

# Climate change and sea turtles: a 150-year reconstruction of incubation temperatures at a major marine turtle rookery

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## Abstract

Sea turtles show temperature dependent sex determination. Using an empirical relationship between sand and air temperature, we reconstructed the nest temperatures since 1855 at Ascension Island, a major green turtle (*Chelonia mydas*) rookery. Our results show that inter-beach thermal variations, previously ascribed to the albedo of the sand, which varies hugely from one beach to another, have persisted for the last century. Reconstructed nest temperatures varied by only 0.5 °C on individual beaches over the course of the nesting season, while the temperature difference between two key nesting beaches was always around 3 °C. Hence inter-beach thermal variations are the main factor causing a large range of incubation temperatures at this rookery. There was a general warming trend for nests, with a mean increase in reconstructed nest temperatures for different months of between 0.36 and 0.49 °C for the last 100 years.

*Keywords:* Ascension Island, climate change, global warming, reptile, sex determination, turtle

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## Introduction

Marine turtles, in common with many other reptiles, show Temperature Dependent Sex Determination (TSD), with a 50:50 sex ratio being produced at a specific 'pivotal' temperature, while above this temperature predominately females are produced and vice versa (e.g. Janzen & Paukstis, 1991; Mrosovsky & Pieau, 1991). Consequently, the long-term survival of turtles is dependent on a sufficient range of incubation temperatures to ensure that both male and female hatchlings are produced. There is great interest in the implications of TSD for the future survival of marine turtles under scenarios of global climate change. In short, warming temperatures might lead to the production of only female hatchlings and so to extinction (e.g. Davenport, 1989, 1997; Matsuzawa *et al.*, 2002). As a consequence of this concern, over the last two decades there have been considerable efforts to measure the pivotal temperature for different marine turtle species and populations and to estimate the sex ratio of hatchlings currently being produced (Mrosovsky *et al.*, 1984a,b; Mrosovsky & Provanha, 1989, 1992; Mrosovsky, 1994; Godfrey *et al.*, 1996, 1999). Such information will provide a vital base-line with

which to assess the impacts of any future global temperature increases. Interestingly these studies have revealed that the pivotal temperature is a conservative trait for marine turtles, always being close to 29 °C for different species and populations (e.g. Freedberg & Wade, 2001).

However, in addition to these efforts to measure the current sex ratio production from turtle rookeries, for several reasons an additional important goal is to assess marine turtle nest temperatures over time-scales of decades and more. Sea turtles are long-lived and may nest over many years. Consequently the hatchling sex ratio produced in individual years may not reflect a female's lifetime production of female and male offspring. Long-term records will allow an assessment of the relative importance of different factors that drive nest temperatures. For example, while a number of factors may influence nest temperatures within individual years (e.g. position of a nest on the beach, date during season, albedo of the sand) the importance of these factors may potentially be dwarfed by inter-annual variability. Long-term nest temperature records will also allow the impacts of global climate change to be assessed and hence allow informed decisions about potential management options to preserve turtle rookeries. Finally reconstruction of past nest temperatures over the last century will help establish if the potential feminising effect of global temperature increases has already started.

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Since direct measurements of sand temperature have been collected for only a few years at individual rookeries, as a way of revealing longer term incubation conditions it has been suggested that proxies to sand temperature, such as the amount of rainfall or air temperature, might be used (Godfrey *et al.*, 1996; Hays *et al.*, 1999). For several reasons, the major green turtle (*Chelonia mydas*) rookery at Ascension Island (7°57'S, 14°22'W) provides an excellent location for exploring long-term trends in incubation conditions. First, at this site nests are laid so deep (mean depth to the top, middle and bottom of clutches being 65, 78 and 92 cm, respectively (Hays *et al.*, 1993)) that diel temperature fluctuations are not evident and instead there is generally a simple monotonic increase in nest temperature throughout incubation caused by the metabolic heating of the eggs themselves (Broderick *et al.*, 2001). Second, the within-beach variations in incubation temperatures are small and so temperature loggers placed at only a few sites can provide a good descriptor of the sand temperature for different beaches (Hays *et al.*, 1995; Broderick *et al.*, 2001). Third, we have recently shown that the mean nest temperature during the middle third of incubation is strongly coupled to the hatchling sex ratio (as has generally been shown for other populations using laboratory incubations of eggs under more controlled thermal conditions) with the pivotal temperature during this middle third being close to 29 °C (Godley *et al.*, 2001a). Here we set out to reconstruct turtle nest temperatures at Ascension Island for the last century and more, and to thereby establish the relative roles of different factors in causing range incubation temperatures to be realised.

