Journal of Herpetology, Vol. 54, No. 3, 371–377, 2020

Later Nesting by Hawksbill Turtle following Sea Surface Warming

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Abstract.—We studied the nesting behavior of the Hawksbill Turtle (*Eretmochelys imbricata*) along the northeastern coast of Brazil, specifically in southern Rio Grande do Norte. We compare the peak of nesting activity for several seasons from 2006 to 2016. The raw data consist of daily records of the presence of hawksbill turtle on a beach ($N = 3{,}717$). In the statistical analysis, we construct a cumulative sum of data and perform a logistic fitting. Furthermore, we use the derivative of the fitting to find the peak of nesting season. We observed a drift in the oviposition peak of the Hawksbill Turtle. In addition, the peak of maximal sea surface temperature in the nesting area followed a similar drift. The results suggest that the Hawksbill Turtle population has been responding to warming environmental changes.

A very large number of scientific studies on the adaptive life strategies of organisms to climate change have been published during the past few decades (Parmesan and Gary, 2003; Walter, 2015). Several of these studies have focused on marine turtle populations, exploring the future impact of climatic change on and the temperature-dependent sex determination of marine turtles (Hawkes et al., 2009; Witt et al., 2010; Marcovaldi et al. 2014). Other studies are concerned with the impact of global warming in nesting grounds, especially with regard to the rise in sea level, the increase in sand temperature, and the increase in cyclonic activity (Fuentes et al., 2011).

Recently, studies on the Loggerhead Turtle (*Caretta caretta*) have reported early nesting associated with increasing sea surface or air temperatures. For example, Weishampel et al. (2004) and Pike et al. (2006) observed early nesting behavior in Florida, USA, and Hawkes et al. (2007) in North Carolina, USA, in coastal areas along the North Atlantic Ocean. Mazaris et al. (2008) recorded a similar pattern in Greece along the Mediterranean Sea. These four studies all present data indicating early nesting behavior is associated with increasing environmental temperature: Loggerhead Turtle populations shifted nesting periods to compensate for the climatic warming. We have noted the same pattern in several terrestrial species of birds, insects, and plants (Parmesan and Gary, 2003).

Our current study expands on these earlier works and offers several new features. Our study focuses on another Sea Turtle species, namely, the Hawksbill Sea Turtle (*Eretmochelys imbricata*). In addition, it concerns the temporal shift phenomenon; the aforementioned Loggerhead Sea Turtle studies observed earlier nesting behavior, whereas our observations point out later nesting. Finally, our study is in the equatorial zone (the zone extending 3° of latitude on either side of the equator) instead of in more temperate latitudes. However, we believe that in all cases, marine turtles are facing adaptive responses to climate changes.

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DOI: 10.1670/19-062

The Hawksbill Turtle is listed as Critically Endangered in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (IUCN, 2017). The reason for the critical state of this species is related to hundreds of years of intense exploitation for meat, eggs, and tortoiseshell (Meylan and Donnelly, 1999). This study of Hawksbill Turtle nesting behavior is opportune to improve conservation strategies for this species, specifically to plan patrolling efforts and nest management.

Sea turtles are good models for tracking environmental changes that can be related to climate. They are long-lived, and individuals of specific populations forage over extensive areas. These characteristics tend to minimize effects of genetic variation inside communities (Bjorndal et al., 2016). The goal of this study is to analyze a possible shift in the peak of the nesting period of the Hawksbill Turtle along the northeastern coast of Brazil, specifically the beaches situated in southern Rio Grande do Norte state. Moreover, this area supports the largest nesting density of Hawksbill Turtle in the South Atlantic (Santos et al., 2013).

Materials and Methods

Characterization of Study Area.—The studied area is located in northeastern Brazil in the southern section of the state of Rio Grande do Norte (Fig. 1). Two coastal localities were monitored: the first area was approximately 4.2 km in length, within the municipality of Tibau do Sul (06.190121°S, 35.084720°W), and consists of Chapadão, Minas, and Sibauma beaches. The second area is a stretch of 4 km coast in the municipality of Parnamirim (05.924182°S, 35.157463°W) close to Natal, and it is formed by three beaches: Alagados, Prainha, and Morro Branco (Fig. 1). The landscape is composed of cliffs, interspersed with dunes, exposing generally a narrow band of beach. The sand is fine grained with a pale yellow color. This region experiences a mesotidal, semidiurnal regime, where normal tidal range is 2.0 m while spring tide is 3.2 m (Hayes, 1979).

