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Nest temperatures in a loggerhead nesting beach in Turkey is more determined by sea surface than air temperature

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ABSTRACT

While climate change is now fully recognised as a reality, its impact on biodiversity is still not completely understood. To predict its impact, proxies coherent with the studied ecosystem or species are thus required. Marine turtles are threatened worldwide (though some populations are recovering) as they are particularly sensitive to temperature throughout their entire life cycle. This is especially true at the embryo stage when temperature affects both growth rates and sex determination. Nest temperature is thus of prime importance to understand the persistence of populations in the context of climate change. We analysed the nest temperature of 21 loggerheads (*Caretta caretta*) originating from Dalyan Beach in Turkey using day-lagged generalised mixed models with autocorrelation. Surprisingly, the selected model for nest temperature includes an effect for sea surface temperature 4-times higher than for air temperature. We also detected a very significant effect of metabolic heating during development compatible with what is already known about marine turtle nests. Our new methodology allows the prediction of marine turtle nest temperatures with good precision based on a combination of air temperature measured at beach level and sea surface temperature in front of the beach. These data are available in public databases for most of the beaches worldwide.

1. Introduction

Global climate change is a major issue in ecosystem and wildlife management throughout the world (Pereira et al., 2011). It has already produced significant and measurable impacts on almost all ecosystems, taxa, and ecological processes, and its impact is expected to increase rapidly (Hughes, 2000; Parmesan and Yohe, 2003; Peterson et al., 2002; Walther et al., 2002). To respond effectively to predicted climatic change, it is important to understand how changes affect biodiversity (Kearney et al., 2009; Margules and Pressey, 2000; Mokany and Ferrier, 2011). This is particularly true for animals, which are considered to be especially vulnerable to climate change. An example is oviparous reptiles, such as sea turtles whose life history, physiology, and behavioural traits are extremely influenced by environmental temperature (Hawkes et al., 2007).

Sea turtles as well as many other turtles have temperature-dependent sex determination, wherein the sex of their hatchlings is determined by the incubation temperature during embryonic development (Pieau et al., 1994). In sea turtles, warmer incubation temperatures produce more females, while cooler temperatures produce more males (Hulin et al., 2009). Variations in sex ratios observed in the wild are thought to be driven largely by local environmental conditions (Godfrey and Mrosovsky, 2001). There is a paucity of data on the contemporary sex ratios of offspring produced by regional marine turtle populations. The lack of such information in turn inhibits the ability of researchers to accurately predict how future meteorological and climate-driven changes may affect turtle populations. Moreover, these data are integral for the development of regional and global recovery plans for declining turtle populations (Fuller et al., 2013).

Many factors have been shown to influence sand temperature at the level of marine turtle nests. For example, seasonal changes in sand temperature occur so that males are mainly produced at the start and end of the nesting season and females during the interim period for loggerhead turtles nesting on the east coast of the USA (Mrosovsky et al., 1984); for green turtles nesting in Costa Rica, the incubation temperature is profoundly influenced by whether the nest is shaded by vegetation (Morreale et al., 1982); while for the green turtle rookery at Ascension Island, there are large inter-beach thermal variations caused by differences in sand

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albedo (i.e., the percentage of incident solar radiation reflected by the sand) (Hays et al., 2001). Further, metabolic heating has been shown to be substantial, with nest temperature being 0.5–5 °C higher than sand temperature at the end of incubation (Sandoval et al., 2011; Zbinden et al., 2006).

Until now, the only fully reliable method for sexing hatchling turtles is to examine their gonad using gross appearance or better histology (Girondot, 2010). However, as these methods are lethal, researchers have pursued methods that indirectly estimate the sex ratios of hatchlings using environmental parameters such as sand temperature (Matsuzawa et al., 2002; Mrosovsky and Provancha, 1992) or sand and air temperature (Hawkes et al., 2007). Recently, it was proposed that the prediction of sand temperature based on air temperature (AIRT) could be improved using sea surface temperature (SST) as a covariate (Fuentes et al., 2009). While the improvement was real, only average monthly temperatures were used. As a result, it was impossible using these data to decipher the relative importance of AIRT and SST at the level of a single nest. In this study, we used data from Dalyan Beach in Turkey to measure the relative contribution of AIRT and SST to predict the temperatures measured in nests of *Caretta caretta* marine turtles while taking into account cross- and auto-correlations. The methodology proposed can be used to predict with good precision and no bias the nest temperature of marine turtles.

