Part II: Species and species groups

Chapter 15

Vulnerability of marine reptiles in the Great Barrier Reef to climate change

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15.1 Introduction

15.1.1 Marine reptiles

Marine reptiles are an important and well-documented component of the Great Barrier Reef (GBR), comprising a single species of crocodile (Crocodylidae), six species of marine turtles (five Chelonidae and one Dermochelyidae), at least 16 species of sea snakes (Hydrophiidae), one species of file snake (Acrochordidae) and one species of mangrove snake (Colubridae). Together these marine reptile species inhabit or traverse through each of the 70 bioregions identified by the Great Barrier Reef Marine Park Authority Representative Areas Program[a]. These marine reptile species, with the exception of some of the snakes, have distributions that span large areas of the GBR. Crocodiles, marine turtles, file snakes, mangrove snakes and sea snakes all have life history traits, behaviour and physiology that are strongly influenced by temperature. All are ectothermic except for the leatherback turtle and thus their body temperatures fluctuate with environmental temperature. For egg laying species (crocodiles and turtles), the temperature of the nest determines incubation period, hatching success and hatching sex ratio. Thus as a group they are potentially vulnerable to climate change.

Extant species of marine reptiles arose from ancient species that existed in the late Miocene or early Pliocene (crocodilians), the Jurassic (marine turtles) and post Miocene (hydrophid sea snakes)[b,10,44,105]. While it is difficult to estimate how long ago today's marine turtle species arose, it was certainly millions of years[105]. Within the southwestern Pacific Ocean sea levels have fluctuated substantially over the last 5000 to 20,000 years and are generally thought to have stabilised around 4000 years ago. While there is evidence of green turtle nesting at Raine Island from around 1100 years ago[79], historical patterns of marine reptile distributions and colonisations prior to European colonisation are not known for the GBR region.

Marine reptile species have persisted through several large-scale climatic and sea level changes that include periods of warming similar in magnitude to patterns predicted for the GBR over the next 50 years (Lough chapter 2). While, quantitative data are available regarding the distribution of marine reptiles within the GBR since the mid 1800s, qualitative data on the abundance, distribution and population sizes of marine reptile species in eastern Australia are only available after the mid- to late-20th century. Hence, there are no precise historical data, or fossil record, to indicate how populations of existing species may have changed, or how they may have coped in relation to historical climate patterns. This is particularly relevant to turtles because 10,000 years ago the GBR region was vastly different. There were no seagrass pastures with foraging turtle herds, nor were there benthic communities of seapens and soft corals to support flatback turtles and none of the currently used nesting beaches were accessible. Hence today's turtles have completely new nesting distribution, foraging distribution and migratory routes. With different climate options, turtles have evolved to cope with climate change in different ways. Green turtles in the Gulf of Carpentaria are winter breeders and thus avoid lethal summer time temperatures on those beaches. In contrast, green turtles breeding along eastern Queensland are summer breeders and avoid the lethal cooler temperatures on the latter beaches. Therefore, we can expect marine reptiles to respond to climate change. However,

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a   www.gbrmpa.gov.au/corp_site/key_issues/conservation/rep_areas/
b   Hydrophiid sea snakes arose from the elapids which first appeared in the Miocene

the pertinent contemporary question is how individual populations, or species, would cope with future climate change, given that over the last century there have been widespread increases in the type and scale of anthropogenic impacts to marine reptiles that have depleted several populations and threatened others[44,57,60,113].

In this chapter we provide an overview of the status of the marine reptile species for which there are data, and then assess the vulnerability of these groups to aspects of climate change based on existing ecological and biological data from the three major groups (crocodiles, marine turtles and sea snakes).

## 15.1.2. Overview of the status and distribution of marine reptile species in Queensland

Marine turtles

Within the GBR, six species of marine turtle have been recorded foraging and four species have major nesting populations. All six species are listed as threatened under Queensland and Federal legislation, and the International Union for Conservation of Nature and Natural Resources (IUCN) Red List. With the exception of the flatback turtle, each of the six species residing within the GBR is found throughout the world's tropical, sub-tropical or temperate waters[4]. Within Queensland and the GBR the population structure, distribution, range and status of these populations have been reasonably well documented so we will only present a short summary for each species here[22,62,59,76,77,79].

There are three breeding populations in eastern Australia for the green turtle (*Chelonia mydas*), two in the GBR (one in the far northern GBR and one in the far southern GBR – centred around the Capricorn Bunker group of Islands and the Swains Reefs Cays) and one in the Coral Sea Islands[95] (Figure 15.1). Turtles from these three populations are widespread throughout the region from latitudes in central New South Wales (NSW) northwards to Papua New Guinea (PNG) and longitudes from eastern Indonesia east to the south Pacific Islands[41,79,75]. Long-term census data on these populations indicate that although significant declines in population size are not apparent, other biological factors such as declining annual average size of breeding females, increasing remigration interval and declining proportion of older adult turtles to the population may indicate populations at the beginning of a decline[62,79].

The loggerhead turtle (*Caretta caretta*) has a single population in eastern Australia and main nesting sites occur on the islands of the Capricorn Bunker group and mainland beaches at Wreck Rock and Mon Repos (Figure 15.1). Furthermore, loggerhead turtles breeding in Queensland are part of the same genetic population as those from the small nesting rookeries (tens of females per year) in New Caledonia, and possibly Vanuatu[82,64]. Foraging immature and adult turtles from this population are widespread throughout the region from latitudes in central NSW northwards to PNG and longitudes from eastern Indonesia east to the Solomon Islands and New Caledonia[64,65]. In Queensland, the loggerhead turtle population has been monitored annually since the late 1960s and has undergone a substantial and well documented decline in the order of 85 percent in the last three decades[65].

Figure 15.1 *Distribution of significant turtle nesting and foraging areas referred to in this chapter*
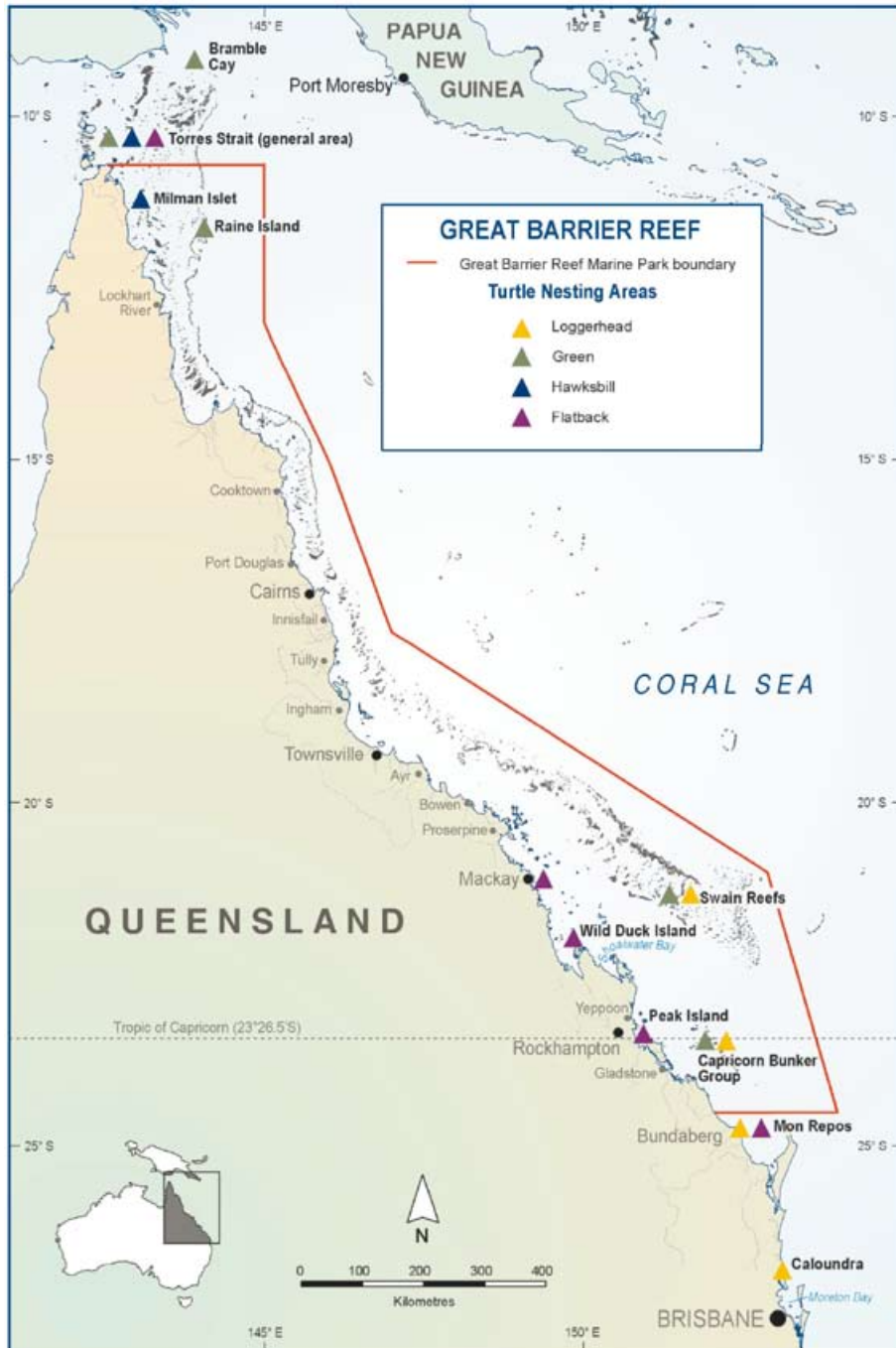
The hawksbill turtle (*Eretmochelys imbricata*) has a single breeding population in Queensland, for which the nesting areas are spread from the islands in western Torres Strait into the far northern GBR[68]. Within the GBR, Milman Island is the main rookery, and it has been regularly monitored by the Queensland Parks and Wildlife Service (QPWS) since the early 1990s[22,68] (Figure 15.1). There are also many medium- and low-density nesting beaches on islands north of Princes Charlotte Bay. Hawksbill turtles that forage within the GBR migrate to breed in areas throughout the Indo-Pacific region[93]. Annual nesting beach monitoring data from Milman Island collected from 1990 to 1999 indicate that the nesting population has declined by around three percent per annum[22,68].