Data Collection.—During the nesting seasons from 2006–07 to 2015–16, we performed morning patrols between 1 November

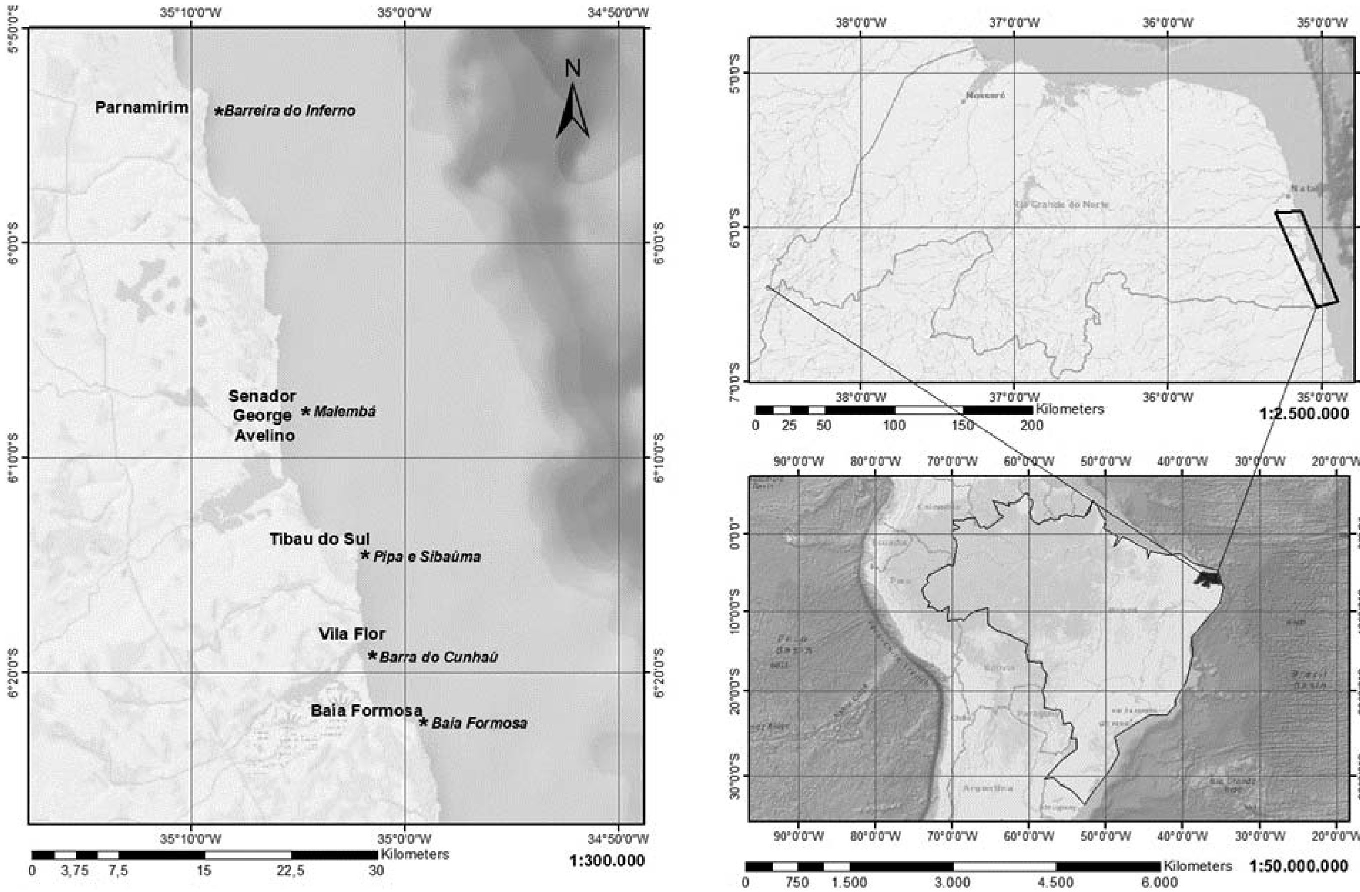

FIG. 1. Location of the study site in northeastern Brazil. The monitored beach is composed of two main areas: the first is a military region close to the city of Natal, Barreira do Inferno; the second area is in the municipality of Tibau do Sul, nearby the touristic beach of Pipa.

and 30 May to record the tracks from the previous night. Intensive night-long patrols, for each nesting season, occurred from 10 December to 15 April from 1900 to 0430 h to intercept and mark nesting females with inconel metal tags (#681 National Band and Tag Company), applied to both front flippers.

