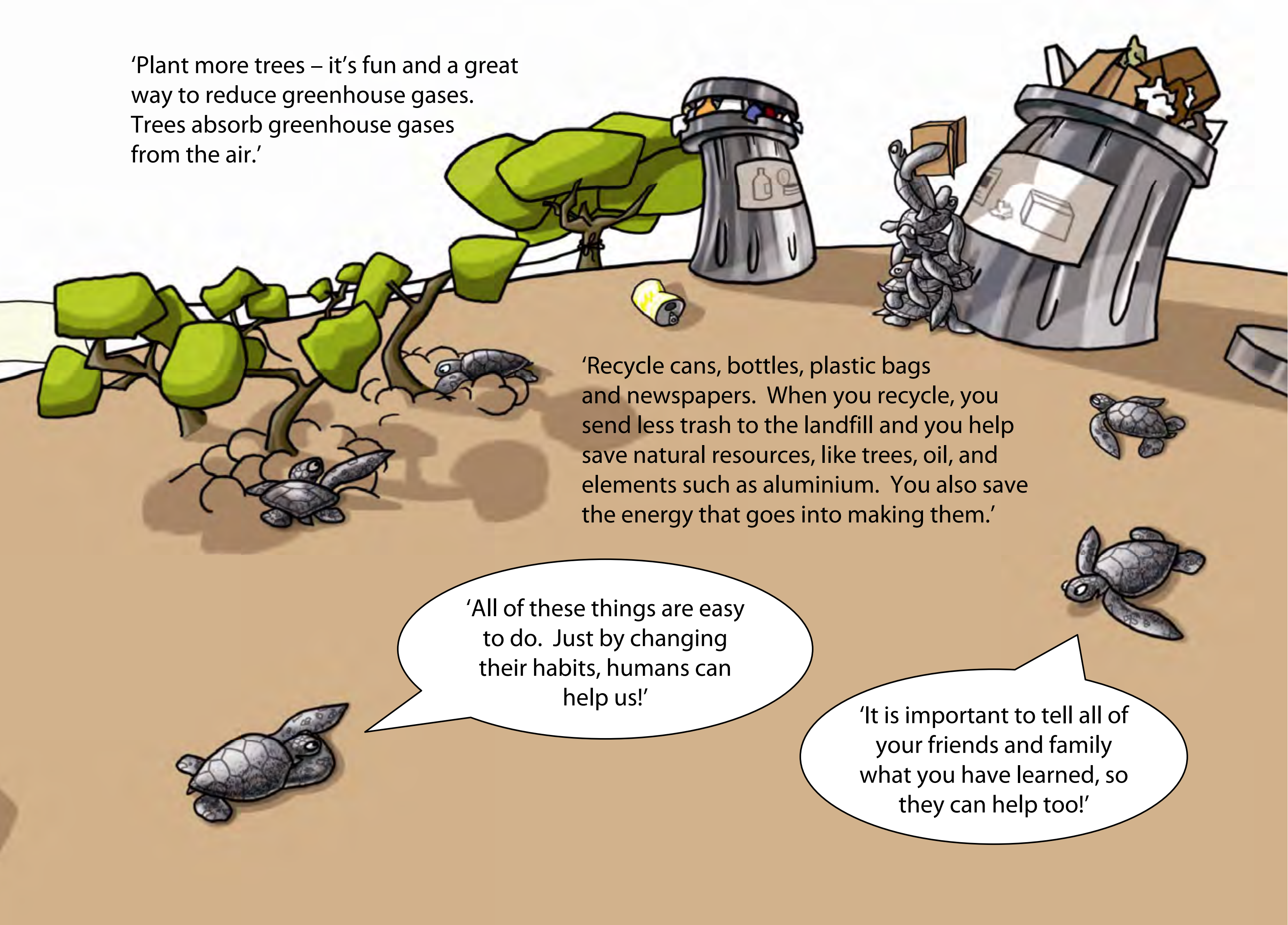


‘Another way to help sea turtles is to reduce the amount of energy humans use. By reducing energy use, the amount of greenhouse gases being put into the air is reduced.’

‘Save electricity. Turn off the TV and computer when you’re not using them. Hang your clothes out to dry in the sun rather than using the dryer. Take shorter showers and turn the lights off when leaving your room.’