No breeding of olive ridley turtles (*Lepidochelys olivacea*) has been recorded along the east coast of Queensland[55,57]. Most available information on the distribution of olive ridley turtles are derived from trawler by-catch data collected in the late 1990s by the Queensland Department of Primary Industries and Fisheries. These data show that olive ridleys reside throughout much of the non-reef areas of the GBR[112].

Green, loggerhead, hawksbill and olive ridley turtles have a common life history trait with hatchlings actively swimming into waters offshore of the rookeries. This is followed by post hatchlings being dispersed by ocean currents out into pelagic waters where they forage on macro-plankton. After variable periods of years in pelagic habitats, these species return as juvenile or sub-adult turtles to coastal waters where they change their foraging strategy to benthic feeding.

The flatback turtle (*Natator depressus*) has a single eastern Australian breeding population centred on rookeries in the southern GBR such as Wild Duck Island and Peak Island[76] (Figure 15.1). However, nesting for this species occurs in low density on many of the mainland and island beaches from Mon Repos north to Cape York[76] (QPWS unpublished data). Foraging turtles from this population are widespread throughout eastern and northern Australia, including southern PNG. Unlike other species of marine turtle in Australia, the distribution of the flatback turtle is generally restricted to the continental shelf, extending into southern PNG and Indonesia[71,121], (QPWS unpublished data). Long term monitoring data collected for the eastern Australian population, from index rookeries at Wild Duck and Peak Island, show no signs of a declining population[76].

During the 1970s and 1980s regular low density nesting of leatherback turtles (*Dermochelys coriacea*) occurred on beaches from Wreck Rock southwards to Mon Repos[66,67,72] (Figure 15.1). Nesting numbers have since declined and no leatherback turtle nests have been reported in Queensland since 1996, despite annual nesting surveys for loggerhead turtles that use the same beaches[40]. This Queensland nesting population has not been analysed to determine genetic relatedness to other regional nesting rookeries such as PNG, Arnhem Land, Indonesia or those of the eastern Pacific (Mexico and Costa Rica)[40]. This species is primarily an oceanic, pelagic foraging species and is rarely encountered in GBR waters.

Marine turtle management within the GBR region over the last 50 years has focussed primarily on: species protection regulations and closures of commercial harvesting protecting most of the nesting areas for each species within eastern Australia under the *Nature Conservation Act 1992*, protecting large areas of their marine habitats within Federal and State managed multiple-use marine parks, controlling foxes on mainland beaches to reduce egg loss through predation, regulating trawl and net fisheries (using temporal and spatial closures and mandatory use of turtle excluder devises), reducing boat strike incidences and rescuing doomed eggs at risk from flooding or erosion.

Estuarine crocodiles

Two species of crocodile occur in northeastern Australia, the estuarine crocodile (*Crocodylus porosus*) and the freshwater crocodile (*Crocodylus johnstoni*). Only estuarine crocodiles are recorded within the GBR and the neighbouring coastal zone. Estuarine crocodiles were intensively hunted from the mid 20th century until they were protected by legislation in 1974. These extensive harvests severely depleted wild populations and subsequently estuarine crocodiles are listed under Queensland State and Australian Federal legislation as vulnerable and endangered under the IUCN Red List.

The distribution and abundance of estuarine crocodiles within the GBR and adjacent coastal zone has been well documented[89,109]. In eastern Queensland, estuarine crocodiles occur from Torres Strait, southwards to Gladstone[109] (Figure 15.2), although sightings have been reported as far south as the Gold Coast. Genetic studies indicate that estuarine crocodiles along the east coast of Queensland are not panmictic, hence there are limits to gene flow, and variance in alleles indicates population structure along the east coast of Queensland has occurred (Nancy FitzSimmons pers comm). Read et al.[109] and Taplin[122] distinguish eight biogeographic regions for estuarine crocodiles in Queensland. Five of these lie along the east coast and include overlap with the GBR. Although the spatial distribution of estuarine crocodiles varies significantly between the biogeographic regions, population densities in the east coast catchments (including the Burdekin and Fitzroy River catchments) are low (see Figure 15.2 for location of catchments). Within the GBR estuarine crocodiles have been recorded from many of the inshore islands in northern areas[89]. While no estuarine crocodile nesting sites have been recorded within the GBR, nesting has been recorded along sections of the coastal fringe (eg the western side of Hinchinbrook Island)[89,109]. Crocodiles found in the GBR are primarily immature sized individuals coming out of adjacent rivers. Therefore the GBR crocodile population is not self-sustaining, it is ephemeral, but dependent on the functioning of the populations in adjacent rivers.
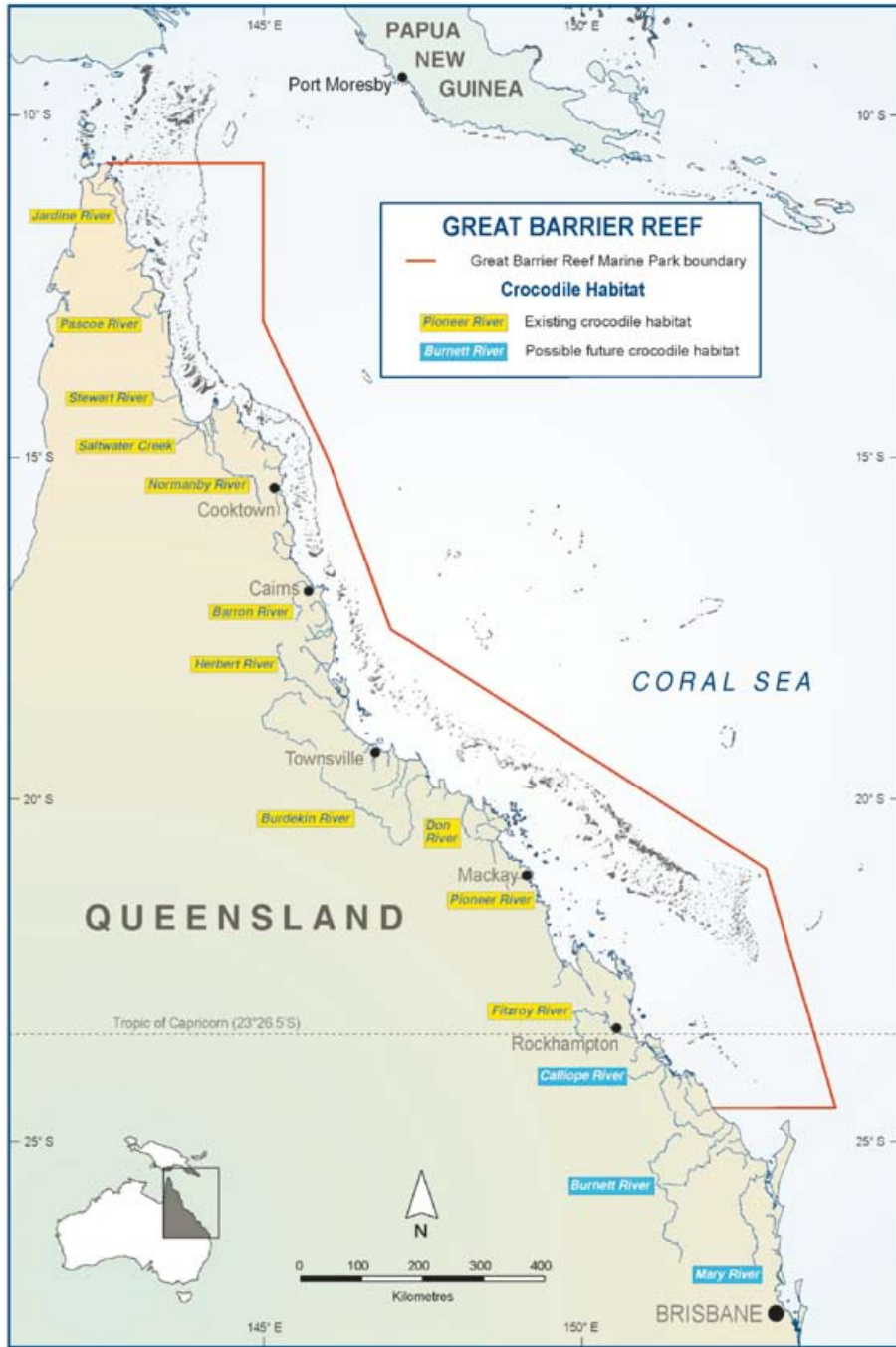
Crocodile management within the GBR region over recent decades has focussed primarily on: species protection regulations and closure of commercial harvesting, protecting large areas of their marine habitats within Federal and State managed multiple use marine parks, removal of problem crocodiles that threaten public safety.