Measurements.—In our analysis, we use 3,717 records of Hawksbill Turtle nesting attempts on the beach. This number corresponds to the sum of successful nesting, $N = 2{,}835$, and crawling records without complete nesting on the beach (i.e., false crawls), $N = 882$. The historical percentage of Hawksbill Turtle in the patrolled area is 97% (Santos et al., 2013). Moreover, other species use the beach for oviposition: *Chelonia mydas* has 27 records, followed by *C. caretta* with 24 records and *Lepidochelys olivacea* with 4 records. These records were excluded from the statistics.

Statistical Analysis.—We started with daily nesting attempt data that, because of the low sampling, was highly irregular. To smooth the data, we performed a cumulative sum. We noted that the maximum of the data corresponded to the inflection point of the cumulative sum; to get the extreme of the curve, the simplest strategy was to perform the derivative of this curve. However, even this curve is not regular enough to properly extract the inflection point; Thus, we performed data fitting to improve the statistical estimation of the maximum. We used the logistic curve to fit the cumulative sum. The results of the fitting as well as the statistical method are illustrated in Figure 2.

The derivative of the logistic curve produced a Gaussian-like curve (Fig. 2). By knowing the Gaussian distribution maximum, we answered our biological question about shifting of the Hawksbill Turtle nesting season. We also explored additional properties of the statistical distribution to make our analysis more robust. Furthermore, we analyzed the SD, the skewness, and the kurtosis of the data. Most of the statistical analysis was performed in the MATLAB environment (The MathWorks, Inc., 2012). Some graphics were done using R programing language (R Development Core Team, 2012).

The data collected used the Gregorian calendar, the usual calendar of Western countries. However, this calendar is a convention that is regularly corrected by the introduction of bissextile years. To avoid this bias, we measure the days based on the equinox time of the year. We chose as the day zero of each season the day of the equinox, that is, the day the number of hours in the night and in the day are the same. Using this astronomical measure, we can properly compare the peaks of marine turtle nesting period among different seasons.

Climate Data.—The surface sea temperature (SST) was estimated using a reanalyze methodology called Simple Ocean Data Assimilation (SODA; Carton et al., 2018); we used version 3.3.1 of SODA3. The SST data were collected in the sea location 6.25°S and 34.75°W, the closest point to Tibau do Sul, the studied Hawksbill Turtle nesting site. We estimated the SST at 5-m depth; we also tested 10- and 50-m depths, and the results were similar. We used the average monthly temperature in our statistical analysis because it presented low variability. We examined the time range from 1980 to 2015, which is larger than the recorded