## Methods

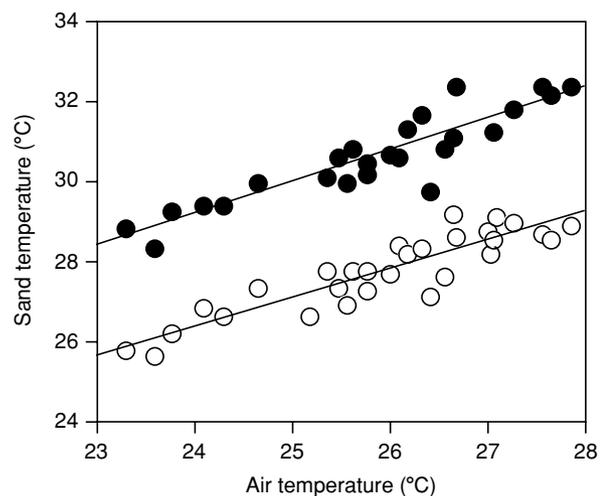
We measured the sand temperature on nesting beaches at Ascension Island in 1992, 1997, 1998, 1999, 2000 and 2001. Measurements were made at a depth of 75 cm, which lies within the normal depth range of eggs laid on Ascension Island (Hays *et al.*, 1993), in the zone of maximal nesting activity on two key nesting beaches on the island: Long Beach and NE Bay. Measurements were made throughout March and April 1992 using temperature probes (Grants Instruments Ltd, Barrington, Cambridge, UK), and using NAMAS calibrated Tinytalk data loggers (Gemini Data loggers, Chichester, UK) throughout May 1997 to February 1998, December 1998 to May 1999, December 1999 to April 2000 and December 2000 to May 2001. See Hays *et al.* (1999) for a full description of methodology.

We obtained air temperature data for around Ascension Island (6–10°S and 12–16°W) from the Comprehensive Ocean Atmosphere Data Sets (COADS) (<http://www.cdc.noaa.gov/coads/>). Comprehensive

Ocean Atmosphere Data Sets (COADS) is a very extensive and widely used set of surface marine data with the basic data including sea surface and air temperatures, wind, humidity, barometric pressure, cloudiness, weather, and wave and swell fields. The data-set covers all oceans of the World with data extending back to 1854. The initial observations in the 19th century were taken by 'ships-of-opportunity' (including merchant and naval vessels) and this approach has been supplemented since around 1900 by near-surface sea temperatures derived from the uppermost levels of oceanographic profiles, and then since around the mid-1970s by measurements from increasingly extensive arrays of drifting and moored buoys (Woodruff *et al.*, 1998; Woodruff, 2001).

## Results

There were strong relationships between the mean monthly sand temperature on Long Beach and NE Bay and the mean monthly air temperature provided by COADS (Fig. 1). We restricted our use of the COADS data to those months in which there were at least 10 air temperature measurements and then, using the equations detailed in Fig. 1, we predicted the mean sand temperature on Long Beach and NE Bay for February, March, April and May for each year since 1855 (Fig. 2). Based on our measurements of the seasonality of nesting on the island (Godley *et al.*, 2001b) these are the months within which approximately 90% of all nests will be in their



**Fig. 1** The mean sand temperature on Long Beach (○) and NE Bay (●) vs. the mean air temperature around Ascension Island. Each point represents the mean sand temperature for a particular month recorded in 1992, 1997, 1998, 1999, 2000 or 2001 (see Methods). Least squares fit regression equations are: mean sand temperature on Long Beach = 0.713 (air temperature) + 9.28 ( $r^2 = 0.81$ ); mean sand temperature on NE Bay = 0.794 (air temperature) + 10.1 ( $r^2 = 0.83$ ).