Sea snakes

There are two groups of sea snakes found in Australia – Hydrophiidae and Laticaudidae. The Hydrophiidae are the only species of sea snakes to have breeding populations in the GBR. There are at least 16 species of Hydrophiid sea snake residing within the GBR[44]. While the broad distributions of most of the species have been documented, abundance estimates are only available for a few species, or for restricted sections of the GBR, and there are no data on which to base status assessments[44]. Eleven species of sea snakes are endemic to Australian waters but none of these are endemic to the GBR. No species of sea snake found in Australian waters is listed as threatened under Queensland or Australian legislation or by the IUCN. However, sea snakes are considered a 'listed marine species' under Australian Federal legislation and are protected species under the *Nature Conservation Act*, *Queensland State Marine Parks Act* and the G*reat Barrier Reef Marine Park Act*. The high diversity of sea snake species within the GBR reflects a high diversity of micro-habitats that are used by the group. These range from coral reefs to shallow soft bottom habitats to deeper open water habitats[44]. While most are benthic foraging species, one species, *Pelamis platurus*, is primarily a pelagic foraging species in oceanic waters.

Figure 15.2 *Distribution of current and potential crocodile habitats along the east coast of Queensland*

Sea snake management within the GBR in recent decades has focused primarily on: species protection regulations and closure of commercial harvesting, protecting large areas of their marine habitats within Federal and State managed multiple-use marine parks.

15.2 Vulnerability of marine reptiles to climate change

15.2.1 Ocean circulation

The post hatchling phase of the marine turtle life cycle was initially coined the 'lost years' because, it was suspected that hatchlings made their way offshore through coastal and offshore oceanic currents, and little was known about dispersal routes, or aspects of their ecology during their oceanic dispersal phase[13,20,56,129]. Through mapping the occurrence of post hatchling turtles coupled with the use of genetic techniques and oceanic current modelling it appears that loggerhead and southern GBR green turtle hatchlings from Queensland rookeries disperse via offshore currents such as the East Australian Current and its eddies. Dispersal patterns for hawksbill and green turtles in the northern GBR are not known. Flatback turtles remain on the continental shelf and do not have an oceanic life stage[125].

Recent population models indicate that oceanic stage green and loggerhead turtles return to coastal foraging areas at around five to ten years and 10 plus years respectively[16,18,65]. Although there are few empirical data on the finer scale movements and diet of turtles during the pelagic stage, or the specific factors that influence delivery of individual turtles to benthic foraging areas, it is likely that these factors are reliant upon currents. Hence, changes to ocean circulation can potentially influence (positive or negatively) the ecology of post hatchling and juvenile turtles. However, due to the uncertainty in predicting how ocean circulation may alter with climate change (Steinberg chapter 3) it is difficult to predict in detail how marine turtles will be affected (positively or negatively) by shifts in the ocean currents over the next 50 years.

15.2.2 Changes in water and air temperature

Temperature is one of the most pervasive variables affecting biological and developmental processes and thus it asserts a strong selective pressure, especially on ectotherms. Animals vary in their sensitivity to environmental temperatures and can be generally classed within two main thermal boundaries, eurytherms, which can operate at a wide variety of body temperatures and stenotherms, which can operate over a narrow range of body temperatures[2]. Marine reptile species fall in different positions within these broad groups, and their positions vary depending on life stage.

For example, estuarine crocodiles generally stay within, or close to, particular catchments and are exposed to seasonal fluctuations in temperature. To regulate their body temperature within an optimal range they use a variety of behavioural and physiological mechanisms such as basking and other behavioural patterns. Moreover, their ability to vary behavioural and physiological attributes on daily and seasonal cycles enables them to function very well in tropical regions and over a wide range of seasonal temperature variations[119]. For marine turtles, while juveniles and adults can function in a range of environmental temperatures while at sea, adult females can overheat while on land for nesting and the successful development of embryos and the determination of hatchling sex occurs

within a definite thermal range[79,91,120] (Figure 15.3). In this section we assess the vulnerability of marine reptiles to increases in air and sea surface temperatures by 2050 of 1.9 to 2.6°C and 1.1 to 1.2°C respectively (Lough chapter 2).

15.2.2.1 Exposure – temperature

In this section we assess the probability and magnitude of exposure of marine reptiles to increased air and sea temperatures.

Marine turtles

There is a high probability that exposure to changes to increased air and sea surface temperatures will affect marine turtles in two broad areas, reproduction and foraging ecology.

Reproduction and reproductive timing

Marine turtles are seasonal breeders and the frequency of breeding varies both within and between species[36,89]. Females of each species are capital breeders, meaning that they accrue the energy needed for reproductive events prior to breeding[36,50]. The actual time it takes to develop enough somatic energy stores to begin, maintain and complete the vitellogenic or spermatogenic cycle is dependent on a combination of food availability, food quality, digestive processes and migration distance (from foraging to breeding)[4,5,11].

The timing of seasonal reproductive events in marine turtles is most likely controlled by a complex system involving genetically entrained energy thresholds and numerous metabolic and endocrine pathways[37,38,39]. Put simply, there are several key decisions that need to be made by an adult turtle with regard to reproductive cycles, such as whether or not to begin spermatogenesis or vitellogenesis or to remain quiescent, when to migrate to the breeding area, and when to cease breeding and migrate back to the foraging area[35]. The results of each of these decisions will rely upon a combination of co-dependent proximal and ultimate cues, such as body condition and environmental factors (eg sea temperature and photoperiod). However, because marine turtles from particular breeding populations come from foraging grounds spread over large geographic areas it is likely that reproductive cycles are linked to a combination of photoperiod and ability of the animal to detect

Figure 15.3 *Operating temperature parameters for marine turtles. MBTF represents minimum body temperature for feeding (except leatherback turtles); MSTR represents mean selected temperature range (Data sources: 1 Spotila and Standora[120], 2 Miller[91], 3 Read et al.[107])*
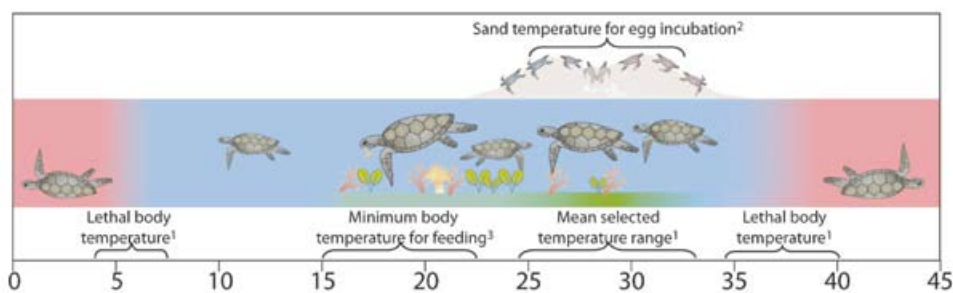
changes such as temperature rises[35]. Moreover, the changes in air and sea temperature are not likely to be uniform over the entire GBR, or indeed throughout the ecological range of the species, with changes likely to be greater in higher latitudes (ie southern GBR, Lough chapter 2). Therefore, while marine turtles will be exposed to increases in air and sea temperature over their range, they will be exposed to differing degrees, and changes will occur at different scales. Consequently, it is difficult to predict the magnitude of exposure for particular species or populations.

There are two general patterns of seasonal nesting for marine turtle breeding in Queensland, dry season (winter to spring) nesting occurs in the Gulf of Carpentaria, western Cape York and western Torres Strait and wet season (summer) nesting occurs in central Torres Strait and along the entire eastern coast of Queensland. Rookeries in this latter group have seasonal peaks of nesting with occasional low density nesting in the 'off season' and in southern Queensland rookeries there is virtually no 'off season' nesting. Within a season female turtles lay multiple clutches of eggs, and each species has a definite peak of nesting[22,36,77].