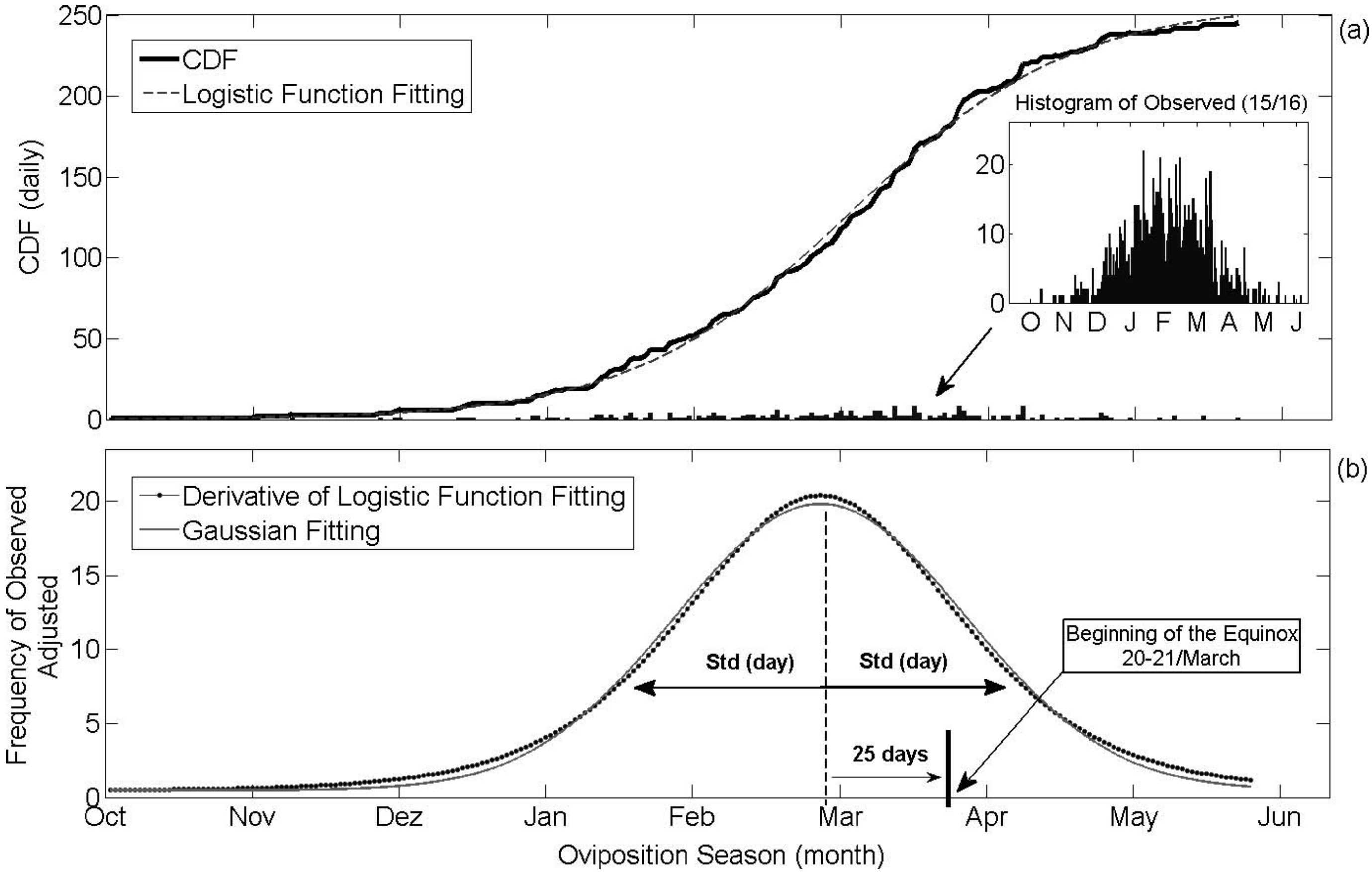

FIG. 2. Summary of data and statistical treatment. (a) Original daily data records of *Eretmochelys imbricata* beach visitations. We based our statistics on the cumulative sum of the data and the logistic fitting. The data are depicted in blue, the cumulative sum in black, and the logistic fit by the red dashed line. (b) Derivative of the logistic curve (red dots) that put in evidence the maximum of the distribution. In addition, the Gaussian fit of this theoretical distribution is presented (full line in green) and the equinox time. This figure represent the 2012–13 season.

Hawksbill Turtle data, because a larger sample better unveils the climatic tendency in the geographical location.

RESULTS

The central premise of this study was to test the hypothesis that the reproductive season of the Hawksbill Turtle is changing over recent years. This hypothesis comes from personal experiences of workers of the TAMAR project that have been monitoring marine turtles in the area for several years. (The name TAMAR derives from the contraction of tartaruga marinha, the Portuguese name for sea turtle.)

The temporal shift in the peak of nesting season is summarized in Figure 3, showing the peak day for seasons from 2006–07 to 2015–16. The day in the y-axis is the number of days before the equinox time. The overall view of the graph points out a temporal change in the peak of nesting season for the Hawksbill Turtle, that is, the population is delaying visits to the nesting beach. The linear fit of the data evidenced a significant negative correlation with Pearson test ($R = -0.70$, df $= 8$, $P = 0.024$). We also performed a correlation test by using the nonparametric Spearman test ($P = 0.028$). The slope of the straight line is -1.2 ± 0.44 days/yr.

