

Past, current and future thermal profiles of green turtle nesting grounds: Implications from climate change

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ABSTRACT

Sex determination and hatching success in sea turtles is temperature dependent and as a result global warming poses a threat to sea turtles. Warmer sand temperatures may skew sea turtle population's sex ratios towards predominantly females and decrease hatching success. Therefore, understanding the rates at which sand temperatures are likely to increase as climate change progresses is warranted. We recorded sand temperature and used historical sea surface and air temperature to model past and to predict future sand temperature under various scenarios of global warming at key sea turtle nesting grounds ($n = 7$) used by the northern Great Barrier Reef (nGBR) green turtle, *Chelonia mydas*, population. Reconstructed temperatures from 1990 to the present 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. Our 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, we found that some nesting grounds will still produce male hatchlings, 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. This allowed us to suggest strategies that can be used at a local scale to offset some of the impacts of warmer incubating temperatures to sea turtles.

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1. Introduction

Global warming has been identified as a major threat to a range of fauna (McCarty, 2001). Animals expected to be the most vulnerable are those that are heavily reliant on environmental temperature for their life history traits and/or those that exhibit temperature-dependent sexual determination (TSD) (Janzen, 1994; Hawkes et al., 2007, 2009; Mitchell, et al., 2009; Telemeco et al., 2009). Oviparous reptiles, such as sea turtles have a life history, physiology and behavioral traits that are extremely influenced by environmental temperature. This is particularly the case during the egg incubation phase (Spotila and Standora, 1985) because successful incubation of sea turtle eggs occurs within a tight 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 primary

sex ratio output is determined by nest temperature during the middle third of incubation (Mrosovsky, 1980; Yntema and Mrosovsky, 1980). Warmer temperatures, above the pivotal temperature — where a 1:1 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 usually being around 29.0–29.5 °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 temperature where 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 Astill, 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 can likely dramatically alter hatchling phenotype and survival (Mrosovsky, 1980).

Consequently, global warming has the potential to impact sea turtles. If sea turtles do not adapt to future climate change, predicted

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increase in temperature could potentially cause lower hatching success (Miller, 1985; Hawkes et al., 2007) and a gradual shift towards a feminisation of sea turtle populations (Mrosovsky, 1994; Hawkes et al., 2007, 2009). These changes will have the potential to compromise the viability of sea turtle populations, especially those severely threatened by other factors (e.g. direct and indirect take, pollution, etc.). Consequently, an understanding of the rates and extents at which sand temperatures are likely to change and the ecological implication from this changes will aid managers to mitigate potential threats and prioritize their efforts to conserve sea turtles in the face of climate change (Hays et al., 2003; Fuentes et al., 2009a). Given the conservation concern for sea turtles (all sea turtle species, with the exception of the flatback turtle, are listed in the IUCN 2004 red list of threatened species) and 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; Fuentes et al., 2009a). 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.

Understanding how green turtles will be impacted by climate change is extremely important as green turtles have important ecological roles (e.g. maintenance of seagrass and algal ecosystems) (Moran and Bjørndal, 2005, 2007), social importance to indigenous people (Johannes and Macfarlane, 1991), and value to the tourism industry (Wilson and Tisdell, 2001). Therefore, we estimated sand temperature for key nesting grounds used by the northern Great Barrier Reef (nGBR) green turtle population. The nGBR green turtle population is the largest green turtle population in the world, with about 50,000 females nesting during peak nesting year (Limpus et al., 2003). This expands on Fuentes et al.'s (2009a) work and thereby provides sand temperature projections for nesting grounds where 99% of the nesting for this population currently occurs. This provides insights into future sex ratio production by this population and ensures that managers will be in a better position to direct and focus management and conservation actions strategically to mitigate the impacts of increased sand temperature to the nGBR green turtle population. In addition we also investigate how beach orientation, shading and the location of nests in relation to the high water mark influences incubation temperatures. This information is important for managers when exploring options to mitigate the impacts of increased beach temperatures on hatching success and sex ratios (Hawkes et al., 2007). With this in mind, we also provide suggestions of strategies that can be used at a local scale to offset some of the impacts of warmer incubating temperatures to sea turtles. Lastly, we reconstruct sand temperature to investigate whether sand temperature at nesting beaches used by this sea turtle population have already started to increase.