Clutch incubation and embryo development

The successful incubation of turtle eggs relies on sand temperatures during incubation being between 25 and 33°C[91]. On nesting beaches located along the east coast of Queensland, sand temperatures within this range generally occur between November and March, with highest temperatures generally occurring in January and February. Hence there is a high probability that projected increases in air temperature of 1.9 to 2.6°C by 2050 (Lough chapter 2) will result in sand temperatures during the Austral summer consistently reaching the upper end of, or exceeding, the narrow thermal window for successful egg incubation at most current marine turtle rookeries with resulting increases in egg mortality. In addition, altered sex ratios are likely to ensue.

Foraging area dynamics and reproductive periodicity

Predictions on how invertebrate (mollusc, crustacean, sponge or cnidarian), benthic communities will respond to climate change are based on limited data (Hutchings et al. chapter 11). Hence it is speculative to predict whether climate change impacts on invertebrate groups may in turn impact on nutritional ecology of carnivorous/omnivorous marine turtle species. In contrast, for the herbivorous green turtle increased sea temperatures at foraging areas will impact the distribution, abundance and health of seagrass and algae and these trophic factors are likely to have flow-on impacts for turtles residing in particular habitats (Diaz-Pulido et al. chapter 7 and Waycott et al. chapter 8).

Foraging area impacts (positive or negative) are more likely to occur for green turtles because the interval between breeding seasons of this species is resource dependent[6,11], and the number of females breeding in a particular year is correlated with an index of El Niño[69,70]. Although mechanisms that underlie this relationship remain unclear, Chaloupka et al.[18] suggested that dietary ecology was the link, based on studies that demonstrated that growth rates of green turtles residing at particular foraging areas vary according to local environmental stochasticity. Therefore, based on available evidence from turtle breeding patterns and information presented in chapters 7 and 8 of this volume, it is likely that the dietary ecology of green turtle populations will be sensitive to changes in water temperature because of temperature related changes to seagrass and algal communities.

Estuarine crocodiles

Reproduction

Miller and Bell[89] provide a review of estuarine crocodile distribution in the GBR World Heritage Area, and nesting site preferences and distribution of nesting sites in Queensland are described by Magnusson[85] and Read et al.[109]. Crocodile nesting has been recorded in coastal zones of the GBR such as Hinchinbrook Island[89] with limited nesting habitat existing in the catchments between Cairns and Rockhampton[49,109]. Predicted levels of climate change will expose nesting sites to increased air temperatures. Exposure of nesting sites to increased temperatures will influence estuarine crocodile population dynamics because, the sex ratio of hatchlings is temperature dependent and temperature plays an important role in embryo development, incubation time and can influence the phenotype of hatchling estuarine crocodiles.

Distribution and abundance

The spatial distribution and abundance of estuarine crocodiles along the coast of Queensland is highly variable[109,122]. Along eastern Queensland highest densities of estuarine crocodiles occur north of Cooktown, and lower population densities found south of Cooktown were attributed to a lack of suitable nesting habitat and decreasing average air temperatures in the southern latitudes[49,109,122]. The southernmost breeding populations of estuarine crocodiles occur within the Fitzroy River, near Rockhampton in central Queensland[109] (Figure 15.2). Although satellite tracking studies indicate that estuarine crocodiles can move considerable distances within river systems, over land, and into the adjoining coastal zone[108] there are few data on factors that influence dispersal and habitat choice for estuarine crocodiles (eg sex/size related shifts in dispersal patterns and habitat choice). However, it is possible that with continued recovery to the populations and increased air and sea temperatures in central and southern Queensland there could be a southwards expansion in the range of estuarine crocodiles concomitant with increased densities in coastal streams. If there are population increases in streams adjacent to the southern GBR, then there is a reasonable probability that there will be increased numbers of immature crocodiles occurring in southern GBR waters.

Sea snakes

All species of hydrophiid sea snakes that reside within the GBR are truly marine and do not come onto land at any stage of their life cycle. Maintenance of body temperatures in sea snakes depends on water temperature, and because of their small surface area to mass ratio, it is difficult for them to raise their body temperatures above their surroundings[44]. Even dark coloured snakes at the surface can only increase body temperatures by around 3°C[43]. Therefore, sea snakes will be exposed to changes in sea temperature. However, there is little known about the fine scale distribution of different species, thermal requirements, thermal tolerances, fine scale aspects of dietary ecology (ie prey selectivity), or how preferred prey items will be influenced to assess their vulnerability to the projected rises in sea temperature of 1.1 to 1.2°C by 2050.

15.2.2.2 Sensitivity – temperature

In this section we assess the magnitude and direction of response to levels of increased temperature on marine reptiles.

Marine turtles

Marine turtles are likely to be adversely affected by increases in air temperature by 1.9 to 2.6°C by 2050. This time frame is approximately one to two generations for the four species that breed in the GBR, green[17], loggerhead[46,64,65], flatback (QPWS unpublished data) and hawksbill turtles[16,68].

Reproduction: clutch incubation and embryo development

All species of marine turtles are oviparous. Within a breeding season, a female will lay multiple clutches of eggs on beaches above the high water mark. Embryo development takes around eight weeks and the incubation period is strongly correlated with sand temperature[1,92]. The successful development of marine turtle embryos occurs within a well defined temperature range of 25 to 33°C[91]. Arguably, the most substantial impact of temperature on marine turtle life history in the short term (one to two generations which equates to 60 to 80 years) is during the embryo development phase.

There are volumes of empirical studies that demonstrate the interactions of temperature and embryo development in marine turtles, and many studies that investigate temperature-dependent sex determination (TSD) (Box 15.1). The determination of sex in marine turtles depends on sand temperatures during the middle third of the incubation period, with cooler and warmer temperatures producing a higher proportion of males and females respectively[28,90]. The constant incubation temperature at which 50 percent males and females are produced is termed the pivotal temperature or TSD_{50}[31,74,96]. Pivotal temperatures based on laboratory experiments have been determined for green and loggerhead turtles nesting in eastern Australia and generally fall between 27 and 30°C. Pivotal temperatures may vary between and within species or even within populations of the same species[74,97].

> **Box 15.1** *Temperature dependent sex determination*
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> Not all vertebrate species determine sex of offspring in the same way. Many animals use genotypic sex determination in which the factors that determine sex are contained in sex chromosomes. This method of sex determination occurs in all vertebrate families. A second method of sex determination is phenotypic, in which the sex of offspring is not determined during conception rather it is determined after fertilisation and is dependent on incubation temperatures. This method of sex determination is commonly referred to as temperature dependent sex determination (TSD) and it occurs in all crocodilians, the tuatara and some turtles (including all marine turtle species), lizards and fish[123]. There are three recognised patterns of TSD – (TSD II) female-male-female in which females are produced at high and low temperatures, (TSD IA) male-female in which males and females are produced at low and high temperatures respectively and (TSD IB) female-male in which females and males are produced at low and high temperatures respectively[123]. In each of these patterns offspring sex is determined during a limited thermosensitive period during incubation. Recent work has demonstrated that during the thermosensitive period temperature initiates a suite of endocrinal pathways that act on the differentiation of gonads[9,27,103].

The determination of natural sex ratios for populations or rookeries is difficult because sand temperatures are not constant throughout the incubation period and they may vary greatly within and between particular rookeries, or beaches, for a population[42,74,97]. While laboratory studies can determine pivotal temperatures, and different models based on natural nest temperature profiles can allow gross prediction of sex ratios at individual rookeries[29], numerous proximate environmental and

geographical factors dictate sand temperature profiles at a population level. For example, sand type and colour, beach location (island or mainland), aspect and shading from vegetation and climatic events such as frequency of rainfall and cloud cover are likely to play a role in ensuring that a mixture of both sexes are produced from each rookery and for each population[7,42,90,97].

Since field based TSD studies began on marine turtles in the early 1980s there have been numerous studies conducted on sex ratios from beaches throughout the world and researchers have commonly reported female biased sex ratios. However, given that archival temperature data loggers have only become readily available in the last 15 years, plus the logistical and financial constraints of conducting multi year and multi rookery projects, most field based studies on TSD and sex ratios have been short (one to three years) and have been rookery focused rather than population focused. To get a better understanding of how sex ratios may change throughout ecologically relevant temporal and spatial scales, longer term studies at population level are warranted[30,42]. While such studies are needed within the GBR, there is sufficient knowledge about species population boundaries, some nesting beach characteristics (eg sand colour), nesting seasonality and baseline sand temperature data for marine turtle species breeding in the GBR to indicate that populations will be sensitive to increased air temperatures of 1.9 to 2.6°C by 2050.