In Figure 4, we explore some parameters that characterize the overall statistical distribution of nesting attempts for the seasons. Figure 3 shows that the peak in nesting seasons is shifting along the years, so we can also ask whether the form of the distribution is changing along the years, which could be

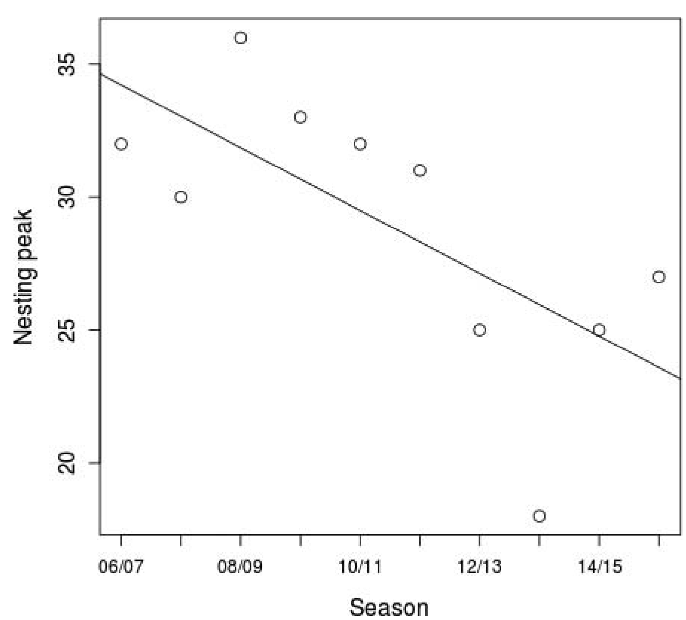

FIG. 3. Nesting peak vs. reproductive season. We plot the peak of the nesting season for several seasons. The vertical axis shows the day before the equinox corresponding to each season. The statistical analysis reveals a significant correlation ($R = -0.70$, df $= 8$, $P = 0.024$), the slope of the line indicates to 1.2 ± 0.44 days/yr.