2. Methods

2.1. Study sites

This study was conducted at nesting grounds used by the northern Great Barrier Reef (nGBR) green turtle population. Selected study sites include: Bramble Cay (9°09' S, 142°53' E), Dowar Island (9°55' S, 144°02' E), Milman Island (11°10' S, 143° 00' E), Moulter Cay (11°24' S, 144°01' E), Raine Island (11°36' S, 144°01' E), Sandbank 8 (13°21' S, 143°57' E) and Sandbank 7 (13°26' S, 143°58' E). The selected nesting grounds encompass almost the whole latitudinal range of the nesting sites used by this population and represent where 99% of nesting for this population occurs (Fig. 1). Raine Island and Moulter Cay have the largest portion of nesting with approximately 90% of the nesting occurring at these islands. Subsidiary nesting occurs at Bramble Cay

and Dowar Island, which have some of the highest densities of green turtle nesting in Torres Strait (Limpus et al., 2003). Minor nesting (50–300 nesting turtles a year) activity takes place at Sandbank 7 and 8 (Limpus et al., 2003) and trivial (10 to 50 nesting females a year), nesting occurs at Milman Island (Dobbs et al., 1999). Occasional nesting for this population also occurs at approximately 60 other nesting grounds in northern Australia.

2.2. Sand temperature

Sand temperature was recorded every hour at the study sites from November 2006 to January 2009 (sampling period varied between sites – see Table 1) using Tinytag TK-4014 data loggers (Hasting Data Loggers, Port Macquarie, Australia). 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 the green turtles' average nest depth (as per Spotila et al., 1987; Hewavisenthi and Parmenter, 2002; Matsuzawa et al., 2002; Van de Merwe et al., 2006). We deployed loggers in all types of nesting habitat used at each site (e.g. shaded and open areas, different beach orientations, etc. – Table 1). To investigate if sand temperature varies as a function of beach orientation and shading we used sand temperature from five sites: Dowar Island, Milman Island, Moulter Cay, Sandbank 8 and Sandbank 7, during the 2007/2008 nesting season (November to April). We 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. We 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).

2.3. Meteorological data

Air temperature (AT) 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 the remaining nesting grounds and sea surface temperature (SST) data for all the nesting grounds, except Sandbank 7 and 8, 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; Fuentes et al., 2009a). 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 data for Sandbank 7 and 8 were obtained from the Commonwealth Scientific and Industrial Research Organization in Australia (CSIRO) and air temperature from the Australian Bureau of Meteorology (BOM) weather station at Coen airport (less than 100 km from Sandbank 7 and 8). Historical AT and SST for each nesting beach were also obtained from ICOADS.