Foraging area dynamics and reproductive periodicity

Marine turtles reside along the entire coast of eastern Australia, though only the leatherback turtle, which is rarely encountered within the GBR, is recorded regularly south of Sydney (latitude 33 °S)[40,62]. However, eastern Australia (eg Moreton Bay north into Torres Strait) provides some of the most important and protected foraging habitats for marine turtles along Australia's east coast, and indeed the Indo-Pacific region. While each of the five species that forage in the GBR has different habitat and dietary requirements and physiological tolerances that limit micro-habitat use, they are found throughout the latitudinal range (14 degrees) of the GBR[62,112]. Most knowledge on distribution, abundance and species ratios in particular areas come from mark-recapture studies managed by Queensland Parks and Wildlife Service, tag returns from Indigenous hunters, the public or commercial fishers and the Queensland Department of Primary Industries and Fisheries trawler by-catch studies in the late 1990s[112]. Presumably, within the GBR the strongest effect temperature has on the life history of individual species of marine turtles while in foraging areas is through its effect on physiological processes, food availability or quality (see chapters 7, 8, 9, 10 and 11 for vulnerability of algae, seagrass, mangroves, corals and benthic invertebrates).

Green turtles are essentially herbivorous in the wild. They are an important component of seagrass, mangrove and algal habitats and feed mainly on seagrasses, algae and mangrove leaves[6,63]. Capture-mark-recapture data from QPWS indicate that green turtles show strong site philopatry to a particular foraging area, and in Queensland it does not appear that they undertake developmental migrations[81,98]. Furthermore, when forage conditions are compromised in particular areas, such as after cyclones or floods, green turtles stay in the general area trading-off the risks of movement with declined growth rates[17,18]. Given a broad distributional range coupled with high site fidelity it is likely that green turtles will be exposed to changes in sea temperature at varying degrees throughout their range. It remains difficult to estimate how sensitive the species will be to increased water temperature at foraging areas until more is known about the finer scale links between temperature and its influence on food availability, dietary processes, growth and reproduction.

Loggerhead turtles are carnivorous and in southern Queensland they have been found to feed mostly on a variety of crustaceans and molluscs. Moreover, diet composition differs spatially, and is presumably dependent on the distribution and abundance of prey items and individual preferences[78]. The diet of hawksbill turtles has not been described in Queensland. However, hawksbill turtles in the Northern Territory have a mixed diet of algae and sponges[130]. Leatherback turtles mainly forage in open water on jellyfish, but outside the GBR. Less is known about the diet of both olive ridley and flatback turtles. They are presumed to be carnivorous feeding primarily on a range of crustaceans, molluscs and soft bodied benthic invertebrates such as holothurians[6].

There is a growing body of literature on the impacts of climate related factors on seagrass and coral habitats as well as the biology or community ecology of marine invertebrates[45,54,104,117] (chapters 7, 8, 9, 10 and 11). While it is often difficult to provide causal links between aspects of climate with changes to biological and/or ecological attributes in marine ecosystems, results generally suggest that marine invertebrates and habitats such as seagrass and coral reefs are sensitive to factors such as increased water temperature, changes in ultraviolet radiation and carbon dioxide (CO_2)[3,54,106] (chapters 7, 8, 9, 10 and 11). However, there is likely to be complex interplay of various environmental factors that underpin spatial and temporal effects within species and community levels. Therefore, although it is likely that changes to air and sea temperatures will effect marine habitats and community structure there is not enough data on specific habitat requirements, or on the precise impacts temperature will have on the distribution, abundance and population structure of seagrass species and marine invertebrates to predict how sensitive marine turtle species will be to climate change over the next 50 to 100 years.

In addition, for ectothermic species such as chenoniid turtles, changes to ambient temperatures can bring about changes in the rates of chemical reactions that underpin physiology. Therefore, with rising water temperature, it is not inconceivable that growth rates may be enhanced and hence age to maturity may decrease or the size at which first breeding occurs may be larger, rates of fat deposition or yolk storage into ovaries (vitellogenic cycle) may increase and hence shorten the intervals between breeding seasons. If the types of physiological change required to underpin these life history traits occur then progressive warming of their habitats will have positive benefits with regard to sea turtle population dynamics.

Estuarine crocodiles

Clutch incubation and embryo development

Estuarine crocodiles are oviparous, and while few data exist on breeding rates in the wild, in captivity most females do not breed annually[48]. Within a breeding season a female estuarine crocodile will make a mound nest during the wet season and lay a single clutch of around 40 to 60 eggs[113]. Eggs take around 90 days to hatch[113]. The determination of sex in hatchling estuarine crocodiles is dependent on the mound nest temperature. In general, crocodilian mound nest temperatures are between 30 and 33°C[86], and metabolic heating can increase nest temperatures by 2 to 3°C[25, 29]. Webb et al.[127] report a female/male/female pattern in which no males are produced at temperatures below 29°C and above 34°C and varying percentages are found in the intermediate temperatures. Moreover, these authors also demonstrate that the sex of the embryos was determined within approximately 17 to 52 days (19 to 58 %) after the start of incubation.

Temperature influence on behaviour and physiology

Estuarine crocodiles are large reptiles, and as ectotherms their internal heat production is negligible. Hence, they generally thermoregulate by using behavioural mechanisms to exploit their thermal environment[118]. In particular, estuarine crocodiles use a combination of atmospheric and aquatic basking, shade seeking, postural adjustments, and changing orientation (reviewed in Grigg and Seebacher[33]) to regulate temperatures to within a narrow range. The importance of water temperature and basking behaviour in estuarine crocodiles for thermoregulation, and consequences for the maintenance of physiological processes and behaviour is becoming increasingly apparent[118]. Furthermore, data derived from experimental studies demonstrates that the sustained swimming speed of juvenile estuarine crocodiles increases in warmer waters (23 to 33°C compared with 15°C) and then decreases as water temperatures rise above 33°C[24]. However, while estuarine crocodiles will be sensitive to increased water and air temperatures associated with climate change, this sensitivity should be seen in the context of them being a tropical species that occur along the equatorial zone of South East Asia.

Sea snakes

There is little known about the thermal requirements and tolerances of individual species of sea snakes, hampering assessment of their sensitivity to projected rises in sea temperature of 1.1 to 1.2°C by 2050. However, *Pelamis platurus* is the most widespread of the sea snake species and its distribution has been empirically linked to sea surface temperature patterns[23]. Distribution of *P. platurus* is linked to thermal zones, and has upper and lower thermal tolerances of between 36.0 and 11.7°C[23,32]. It is likely that other sea snake species have a thermal range within the boundaries of those of *P. platurus*.

Seasonal reproduction in marine reptiles

The cycles and physiological mechanisms that underlie ovarian and spermatogenic processes have been well reviewed in marine turtles, but less information is available for estuarine crocodiles and sea snakes[36,51,99]. Each of the four marine turtle species that breed in eastern Queensland have summer nesting seasons. Estuarine crocodiles breed in early summer and clutches are laid during the summer wet season[111]. In contrast, although less data are available, it appears sea snakes have reproductive cycles and gestation periods that vary in length and timing both within and between species, although they generally culminate with young being born in late summer and autumn[12,44,53]. There are not enough data to indicate what factors underlie the variation in reproductive cycles in sea snakes and this area warrants further attention.

Reptiles have large pineal glands; indeed marine turtles have one of the largest pineal glands per body size of all vertebrates[100]. It is therefore generally believed that the timing of reproductive events in marine turtles and other reptiles is determined by a combination of photoperiod and temperature that act via melatonin to interact in the hypothalamus with other endongenous cues to tell the animal the appropriate time for breeding[35,38,99]. The proximate and ultimate cues that underlie reproductive cycles and allow synchronous breeding within a population are not well studied in marine reptiles. This area warrants further attention before estimates can be made of how sensitive reproductive cycles are to climate change.

15.2.2.3 Impacts – temperature

Temperature-dependent sex determination

Loggerhead turtles

There are several potential impacts of increased air and sea temperature on the incubation and sex determination of marine turtle embryos. Indeed, some thermal influences are evident in loggerhead turtles at Mon Repos where sand temperature data has been collected from nest depths since 1968. Since 1997, sand temperatures at nest depth have been commonly recorded above 34°C for weeks at a time[61]. Consequently, sand temperatures exceed the temperature at which 100 percent female hatchlings are produced, and often exceed the upper limit for successful incubation. This is significant because although loggerhead turtles nest on the white coralline sand islands of the southern GBR, and scattered nesting occurs on the white sand beaches south of Fraser Island, the dark coloured beaches of Mon Repos and Wreck Rock support around 70 percent of nesting for the population[65] and produce mostly females. To monitor the magnitude of exposure to high and increasing sand temperatures at a population level, systematic sand temperature collection is needed at all main rookeries and a selection of peripheral ones. Only through the collection of thermal data from incubation environments can longer-term impacts at a population level be predicted.

Marine turtles in general

Temperature data from most rookeries in Queensland are not yet sufficient to imply how sensitive particular rookeries or populations are, or the degree of impact faced from increases in air temperature over the next 50 to 100 years. Studies that have been conducted in the GBR highlight a need for routine monitoring of sand temperatures at all main and peripheral rookeries for each species[7,8,47,68,80,81]. In particular there are few baseline sand temperature data available for green and hawksbill turtle beaches in the far northern GBR and Torres Strait.