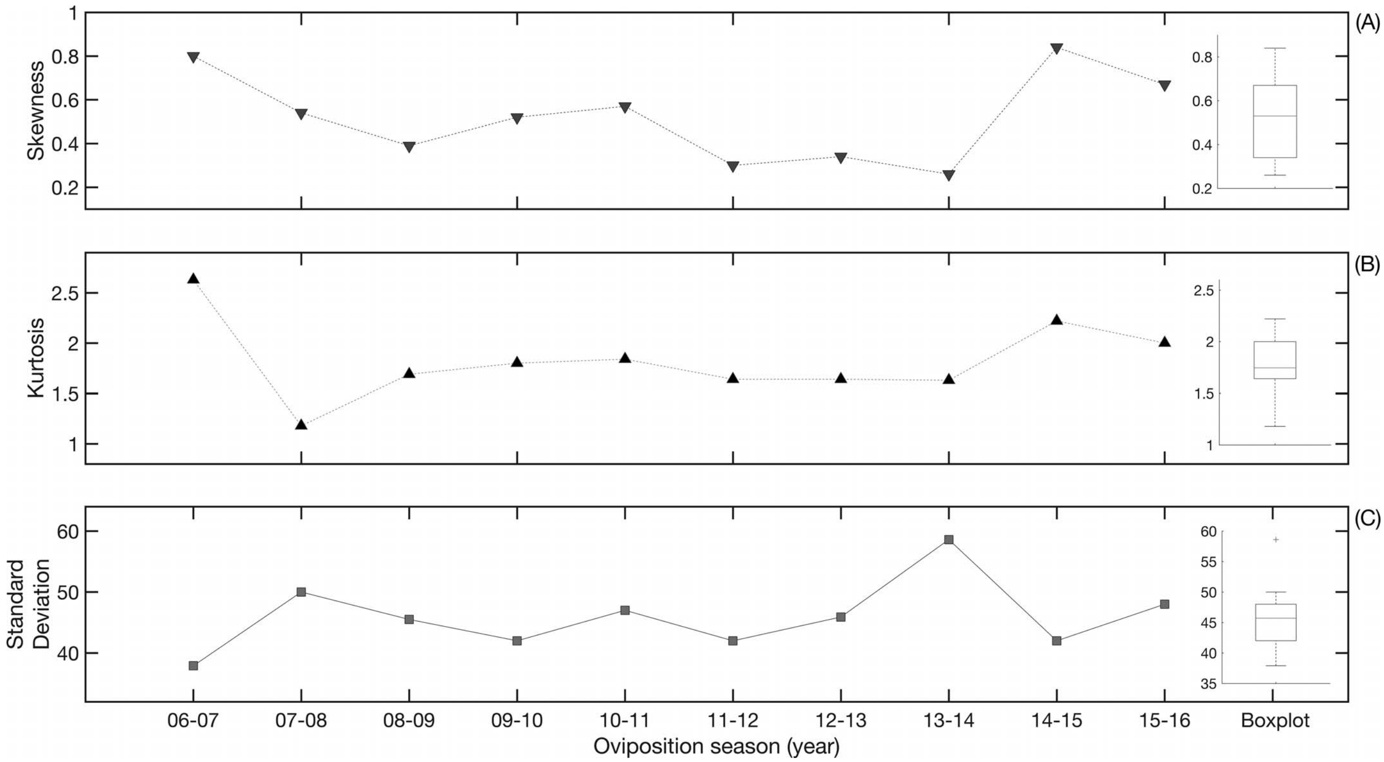

FIG. 4. Properties of the distribution of marine turtle beach nesting visitations. We refine the statistical analysis of the data exploring the SD, the skewness, and the kurtosis of the fitted Gaussian. In all cases, the shape of the curve does not suffer significant transformation along the reproductive seasons. This figure points out to a stable form of the distribution along the seasons. This analysis reinforces that only the peak of the distribution is changing along the seasons, not the statistical distributions.

related to some bias in the data collection. To answer this question, we calculated three moments of the distribution: the SD, the skewness, and the kurtosis. The most important result shown in Figure 4 is that despite the shift of nesting season peak, the overall nesting distribution remains constant. The main parameters of the distribution do not present a significant change with time in the studied period. The same histogram that showed a significant trend in the peak of nesting season (Fig. 3) also showed trends neither for SD ($R = 0.34$, df $= 8$, $P = 0.33$) nor for skewness ($R = -0.05$, df $= 8$, $P = 0.89$) nor kurtosis ($R = 0.29$, df $= 8$, $P = 0.41$). These last results indicate that the shape of the statistical distribution remains stable (dispersion, kurtosis, and asymmetry) without tendencies throughout time.

The SST in the Hawksbill Turtle nesting area shows a typical annual oscillatory pattern, with temperatures ranging from 25°C to 29°C. In Figure 5, we show the monthly SST average from 1980 to 2015, and we indicate the months of maximal average temperature for each year. In addition, we observe a warming trend in the monthly SST average (F test: $F = 7.21$, df $= 418$, $P = 0.011$). In addition, the annual monthly maximal SST undergoes a shift from March to April, and the F test also shows a significant trend ($F = 5.34$, df $= 33$, $P = 0.021$).

The observed SST warming in the Hawksbill Turtle nesting area is not homogeneous along the months. Figure 6 shows the SST for all months in the studied period. The increase in the SST is more evident in April, May, and June. For each panel, the averaged SST is indicated with a dashed line. We note a positive slope of the fitting line, indicating an SST warming for all months. However, a significant trend is verified in March, April, May, June, and July, with a significance level of 5% (Mann–Kendall test). Figures 5 and 6 point out a tendency of temperature peaks to move from March to April as well as a significant warming in these months.

Discussion

In this study, we evaluated the peak of nesting season for Hawksbill Turtle in the southern coast of Rio Grande do Norte, Brazil, during 10 reproductive seasons. We found evidence of a temporal shift in the peak of nesting season of 1.2 ± 0.44 days/yr. The observed peak of nesting season ranged from 12 February to 2 March. In the Southern Hemisphere, this period corresponds to the end of summer; therefore, the turtles are moving their nests with milder temperatures. Once the average incubation period of this species is 56 days (Robins, 2003), the tendency is favorable for nesting in colder and rainy periods of autumn in this region (Marcovaldi et al., 2014). Therefore, the observed behavioral shift of Hawksbill Turtle compensates the climate change tendency of increasing temperatures of both the ocean water and the atmosphere (Abraham et al., 2013; IPCC, 2014).