2.4. Statistical analysis

2.4.1. Variation in sand temperature and current thermal profiles

Sand temperature data was 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

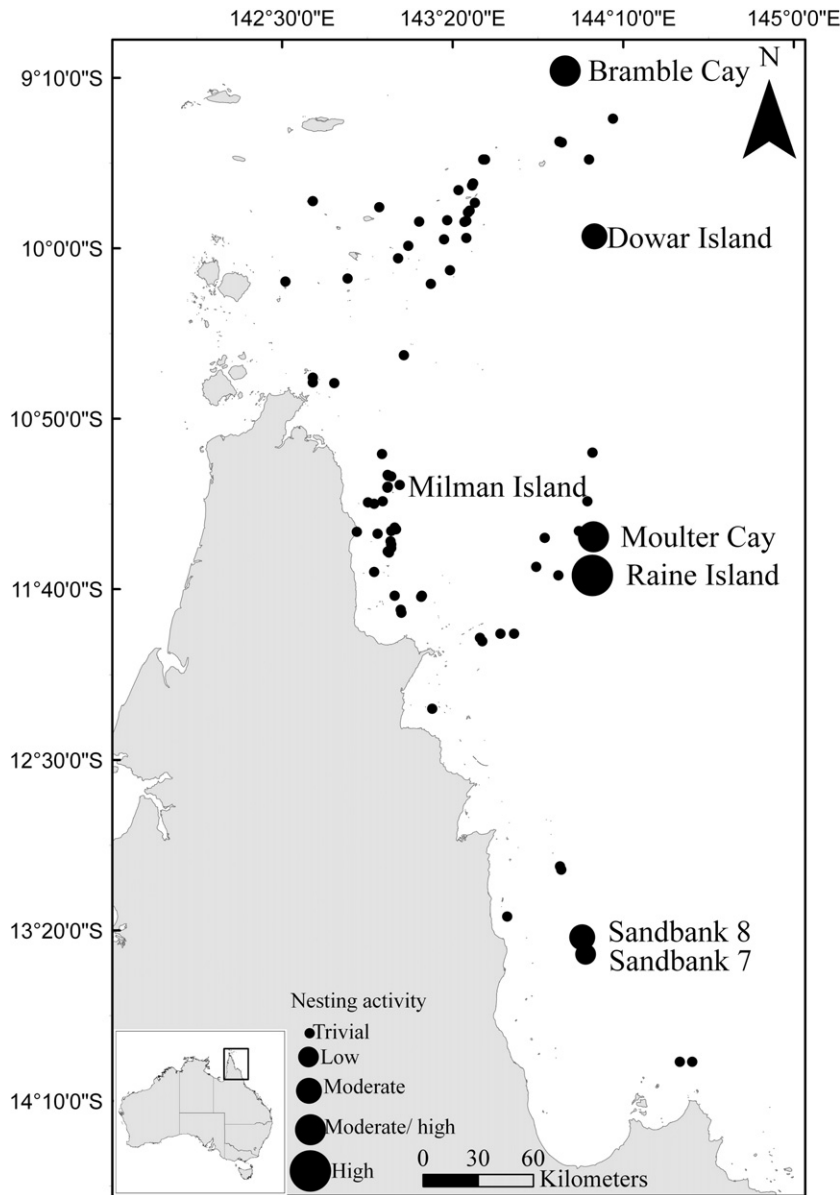


Fig. 1. Map of nesting grounds used by the northern Great Barrier Reef green turtle population. Size of dots indicates importance of each nesting ground; trivial nesting (10 to 50 nesting females a year), low (50–300 nesting turtles a year), moderate (300–1000 nesting females a year) and high (more than 1000 nesting females a year); because green turtle nesting numbers fluctuates as a result of El Niño the numbers specified are based on a high nesting year.

April 2008). When a significant difference was found post hoc testing (least significant difference – LSD) was conducted to identify which groups were significantly different.

2.4.2. Reconstructed and predicted thermal profiles

Previous studies have used the relationship between AT and sand temperature to reconstruct and predict sand temperature (e.g. Janzen, 1994; Hays et al., 1999, 2003; Glen and Mrosovsky, 2004; Hawkes

et al., 2007) however Fuentes et al. (2009a) indicates that the relationship between AT and SST best describes sand temperature at our study region. Fuentes et al. (2009a) used regression analyses between mean monthly sand temperature at Bramble Cay, Milman Island (south) and Moulter Cay and mean monthly SST and AT to generate a linear regression model. We used the same methodology for the remaining nesting grounds used by the nGBR green turtle population.

Table 1
Summary of sampling effort at each nesting ground 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

Table 2

Models used to reconstruct and model sand temperature for 2030 and 2070 for each nesting beach. SST refers to sea surface temperature and AT to air temperature. *As in Fuentes et al. (2009a).