There are insufficient data to indicate what degree of female bias a population of marine turtles can sustain. However, population models have implicated incorrect hatchery procedure, and the subsequent production of a highly skewed female sex ratio in the demise of the Malaysian leatherback turtle population[14]. Based on available data for Queensland, and predictions of warming over the coming 50 years, we speculate that ratios above one male to four females are possible for many GBR rookeries and these ratios (in terms of female bias) may not be sustainable.

Other temperature related factors

In addition to effects on sex determination, increased sand temperatures have been found to decrease the incubation time of eggs of all marine turtle species[91]. Hatchlings raised in warmer nests with shorter incubation times have lower residual yolk reserves at hatching[7]. In addition, clutches incubated at temperatures near the upper limits for incubation survival (33°C) result in hatchlings with higher rates of scale and morphological abnormalities[87,91,116]. Laboratory experiments demonstrated that incubation temperature and incubation environment have an effect on swimming performance with hatchlings raised in higher temperature nests, or from nests placed in hatcheries having decreased swimming ability over a six hour period[116,124]. Therefore high, but sub-lethal, temperatures could have a profound impact on hatchling phenotype, health, condition and performance.

Estuarine crocodiles

Clutch incubation and embryo development

The influence of incubation temperatures on various aspects of embryo development and hatchling phenotype has been well investigated in crocodilians, although not always for estuarine crocodiles[110]. In short, incubation temperatures have been demonstrated to influence hatchling morphology, pigmentation, thermal responses, locomotive performance, feeding responses and growth[110]. However, there are few threshold data to develop a precise understanding of how increased air temperatures will impact estuarine crocodiles at all levels of biological organisation.

Temperature influence on behaviour and physiology

The behaviour, physiology and distribution of estuarine crocodiles in the GBR and its catchments are closely linked to temperature. Grigg et al.[34] report that captive estuarine crocodiles in a naturalistic setting maintained modal body temperatures of between 25 and 28°C in winter and 28 to 33°C in summer. However, there are few data on environmental temperatures (water and air) for wild foraging sites, and how these temperatures vary daily, seasonally and with micro-habitats. Hence, it is difficult to identify specific impacts that rises in air temperature by 1.9 to 2.6°C over the next 50 years will have on crocodiles. Additionally, temperature, along with other environmental cues such as rainfall, affects the degree and timing of nesting. In particular, high water levels and cool conditions late in the dry season are the key stimuli required for courtship and mating[48,84,126]. Hence changes in when these environmental cues occur, or the magnitudes to which they occur, may lead to changes in the timing of reproductive events.

Sea snakes

The optimum temperature ranges for most species of sea snake are unknown. However, if they have a similar upper thermal limit to *P. platurus* (36°C) then it is possible that gradual shifts in range will occur over the course of the next 50 to 100 years.

15.2.2.4 Adaptive capacity – temperature

Marine turtles

There are likely to be two main autonomous adaptations to cope with increased temperatures and inundation of nesting sites. Firstly, a shift in the start, end and peak of the nesting season to coincide with cooler temperatures and secondly, a shift in the main nesting beaches used[61]. An overall shift in the timing of the nesting season is a possible scenario, and one that has been documented in seasonally breeding birds[19] and for the loggerhead turtle population that nests along Florida's Atlantic coast. In this loggerhead turtle population, Weishampel et al.[128] found that between 1989 and 2003 the median nesting date for the population became earlier by around 10 days. The authors further speculate that this change in nesting seasonality is driven by increased sea surface temperature in adjacent waters[101,128]. However, in eastern Australia turtles that nest in a particular population come from a variety of regionally dispersed habitats, and these habitats will experience variable magnitudes of climate change influences. Therefore, the large-scale coordination required for phenological shifts of a nesting season may take a longer time frame, (ie generations) to develop. In most cases this would also be hard to detect without substantial increases in monitoring effort because subtle shifts would only be detectable at rookeries that have close to saturation monitoring of the nesting beach and high site fidelity of turtles.

Distinct population boundaries exist for marine turtles because female turtles exhibit natal homing, that is, when they reach maturity and begin breeding they return to the region of the beach where they hatched[83,88]. After the first breeding season female turtles exhibit strong site fidelity and most females will return to the same rookery to lay clutches within seasons and in each of their subsequent seasons[38,83,92]. It is unclear what mechanisms female turtles use to select a nesting site, but they are able to shift between beaches in a particular area, and readily do. For example, in the 1977 season at Heron Island and Wreck Island 2.2 to 9.2 percent of green turtles and 3.9 to 7.9 percent of loggerhead turtles were previously recorded nesting on another island earlier in the season (islands within about 100km of each other)[72]. In addition, tagging data from the 1998–1999 season show that 6 percent and 1.6 percent of the 8156 green turtles recorded nesting in east coast rookeries shifted nesting beaches between and within seasons respectively[21]. Ability for female turtles to shift between rookeries both within and between seasons could be one mechanism that enables populations to endure changes to nesting habitats that prevent or restrict nesting or clutch success.

For loggerhead and green turtle rookeries in southeast Queensland, detecting and monitoring changes in the numbers of turtles using particular nesting beaches would be relatively easy to detect given the strong public interest in marine turtles and high public visitation during the summer months. In comparison, because rookeries for hawksbill, flatback and green turtles in the northern GBR are remote and infrequently visited, the detection of changes in the phenology or fidelity will be difficult to document until relatively large shifts have occurred. However, while slow change will be hard to detect, longer-term changes in nesting distribution will be detectable because the distribution of nesting has been well mapped in Queensland.

Marine turtles

Foraging behaviour

It is not known what mechanisms influence the initial choice of foraging location. It is important to note that capture-mark-recapture studies on several species in Queensland indicate that turtles found at a particular foraging location as a juvenile retain that site as their foraging location for life, and very seldom do turtles switch locations[80] (QPWS unpublished data). It is therefore possible that shifts in foraging location or habitat selection within a location will be altered if there are substantial negative changes to forage pastures.

Estuarine crocodiles

Behaviour, physiology, reproductive timing and reproductive output of crocodilians and alligators are linked to temperature[34,52,119]. From a behavioural and physiological perspective, estuarine crocodiles have an optimum body temperature range they adjust via thermoregulatory behaviour, metabolism and cardiovascular responses to match daily and seasonal changes in environmental temperature[34,119]. Indeed, mathematical approaches such as that used by Seebacher et al.[119] could be adapted to predict changes in thermoregulatory patterns with increases in environmental temperatures.

Estuarine crocodiles are opportunistic breeders and the frequency and timing of reproductive events is largely determined by temperature. While there are few data available for wild populations of estuarine crocodiles, American alligators have adapted to varying environmental conditions throughout their range by having different onset of breeding seasons in northern and southern ends of their range

and reaching sexual maturity at a younger age in warmer climates[52]. Therefore, estuarine crocodiles have behavioural and physiological attributes that will allow them to adapt to projected temperature rises by 2050.

Sea snakes

There is insufficient information on thermal sensitivity of individual species of sea snake to estimate how particular species will respond to increased sea temperature. Potential changes could include changes in distribution of certain species and/or their prey, timing of movements and reproductive events.

15.2.2.5 Vulnerability and thresholds – temperature

If climate change were operating alone, at the forecasted levels, there would be minimal risk of localised (population) extinction for each of the groups, especially marine turtles and crocodiles, over the next 50 to 100 years. However, the question of how depleted or recovering populations (eg loggerhead turtles and estuarine crocodiles) cope with climate change in the longer term in addition to other pervasive threats remains unanswered. For example, a southwards shift in nesting distribution is one proposed coping mechanism that loggerhead turtles could undertake[61]. This could have the impact of shifting the main nesting beaches out of the protected zone of Mon Repos (latitude 24.80° S) to more developed beaches such as those on the Sunshine Coast (eg Caloundra – latitude 26.80° S). Consequently, a whole new suite of issues for management agencies will arise. Currently, the small numbers of nests laid on the beaches of Caloundra are monitored and once fox predation is curtailed it is believed that these nests should function well (QPWS unpublished data). For the northern GBR green turtle population the impacts of climate change need to be assessed with consideration for existing threats such as decreased hatchling production, illegal fishing, overseas village harvests and traditional Australian take. Similarly, for estuarine crocodiles, much of their habitat south of Cooktown has been encroached by urban or agricultural development. Hence, any changes in the animal's behaviour, southwards shift in distribution, or higher abundance will need to be seen in light of possible increased human-crocodile interactions.

15.2.3 Changes in ocean chemistry

Ocean pH is expected to decrease by between 0.15 and 0.25 by 2050. There are no available data to indicate whether ocean acidification would have any affect on marine reptiles in the GBR. Since ocean acidification is a result of changes to carbonate buffering, if any direct impacts were to be found they would most likely occur during neonatal life stages when individuals are developing skeletal structure. In addition, it is possible that indirect effects through ecosystem linkages could occur. However there is insufficient data from which to draw speculation on sensitivity or specific impacts.