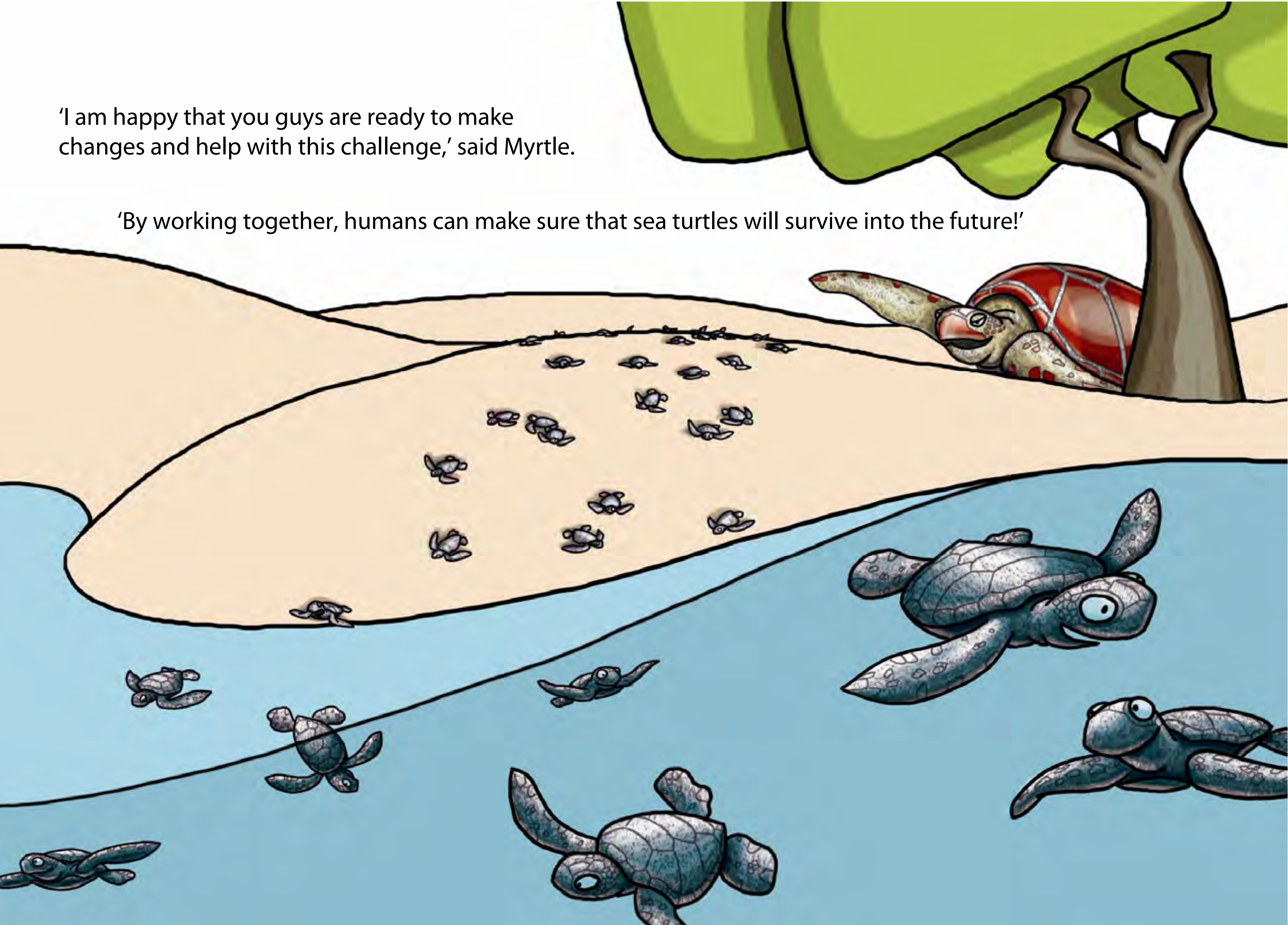


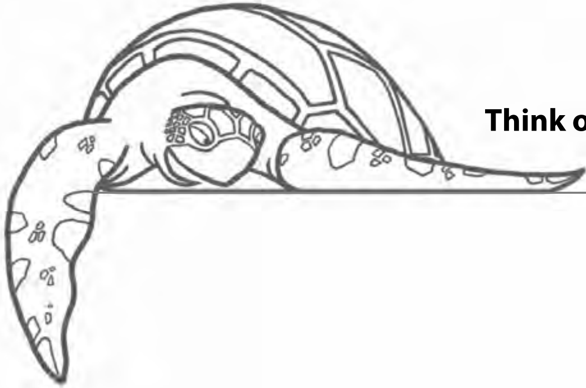
‘Walk or ride short distances, instead of taking the car. Use the bus or ‘car pool’ for longer trips.’


'Plant more trees – it's fun and a great way to reduce greenhouse gases. Trees absorb greenhouse gases from the air.'
'Recycle cans, bottles, plastic bags and newspapers. When you recycle, you send less trash to the landfill and you help save natural resources, like trees, oil, and elements such as aluminium. You also save the energy that goes into making them.'
'All of these things are easy to do. Just by changing their habits, humans can help us!'
'It is important to tell all of your friends and family what you have learned, so they can help too!'

'I am happy that you guys are ready to make changes and help with this challenge,' said Myrtle.

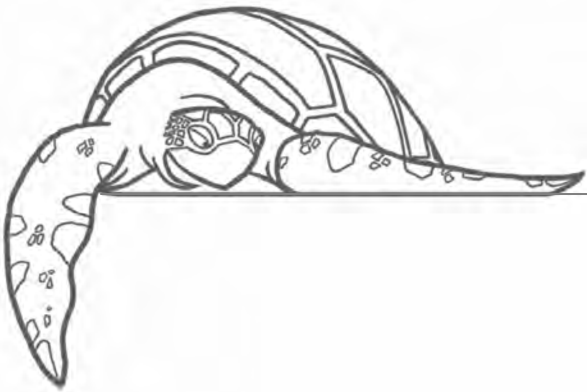
'By working together, humans can make sure that sea turtles will survive into the future!'





How can you help sea turtles to survive climate change?

Think of the ways you can work together to reduce the threats faced by sea turtles in your local community and write them here:



GLOSSARY

Adapt
To make suitable or fit for a specific use or situation

Development
The process of growing, progressing or developing

Habitat
A natural place where a plant or animal lives. For example, a fish lives in the ocean – the ocean is its *habitat*

Threat
Something that is a source of danger