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 – shaded	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 – shaded	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 – shaded	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

We reconstructed sand temperature by using regression models (Table 2) and historical air and sea surface temperature from ICOADS (see meteorological section for more information). Since we only

used data for months where more than 10 observations were recorded we could only reconstruct nest temperature for the past eighteen years and for Bramble Cay, Milman Island and Moulter Cay.

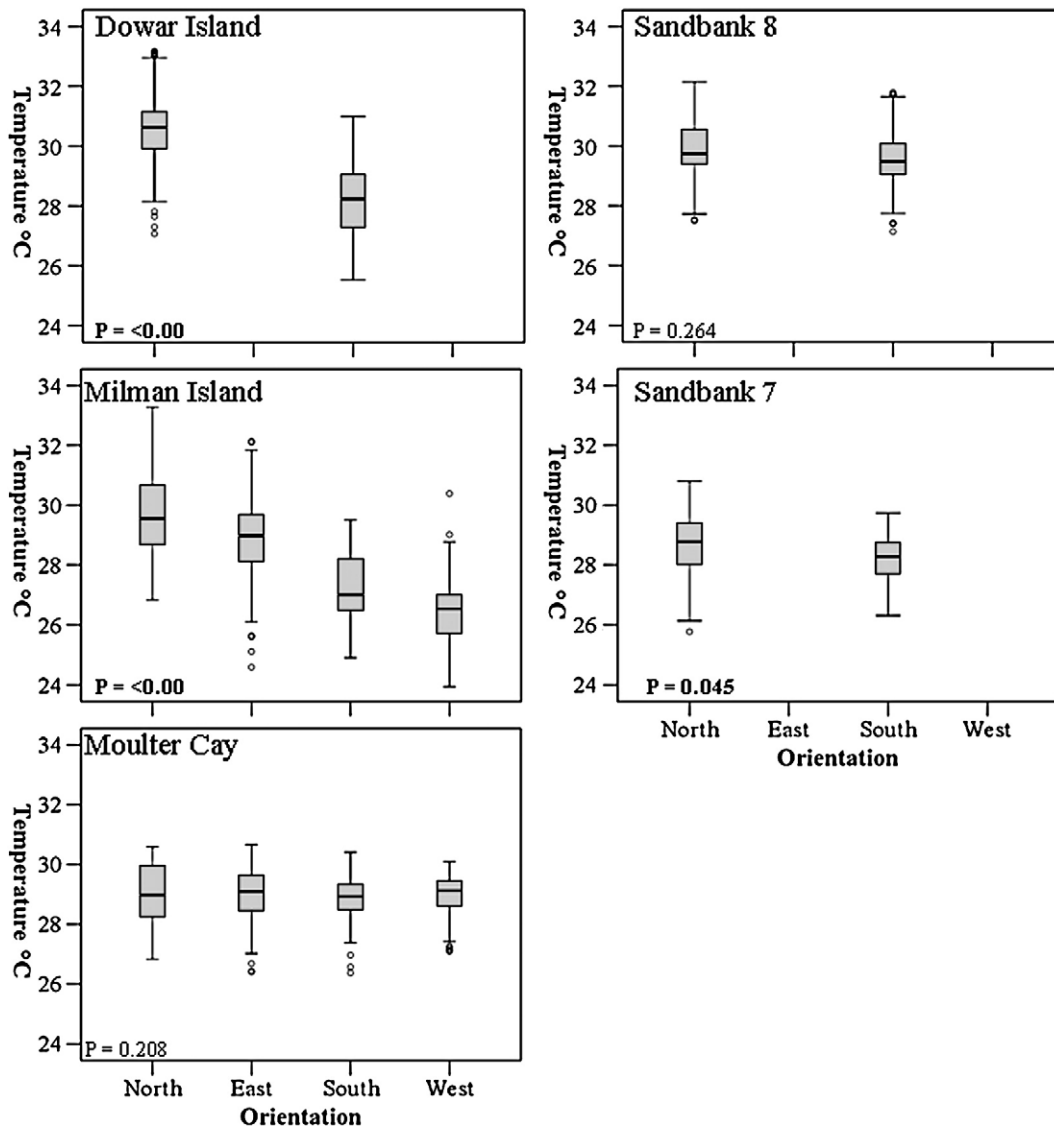


Fig. 2. Comparison of sand temperature at different beach orientations for nesting grounds used by the northern Great Barrier Reef green turtle population during the 2007–2008 nesting season. Bold indicates a significant difference in sand temperature between the different profiles.