15.2.4 Changes in light and ultraviolet radiation

The most likely impact that light and ultraviolet (UV) changes will have on marine reptiles is through disturbance to food chains, especially for the herbivorous green turtle. As detailed by Diaz-Pulido et al. (chapter 7) and Waycott et al. (chapter 8) most macroalgae and seagrass species in the GBR will be influenced by changes in the quality or quantity of light. However, the impacts to seagrass and algae from pervasive light reductions may be highly variable between and within species and ultimately

depends on each plant species minimum light requirements and tolerance to changing light. The condition, distribution and abundance of some seagrass and macroalgae species are inextricably linked to the diet, growth and reproductive output of green turtles. Conversely, these habitats are strongly influenced by the size of the foraging herd, and the herd's dietary ecology. However, given the uncertainty in light and UV predictions (Lough chapter 2), and a lack of data about direct effects on the nutritional and dietary ecology of green turtles, it is hardly possible to evaluate the potential sensitivity and vulnerability of green turtles to changes to light and UV.

15.2.5 Sea level rise

There is high confidence that sea level in the GBR will rise by 7 to 38 cm and 13 to 68 cm by 2020 and 2050 respectively. This rate of increase could be even greater if the recently observed rapid melting of the Greenland ice sheet continues (Lough chapter 2).

15.2.5.1 Exposure – sea level rise

In this section we assess the probability and magnitude of exposure of marine reptiles to sea level rise.

Marine turtles

Marine turtles will be exposed to changes in sea level through the impact these rises will have on nesting beach stability. The four species of marine turtles that nest in, or in close proximity to, the GBR use beaches with different physical characteristics (Table 15.1).

Table 15.1 *Main nesting areas for marine turtles in the GBR*

Flatback turtles	Continental islands of the central GBR
Loggerhead turtles	Coral cays of the Capricorn Bunker group and Swains Reef in the southern GBR and the mainland beach at Mon Repos and Wreck Rock
Green turtles (southern population)	Coral cays of the Capricorn Bunker group and the Swains Reef
Green turtles (northern population)	Coral cays of the far northern GBR, and Torres Strait (Bramble Cay) and islands in Torres Strait (Murray Island group)
Hawksbill turtles	Inner reef cays of the far northern GBR and central Torres Strait

Nesting populations span a variety of beaches that often have very different thermal profiles[74], and differ drastically in the number of nests per kilometre[68,73]. Turtles are well able to change beaches within and between breeding seasons. If nesting habitat is unsuitable turtles can be expected to shift, especially for young adults choosing their first beach. When this happens a degraded nesting beach could be effectively abandoned within one generation. A pertinent question is whether turtles will respond to changed temperature or sea level in relation to nesting beach choices. In essence, because sea level rise will affect some islands, cays and beaches to different degrees based on a suite of physical characteristics (Smithers et al. chapter 21) it is not possible to estimate the degree to which each of the species will be affected.

Estuarine crocodiles

Estuarine crocodiles are likely to be exposed to the predicted rise in sea level through effects on low-lying rubble cays, mangrove forests and salt marshes (Turner and Batianoff chapter 20 and Smithers et al. chapter 21). It is also probable that sea level rise will influence the reach of the estuarine zone and expose current nesting sites in low lying areas of catchments.

Sea snakes

Sea snakes have a low probability of exposure to increased sea level. However, there could be indirect effects to reef species if the fish communities they rely on for food are impacted by sea level rise.

15.2.5.2 Sensitivity – sea level rise

In this section we assess the magnitude and direction of response to levels of sea level rise on marine reptiles.

Marine turtles

Marine turtle nesting areas will be exposed to sea level rise to varying degrees. In the short term (next 50 years) it is most likely that the effects will be most predictable and noticeable at rookeries that have had long-term marine turtle monitoring programs, including Raine Island, Heron Island (and other Cays in the Capricorn Bunker Group), Mon Repos, Milman Island, Peak Island, Wild Duck Island and Bramble Cay. However, over the longer-term (more than 50 years) sea level rise may help other coral cays to develop and/or stabilise (Turner and Batianoff chapter 20) and thus other nesting sites may become available, or become better suited to providing an incubation medium. Alternatively, sea level rise may remove available nesting habitat and the remaining sites might not be suitable because of human uses such as established coastal development. However, mainland beaches are within the range of the existing inter-nesting change of rookery that is currently used by southern GBR turtles[21], and human activities can be managed.

15.2.5.3 Impacts – sea level rise

Raine Island – marine turtle rookery

There are seven main nesting rookeries for the northern GBR green turtle population, the largest green turtle population in the world, of which Raine Island and Moulter Cay receive over 90 percent of nesting female turtles. Over the last 10 years it has become apparent that hatchling success of clutches laid at Raine Island is poor, and in some years virtually no hatchlings are being produced from the rookery[79,81]. The most compelling argument as to why this is occurring is that the beach system is being eroded, and hence there are fewer suitable nest sites and nests are more exposed to inundation by the freshwater table and salt water from wave intrusions[79,81]. Whether or not the erosion of beach dunes has been accelerated due to blasting of the reef for construction of a guano mining facility, or a natural coral cay process is unknown. Regardless of the underlying reason, predicted sea level rise is likely to accelerate the erosion process and the frequency of nest innundation.

15.2.6 Physical disturbance – tropical storms

While the intensity of tropical cyclones in Queensland is likely to increase, there is limited confidence in the precision of the estimate with regard to spatial and temporal variability (Lough chapter 2). Increased frequency or intensity of tropical storms will affect marine reptiles to varying degrees. However exposure is likely to vary both spatially and temporally.

Marine turtles

There is substantial empirical and anecdotal data on the impacts of tropical storms on marine turtle nesting beaches throughout the world. In general, most authors report aperiodic, localised and seasonal effects on nesting beaches which consist of changes to beach profile or inundation of incubating nests with sea water, and rarely does a storm effect all beaches for an entire population[58,94,114,115]. However, several factors influence the formation, path, longevity and severity of tropical cyclones. Therefore it is not possible to predict the likelihood of exposure to, or potential impacts on marine turtle populations in the GBR. For example, severe cyclones passing over non-critical habitat or at non-peak nesting times may have less of an impact than low intensity cyclones passing directly over key nesting areas at peak nesting times. Furthermore, the magnitude of adverse effects are difficult to predict because they depend on the intensity and timing of the cyclone (with regard to turtle nesting seasons), frequency of cyclones, tidal influences and the size of storm surges and proximity of the cyclone to the nesting beaches.

Estuarine crocodiles

Since the distribution of estuarine crocodiles residing on islands within the GBR is patchy and low density, estuarine crocodiles residing on islands are likely to have a low probability of exposure to, and impact from, aperiodic tropical storms. However, for estuarine crocodiles in estuarine and freshwater rivers along the east coast of Queensland, especially breeding areas, there will be a moderate probability of aperiodic, localised and seasonal effects from cyclones because of localised flooding. Such events are likely to include washing away of nests or nest material, inundation of eggs and disruptions to normal nest attendance behaviour during flood events.

15.2.7 Rainfall and river flood plumes

There is low confidence in the predictions for changes in total rainfall that correlate with frequency and intensity of river flood plumes as a result of climate change. Total rainfall may increase in the southern and northern GBR but may decrease in the central GBR. If this is the case, then small-scale river flood plumes may increase in the southern and northern GBR but decrease in the central GBR (Lough chapter 2). Increased rainfall could potentially affect the timing and success of reproduction in estuarine crocodiles and marine turtles and the foraging ecology of marine turtles and potentially sea snakes.

Marine turtles

One aspect of marine turtle nesting behaviour that is linked to rainfall is the ability of a female turtle to successfully complete digging a nest and laying eggs. One common reason that female turtles abandon nesting attempts is a failure to be able to dig a body pit and egg chamber in loose dry sand. For most GBR turtle rookeries on coral cays nesting success in an average year would be expected to be in the order of 50 to 80 percent[22,35]. Indeed, at Bramble Cay in the Torres Strait nesting success increased

from less than 70 percent to greater than 90 percent after the onset of consistent wet season rainfall[77]. However, in drier than average years, dry sands coupled with high density nesting at some rookeries can lead to rates of nesting success of less than 10 percent[79,81]. Female turtles that make repeated unsuccessful nesting attempts throughout a season run the risk of prematurely depleting energy stores and therefore need to reduce energy use in order to have sufficient energy to fuel homewards migration[37]. In addition, increased rainfall helps to reduce the occurrence of potentially lethal fungi on incubating marine turtle eggs[102]. However, the influence of rainfall on marine turtle nesting biology is ultimately dependent on spatial and temporal variations in rainfall events. There is not enough precision in rainfall estimates for the next 50 years, or the likely temporal and spatial variability of these estimates to indicate how vulnerable marine turtles will be to increased rainfall. It is, however, likely to remain an aperiodic factor that shapes intra- and inter-annual variation in nesting success and embryo development.