middle-third of incubation (the period when temperature determines the sex of the hatchlings) and hence this is the key period determining the overall sex ratio of hatchlings produced from the island. To each of the predicted mean sand temperatures, we added 1 °C, which is the mean extent of metabolic heating within the clutches on Ascension Island by their middle third of incubation (Broderick *et al.*, 2001). In this way we calculated the mean nest temperature for each month for those nests in their middle-third of incubation. These reconstructed mean nest temperatures showed that the inter-annual variability in mean incubation temperatures was small compared to inter-beach variation. For example, the mean monthly nest temperatures for Long Beach during February, March, April and May were 29.1 °C

( $n = 94$  years,  $SD = 0.47$ ), 29.5 °C ( $n = 99$  years,  $SD = 0.38$ ), 29.5 °C ( $n = 101$  years,  $SD = 0.35$ ) and 29.2 °C ( $n = 105$  years,  $SD = 0.39$ ), respectively; while for NE Bay they were 32.0 °C ( $n = 94$  years,  $SD = 0.52$ ), 32.5 °C ( $n = 99$  years,  $SD = 0.43$ ), 32.5 °C ( $n = 101$  years,  $SD = 0.39$ ) and 32.1 °C ( $n = 105$  years,  $SD = 0.43$ ), respectively. Consequently the lowest mean monthly nest temperature for the darker beach was above the highest mean monthly nest temperature ever recorded for the lighter beach.

For the key months of the year (February–May), there was a general warming of the reconstructed mean nest temperatures over the 150-year time-series (Fig. 3). Using the regression equations for each month that described this warming, the average warming per 100 years for February, March, April and May was 0.36, 0.41, 0.45 and 0.49 °C, respectively.

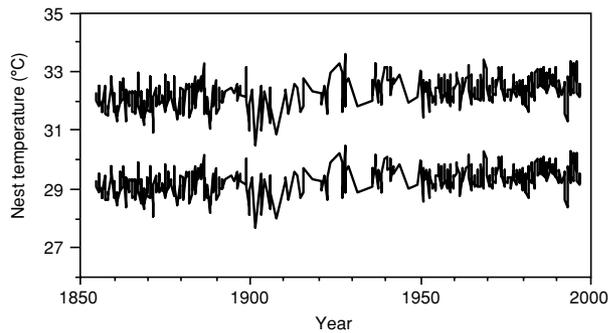


Fig. 2 Reconstructed mean monthly (February–May) nest temperatures for Long Beach (lower line) and NE Bay (upper line).

## Discussion

The absence of long-term direct measurements of sand temperature means that we must explore indirect approaches to reconstruct past nest temperatures for sea turtles. One approach that has been outlined is to use incubation duration as a proxy for nest temperatures since incubation durations have been measured by some projects for several years (Marcovaldi *et al.*, 1997; Mrosovsky *et al.*, 1999). However, for many important rookeries, data on incubation durations are lacking and, even where available, data are unlikely to extend back for many decades. Since meteorological records for many