Table 3
Current and modeled mean sand temperature (°C) during nesting season (November to April) for each nesting beach under conservative and extreme climate change scenarios for 2030 and 2070. *As published in Fuentes et al. (2009a).

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 – shaded	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 – shaded	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 ± 0.02
*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

ICOADS dataset is sparse prior to 1990 and not available for the other remote sites.

Sand temperature was predicted for a conservative – B1 emission scenario (IPCC, 2007) and extreme scenario – A1T emission scenario (IPCC, 2007) for 2030 and 2070. For this we used air and sea surface temperatures projected by the Commonwealth Scientific and Industrial Research Organization in Australia (CSIRO, 2007).

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 Freeman, 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).

The pivotal temperature for the nGBR green turtle population has been previously measured at 29.3 °C (Limpus, 2008) and therefore sand at this temperature during the middle third of incubation produces 50% females and 50% males. As no data exists delimiting the full transitional range of temperature (TRT) for this population, we assumed the TRT to be 3 °C wide centered around the pivotal temperature as suggested by Mrosovsky (1994). Considering this, we 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.

3. Results

3.1. Variation of sand temperature

3.1.1. Beach environment

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 (Fig. 2 and Table 3). No significant difference was found across the different beach orientations at Moulter Cay and Sandbank 8 (Fig. 2).

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 (\pm SE), 1.9 ± 0.05 °C (\pm SE) and 0.7 ± 0.07 °C (\pm SE) cooler at north Dowar Island, south Dowar Island and Milman Island, respectively.

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 $p < 0.00$) (Fig. 3), with an average increase of 1.7 ± 0.03 °C from the beach berm to the back dune.

3.1.2. Nesting beaches

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 (Fig. 4 and Table 3). We did not find any pattern between the latitude of each nesting ground and their thermal profile (Fig. 5).

3.2. Thermal profiles

3.2.1. Current

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

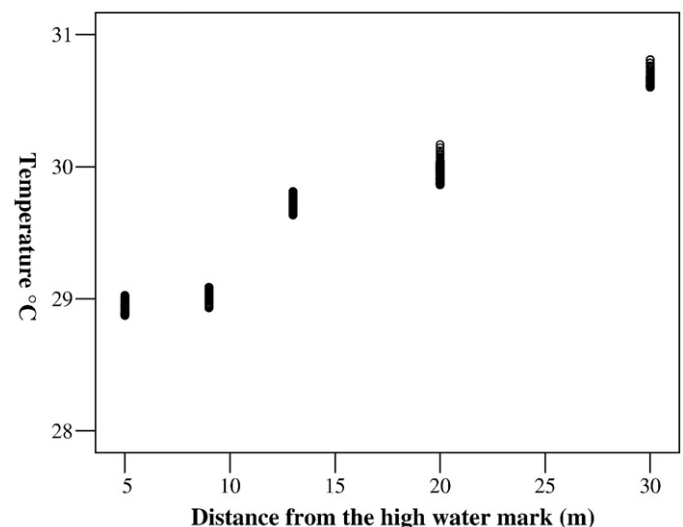


Fig. 3. Sand temperature across a beach profile at South Dowar over 3 days during February 2008.