Estuarine crocodiles

The number of female crocodiles breeding in a particular year, and the timing of reproduction events such as nesting, are closely related to climatic events in the later part of the dry season[126]. In general, higher than average rainfall (ie higher water levels) at the end of a dry season coupled with cool temperatures will trigger mating and courtship[48,84]. However, while this relationship has been found in a limited number of populations, it has not been explored in Queensland populations and it is likely to have spatial and temporal variability over the latitudinal range of the species. Further, rainfall or temperature thresholds that underlie the reproductive behaviour are unknown and thus it is not possible to comment on how vulnerable estuarine crocodiles are to changes in rainfall. Rainfall is, however, likely to remain an aperiodic factor that shapes intra- and inter-annual variation in reproductive periodicity, reproductive success and embryo development.

Sea snakes

There are insufficient data on water quality requirements for sea snakes to determine whether or not increases in rainfall will have any impacts on sea snakes.

15.3 Linkages with other ecosystem components

Collectively, marine reptiles reside in, migrate through or breed in a large variety of habitats, or bioregions identified within the GBR Marine Park[26]. Broad scale ecosystem components such as seagrass meadows, coral reefs, islands, mainland beaches, mangroves, estuaries and freshwater systems are especially important for marine reptiles, yet there are substantial gaps in understanding the specific roles of marine reptile species in the ecosystem. Moreover, there is recognition that the ecological roles of marine reptile species may vary both temporally (including ontogenetic and seasonal shifts) and spatially (including latitudinal variation and variation between genetically distinct populations) and their roles are shaped by variation in climatic events.

15.3.1 Constraints to adaptation

Although few data are compiled on the biological traits of many sea snake species, there is a growing base of knowledge on population dynamics, distribution and abundance of estuarine crocodiles and marine turtles in eastern Queensland. These two groups of reptiles include slow growing, long-lived

species with delayed maturity. Both groups have experienced large-scale variation in climate over thousands of years and have life history traits that enable them to endure aperiodic climatic events that threaten seasonal reproductive output. Consequently, in the temporal and spatial context of this assessment, out to 2050 and 2100, and for the GBR, the current constraints for adaptation are life history traits (eg slow growth, low reproductive output and high egg and hatchling mortality); declining (hawksbill turtles), depleted (loggerhead turtles) and recovering (estuarine crocodiles) populations; anthropogenic threats (coastal development, agriculture, hunting, incidental capture in fisheries or bather protection programmes, boat strike and marine debris); and restricted alternative nesting sites.

15.3.2 Interactions between stressors

For each of the marine reptile groups there are numerous stressors to population function that have only recently (ie within one to two generations) been managed. Stressors include the commercial hunting of estuarine crocodiles in Queensland, fisheries based interactions, coastal development and agriculture, predation by introduced wildlife, Indigenous hunting within Australia and overseas, natural mortality and climate related impacts. Given that for many of these stressors it is difficult to gain estimates of their magnitude, and their spatial and temporal variability, it is difficult to make specific statements about interactions. However, because there are numerous stressors, including numerous climate related stressors, the cumulative impact may be significant. The recent green turtle population model developed by the Great Barrier Reef Marine Park Authority and the Queensland Environment Protection Agency[15] could be used to predict consequences of climate related impacts such as changes in sex ratio, or increased nest failure in relation to other stressors. Remediation of stressors to marine reptile populations within the GBR will need to involve a whole of government approach to develop a series of tools aimed at reducing the impact individual stressors, and crucially their cumulative effect, may have on marine reptiles.

15.3.3 Threats to resilience

The primary threats to resilience of climate related impacts vary for each of the marine reptile groups, species and populations. In general, marine reptiles include long-lived, slow to mature species. Each group faces a variety of anthropogenic threats throughout their range and in some cases populations have undergone substantial declines over the last 30 to 40 years. Therefore, the main threat to resilience for marine reptiles is the cumulative impact of multiple stressors on a particular species, and these threats vary in magnitude temporally and spatially for each species.

15.4 Summary and recommendations

15.4.1 Major vulnerabilities to climate change

This chapter has highlighted that the major vulnerability for marine reptiles to climate related events is to increased air and sea temperatures. Each of the marine reptile groups comprise tropical or sub-tropical species that are adapted for life in warmer climates and they have historically experienced time periods of warmer temperatures and vastly different coastal geomorphology. However, the contemporary question is how these species will cope with increased temperature in conjunction with

numerous other threatening processes. Essentially if average seasonal sand temperatures at marine turtle nesting beaches consistently rise above 30°C they are likely to impact embryo development through alterations to sex ratios (in favour of females), phenotype or through direct mortality. If they consistently rise above 33°C alterations to the success of embryo development and changes to the phenotype of emerging hatchlings are likely. Increased temperatures are likely to have a similar impact on the incubation of estuarine crocodile eggs, but the thresholds are more difficult to quantify. Likely responses to these impacts include shifts in the timing of the nesting season and shifts in nesting locations (this could also arise from sea level rise).

Marine reptiles will be exposed to increased water temperature, and increased ambient temperatures are likely to alter rates of physiological and biochemical processes. Consequently, increased water temperatures could exert a positive influence through increased growth rates, increased reproductive output and changes to distribution and abundance.

Marine turtles are vulnerable to sea level rise. However, while the magnitude and direction will vary both among and between species, some rookeries will be more sensitive than others. For example, there are both anecdotal and empirical reports of long-term erosion at several important marine turtle rookeries in the Torres Strait (eg Bramble Cay), the far northern GBR (eg Raine Island) and the Capricorn Bunker group (eg Heron Island). Hence these rookeries will be particularly susceptible to increased sea level rise and turtles can be expected to shift their nesting distribution. Therefore, managers need to plan for protection of future potentially important nesting beaches (eg resilience of beaches to climate for turtle nesting reasons).

Marine reptiles, especially estuarine crocodiles and marine turtles are vulnerable to shifts in the frequency and intensity of storms, El Niño, rainfall and flood events. Since there is uncertainty on how each of these factors will change over the next 50 years it is difficult to predict the magnitude and direction of the effect. However, they are all likely to continue to be aperiodic shapers of seasonal reproductive output for marine reptile species in the GBR.

15.4.2 Potential management responses

Marine turtles

Protection at nesting beaches from increased temperature

Shading of incubating nests, or the relocation of clutches into cooler zones (ie under trees), has been used as a management tool by wildlife agencies in several countries (eg Malaysia). However, these shading and relocation programs have tended to be associated with hatcheries, or on small rookeries (less than 500 nests per season). Similar programs could be established in some GBR rookeries, however, the costs of developing and maintaining a similar program at larger rookeries have not been examined but are likely to be very resource (money and labour) intensive.

Identification of the cause of poor hatchling success at Raine Island

A concerted effort should be taken by management agencies to identify the cause(s), and possible solutions to the sand loss and poor hatchling success at Raine Island. This will take a coordinated approach including marine 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.

Estuarine crocodiles

Manage human-crocodile interactions

Estuarine crocodiles are opportunistic foragers and breeders, and along eastern Queensland much of their habitat has been encroached upon by urban and agricultural development. Any changes to distribution, abundance, density or behaviour of estuarine crocodiles, whether related to climate changes or not, may alter current risk of human-crocodile interactions occurring. The Queensland Parks and Wildlife Service has a statutory plan and procedural guidelines that relate to the classification, management and removal of problem estuarine crocodiles. In addition, the QPWS assess the risk of human-crocodile interactions using a standard framework for identifying the likelihood and consequences of these interactions[c]. Regular standardised surveys for estuarine crocodiles within coastal catchments[109], and regular communication with water users, land holders and other stakeholders needs to be continued to monitor any changes in the likelihood and consequences of human-crocodile interactions.

15.4.3 Further research

Increased monitoring of current and future marine turtle sites

Monitoring programs at key foraging and nesting areas for each of the marine turtle species in the GBR should be continued. Monitoring programs should be expanded and refined to include aspects such as beach and air temperatures at a population scale, and designed to determine shifts in nesting sites or season length.

Risk assessment of climate change threat to populations of marine turtle and estuarine crocodiles

Research activities that focus on determining the risk to particular species are warranted, and these should include (but not limited to) determining current and future exposure to environmental temperature, impacts on reproductive output, distribution (nesting and foraging) and possible alterations to existing threats from human interactions.

Investigate impacts of increased temperatures on estuarine crocodile reproduction and distribution

Research activities that aim to assess nest and hatchling distributions, clutch success, breeding rates and temperature effects in wild nests are warranted. This information would provide strong empirical support for any future climate related vulnerability assessment.

Determine distribution, abundance and ecological status of sea snake species

One clear outcome of this vulnerability assessment is that there are substantial gaps in our knowledge on the distribution, abundance, population structure, diet and reproductive ecology of sea snakes. Future research on sea snake ecology and conservation status is warranted.

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c   principles outlined in AS/NZS4360:2004 Risk Management

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