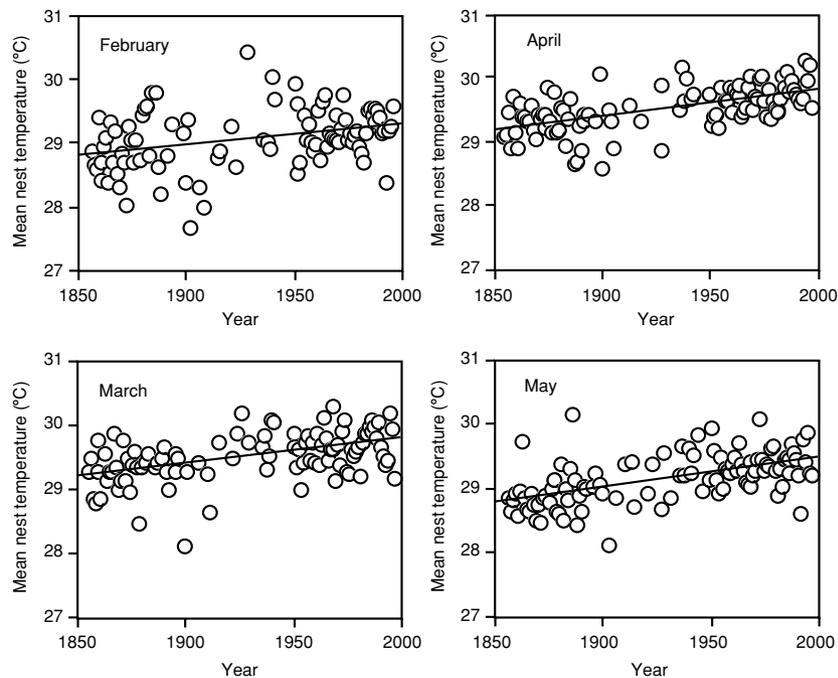


Fig. 3 Reconstructed mean nest temperatures for Long Beach, Ascension Island, between 1855 and 1997. Least squares fit regression equations are shown and in each case are significant ( $P < 0.001$ ).

areas of the world extend back for a century and more, establishing links between meteorological conditions and turtle nesting temperatures is an attractive approach. The sand temperature is ultimately determined by the exchange of thermal energy at the sand/air surface and heat transmission within the beach, and so the air temperature/sand temperature relationships that we recorded are not directly causative. Nevertheless the strength of these relationships means we can, with some confidence, predict past sand temperatures on Ascension Island from historically measured air temperatures.

At Ascension Island we have previously shown that the large inter-beach thermal variations are driven by the colour (or more strictly the albedo) of the sand, with lighter coloured beaches being cooler (Hays *et al.*, 2001). Further, we have calculated that while both male and female hatchlings may be produced on a lighter coloured beach (Long Beach) with the estimated sex ratio (% females) from this beach being 73.8% in the 1998/99 nesting season, on a darker beach (NE Bay) almost all (99.4%) of the hatchlings produced were female (Godley *et al.*, 2001a). The implication of our reconstructed nest temperatures is that the darker beaches at Ascension Island will have produced almost exclusively female hatchlings for 150 years, whereas males will have been produced from the lighter beaches during the same years. In short, inter-annual variations in sand temperature have been relatively small compared to the inter-beach thermal variations. How different beaches are selected by turtles is not fully known, although offshore bathymetry seems to be important with heaviest nesting at Ascension Island on those beaches where the offshore approach is deepest (Mortimer, 1995).

Although climatic fluctuations have been shown to have impacts on some marine reptiles (Wikelski & Thom, 2000), there has mainly been only theoretical consideration of the potential for long-term thermal changes on marine turtle nesting beaches (Davenport, 1989; Janzen, 1994). Importantly our reconstructed nest temperatures suggest that a general warming of the sand at Ascension Island has occurred over the last century and a half and so any future temperature increases will only amplify warming that has already begun. It is possible that turtles might circumvent global temperature increases by shifting their nesting seasons to relatively cooler months of the year. Such a phenological response has been seen, for example, in the laying dates of some birds (Sanz, 2002). Although there is little information on how nesting seasonality changes in turtles between 'cold' and 'warm' years, there is at least cursory evidence that a change in nesting seasonality does not occur in response to warmer conditions. For example in Florida, where the hatchling sex ratio for loggerhead (*Caretta caretta*) turtles is massively skewed towards females, the nesting season

is centred around the warmest time of year (Mrosovsky *et al.*, 1984a,b).

While marine turtle populations are in decline in some parts of the world, the green turtles at Ascension Island are a conservation success story with complete protection at the island since the mid-1950s and a relatively stable population size over the last 30 years (Godley *et al.*, 2001b). The current skew towards female hatchlings at Ascension Island is, in itself, not unexpected since female skewed sex ratios have been widely reported for different populations and species (Freedberg & Wade, 2001). However, our findings do show that the continued success of the Ascension Island green turtle rookery relies on the production of male hatchlings from the lighter coloured beaches on the island. In the broader context, lighter (and hence cooler) beaches in other regions of the world may become increasingly important even if they currently only support low nesting numbers. Finally, this work suggests that linking sand temperatures to routinely measured meteorological parameters may have wide application for reconstructing sea turtle nest temperatures over timescales of a century or more.

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