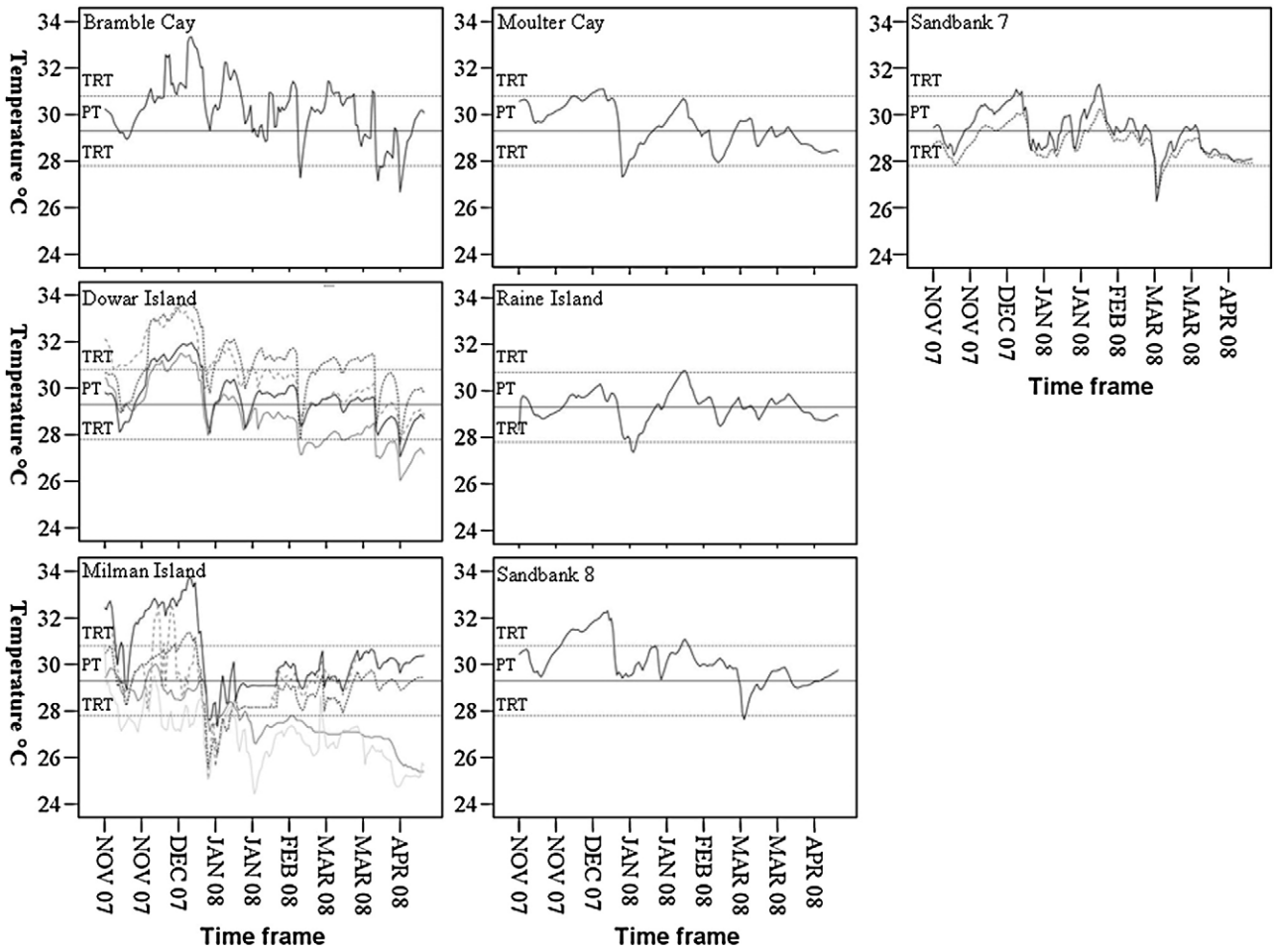


Fig. 4. Thermal profile for the key nesting grounds used by the northern Great Barrier Reef green turtle population during the 2007–2008 nesting season. Pivotal temperature (PT) refers to the temperature where a 50:50 male to female sex ratio is produced and transitional range temperature (TRT) is the range of temperature where sex ratio shifts from all males to all females. — North open, - - north shaded, . . . south open, - . - south shaded, - - - west open, - - - east open (only for Milman Island).