We could speculate that the observed tendency of the Hawksbill Turtle to move the nests to colder temperatures is a species adaptive strategy to preserve the sex ratio. Indeed, marine turtles show a temperature-dependent sex ratio (Kamel and Mrosovsky, 2006), with higher temperatures increasing number of female offspring (Mrosowsky, 1994). Previous studies have already drawn attention to the complex topic of sex ratio and global warming (Marcolvaldi et al., 2014). To keep the temperature-dependent sex ratio in a good proportion, the turtles should either move the nesting location to higher

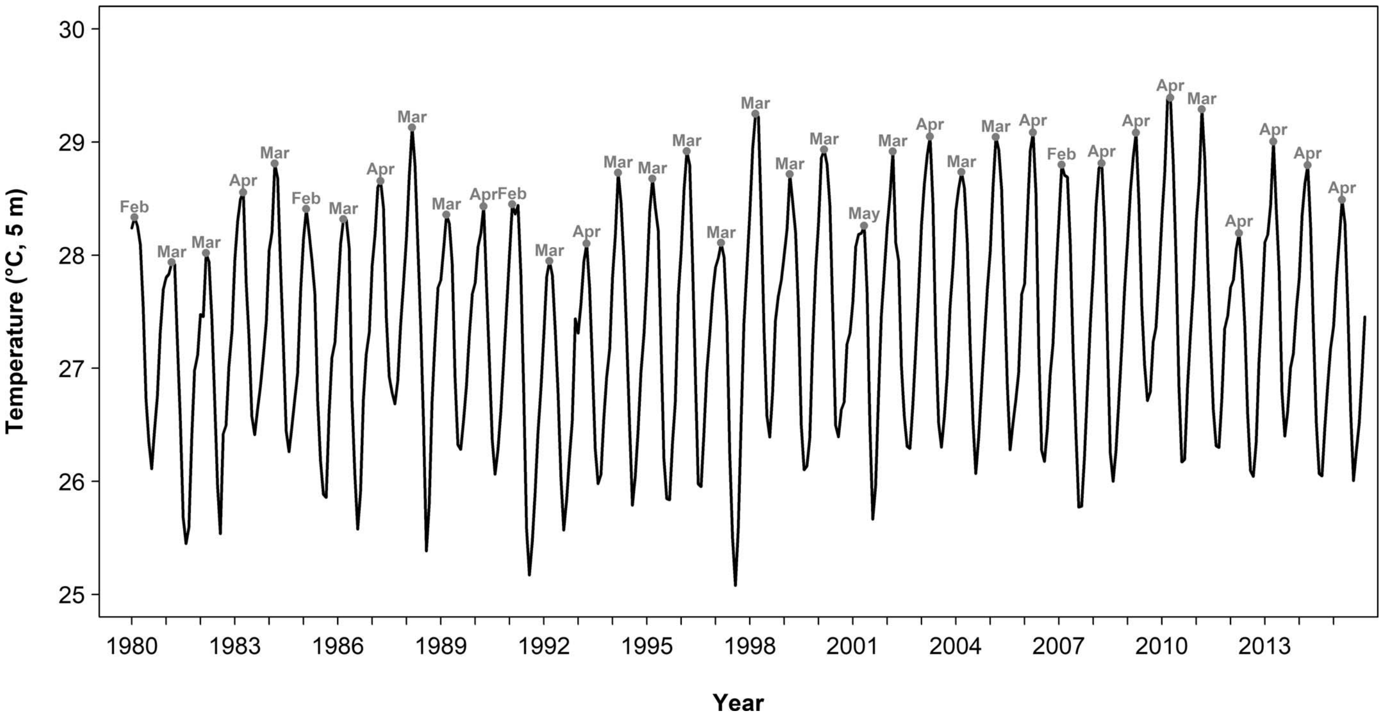

FIG. 5. Average sea surface temperature, at 5-m depth, in the area of the nesting site. The month of the maximal average temperature per year and a temperature peak shift from March to April are shown.

latitudes or shift the oviposition periods to autumn or winter. This last alternative agrees with our observations.