2. Materials and methods

2.1. Field data

With a total length of 4.5 km, Dalyan Beach (latitude = 36.791, longitude = 28.621) starts from the Dalyan Channel and finishes at Iztuzu Beach: Inceburun Hill and Dalyan Lagoon are located at the northern end of the beach. Inceburun Hill is covered by a red pine (*Pinus brutia*) forest, providing a refuge for wild animals such as foxes. There are cafes, showers, and bathing facilities at both eastern and western ends of the beach. Loggerhead (*C. caretta*) nesting season on this beach spans from early May to early August with a peak in mid-June. In total, 250–300 nests are deposited annually on this beach. A hatchery site of approximately 10×15 m^2 is located in the middle part of the beach. Nests deposited in potentially inundated parts of the beach are transferred to this hatchery (Başkale and Kaska, 2005). The distance between nests was set at 1 m in order to prevent any interaction. The temperatures of 21 loggerhead turtle nests were recorded during the 2010 nesting season on Dalyan Beach using Tiny Talk temperature recorders (resolution 0.37 °C, Orion Components Ltd., UK). These were placed in the middle of the nests (ca. 45 cm depth) during oviposition, on the same night, or the following morning in the case of relocated nests (Sarı, 2011). The dates of oviposition for the 21 nests cover the entire nesting season (from 15 May to 26 July) and they were localised along all the length of the beach. The distance from the nest to the nearest shoreline was also measured (mean = 21.64 m, SD = 4.54 m, minimum = 15.5 m). As the tide amplitude is low in this part of Mediterranean Sea (93 cm on average), this effect is not taken into account. For each of the 21 monitored nests of *C. caretta*, we obtained temperatures every 90 min from the time of egg deposition to the emergence of hatchlings.

2.2. Air temperature and SEA surface temperature

AIRT was recorded every 3 h (resolution 1 °C) in a meteorological station located 5 km from the beach. The daily SST in front of the nesting beach was also obtained (Reynolds et al., 2007). Five years of data were thus used (Figs. 1 and 2).

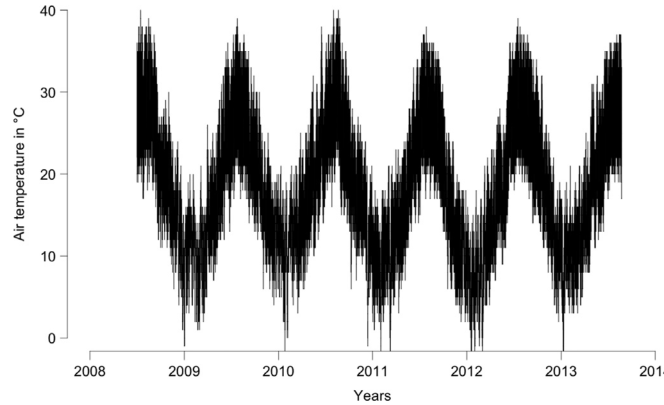

Fig. 1. Air temperature measured every 3 h 5 km from Dalyan Beach (Turkey) from 2008 to 2013.

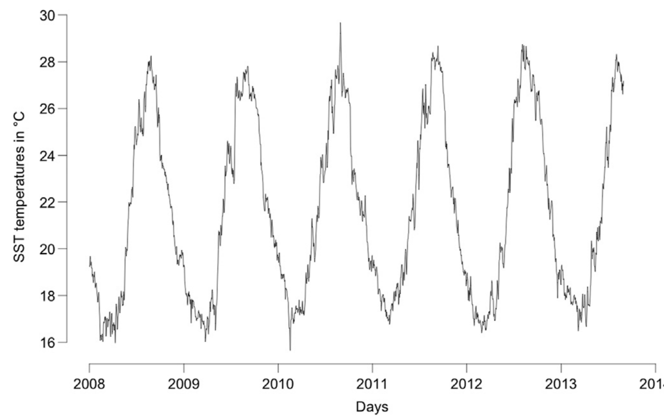

Fig. 2. Daily sea surface temperature in front of Dalyan Beach (Turkey) from 2008 to 2013.

The five years of data for daily SST and mean daily AIRT were then fitted using a generalised linear model (GLM) with sine and cosine transformed ordinal days as covariates using a Gaussian distribution with identity link (see, for example, Girondot et al., 2014). This procedure allows a periodic model to be fitted with a GLM.

2.3. Statistical properties of nest temperatures time series

Autocorrelation between successive recorded temperatures was assessed, with lag increasing until autocorrelation became non-significant. Partial autocorrelation was also searched for using the same procedure. A partial autocorrelation is the amount of correlation between a variable and a lag of itself that is not explained by correlations at all lower-order-lags.

2.4. Nest temperature determinants

SST, AIRT, distance of the nest to the sea, and proportion of development (0 for oviposition and 1 for hatching; used to measure metabolic heating) and first-order interaction between SST and AIRT as well as between SST and distance of the nest to the sea were used to fit the mean daily nest temperatures. SST and AIRT were lagged from 0 to 10 days, and for each combination, the parameters were fitted. A Gaussian distribution with identity link was used to estimate likelihood. The identity of the nest was included as a random effect (Schall, 1991). Autocorrelation structure of order 1 (see Section 2.3 above) and penalised pseudo-likelihood were used (Wolfinger and O'Connell, 1993) with the function