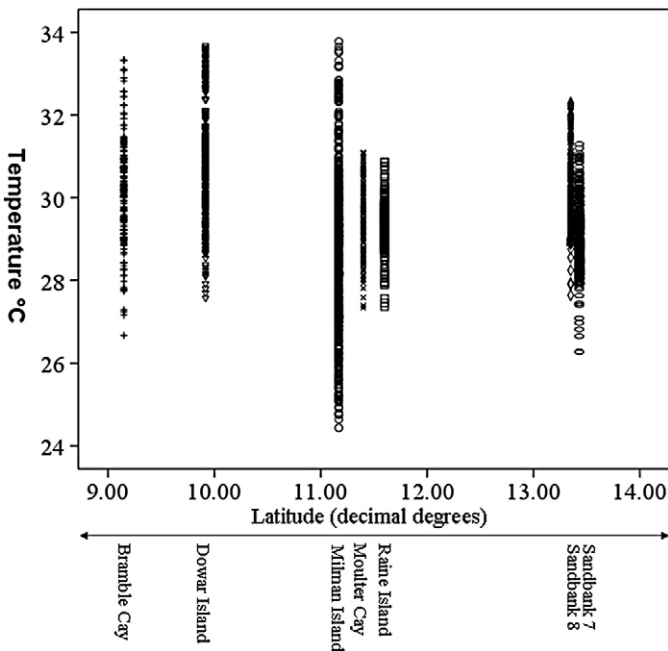


Fig. 5. Comparison of the temperature range found at each nesting ground used by the northern Great Barrier Reef green turtle population during the 2007/2008 nesting season and indicated across their different latitudinal range.

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 (Fig. 4).

3.2.2. Reconstructed

For the past 18 years there has been no change in the mean monthly sand temperature at Bramble Cay (north), Milman Island and Moulter Cay (Fig. 6) (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).

3.2.3. Future

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. Our 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). By 2070, under an extreme scenario of climate change (see IPCC, 2007) 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

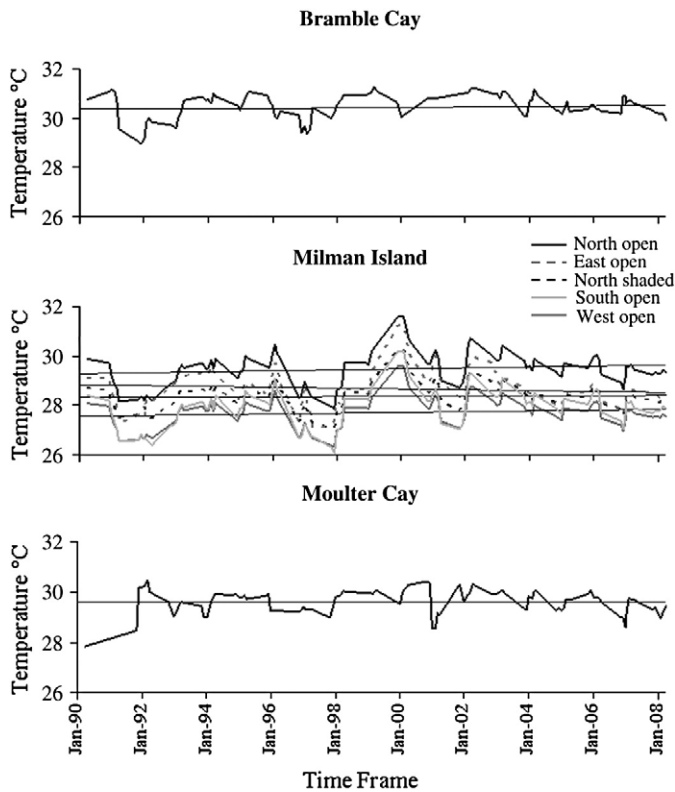


Fig. 6. Reconstructed mean monthly (November–April) sand temperature for nesting grounds used by the northern Great Barrier Reef green turtle population. Lines represent best fitting line. — North open, - - - East open, ··· North shaded, - · - South open, ——— West open.

regularly incubate at temperatures near/above the maximum thermal threshold (Table 3) increasing hatchlings abnormalities and decreasing hatching success (Table 3).

4. Discussion

Sand temperature varied greatly between and within the nesting grounds, reflecting a high level of complexity and variability in thermal profiles. Latitude did not seem to significantly influence the thermal profiles observed between the nesting sites. Nevertheless, some general patterns in sand temperature were observed within our 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 beaches and have been attributed to northern beaches proportionally greater exposure to solar radiation (Limpus et al., 1983; Booth and Freeman, 2006). Our study also found warmer temperatures at beach dunes (areas further from the high water mark); however this pattern may be different at other beaches that have dune vegetation as vegetation may act as insulation. Sand albedo is also known to influence the temperature of the sand, where sand with greater absorption of the incident solar radiation have higher temperatures and are usually composed of dark sand (Hays et al. 2001). As all the studied nesting sites have light sand it is probable that nesting sites nearby with darker sands will experience warmer temperatures.

By nesting at sites with a range of thermal profiles, nesting turtles ensure that both male and female hatchlings are produced. However, our results suggest a bias towards female hatchling production because the majority of nesting grounds, including some 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 only the data from one data logger

were available, will be necessary, as will information on the variation of sand temperature found at these sites. Nevertheless, for the past 20 years, female-biased sex ratio for immature and adult turtles has been observed widely at green turtle foraging grounds in Australia (Limpus, 2008; Heithaus et al., 2005). The only exception to this has been 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). Indeed, a female bias has been commonly reported for different sea turtle species and nesting grounds (e.g. Booth and Astill, 2001; Mrosovsky and Provanca, 1992; Godley et al., 2001) with populations appearing to function successfully with 1:2 or 1:3 male to female ratio (Hamann et al., 2007).

Our models predict that climate change will increase sand temperature at the nesting grounds studied, resulting in increased feminization of hatchling 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). 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. Most importantly, we found that west Milman Island, south Raine Island and south Sandbank 7 will have temperatures that produce male hatchlings. This is an extremely important finding since production of male hatchlings under extreme scenarios of climate change is not predicted to occur at other locations (see Hawkes et al., 2007). Male producing nesting grounds will be extremely important on the future as they will maintain turtle population viable (Hawkes et al., 2009). All projections presented here are likely to vary 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 a periodic 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).

If the nGBR green turtle population is not able to adapt to a 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 indigenous Australians 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 climate change 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); 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, cannot 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 behavioral 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). 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). Similarly, Raine Island did not exist during the last age and has developed as a green turtle nesting beach only in the last few thousand years (Limpus, 1987, 2008). It is important to note, however, that predicted climate changes are expected to occur at a much more accelerated rate than past changes (Brohan et al. 2006; IPCC, 2007). Thus, the capacity for marine reptiles to quickly adapt to rapid climate change is questionable and not well known (Fuentes et al., 2009b).

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 hatched from. If this happens, a degraded nesting beach could be effectively abandoned within one turtle generation – 40 years (Hamann et al., 2007). It is also likely that sea turtles will change their spatial distribution to adapt to sea level rise, as thus, current nesting sites may not be existent and used in the future (Fuentes et al., in press). Consequently, the gender ratio predicted for this population may be different from what has been predicted by this study. 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).

Sea turtle populations are now impacted by a range of anthropogenic activities (see Johannes and Macfarlane, 1991; Harris et al., 2000; Lutcavage et al., 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. 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), 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. 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 this 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.

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