Most of the studies on climate change and biology are related to phenology, that is, biological features depending on the season. In fact, a huge number of studies point out changes in phenomenological features related to an increase in temperature. The examples range from early plant flowerings to bird migration, early chorus of amphibians, first butterfly appearance in spring, and phytoplankton bloom, among others (Hughes, 2000; Wuethrich, 2000; Walther, 2015). Thus, our work

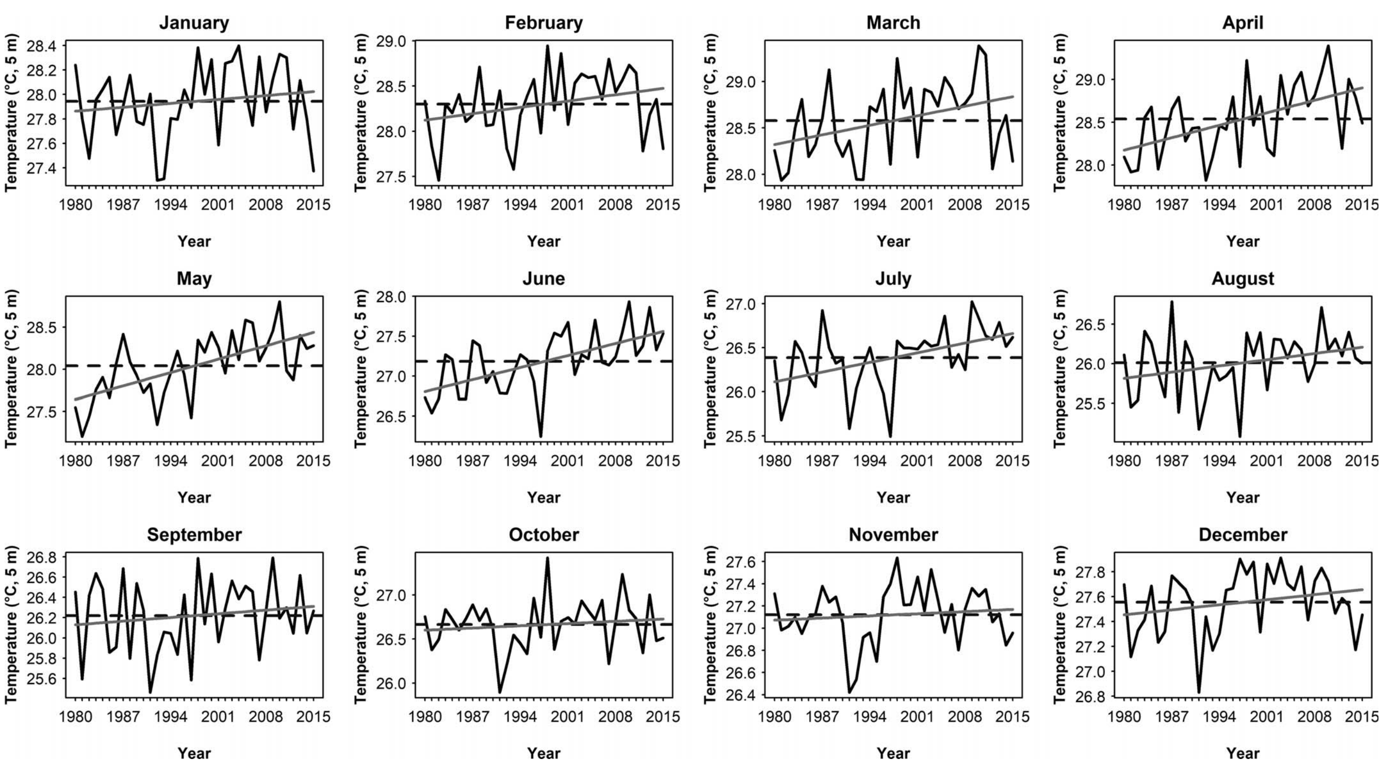

FIG. 6. Monthly average sea surface temperature, illustrating the trend in the sea surface temperature for each month from 1980 to 2015. The average temperature for the full time period is indicated by the dashed baseline. The continuous line is the fitted trend, indicating a positive slope. However, a significant P value (<0.05) is found in March, April, May, June, and July.

follows most papers situated in the interface between climate change and biology. However, we notice that the most studies in this field refer to arctic and temperate zones, not to tropical biomes (Parmesan, 2006). The reason for insufficient evidence of biotic changes related to climatic changes in the tropics is related to the complexity of tropical ecosystems (Pan et al., 2013) or to the negative effect of deforestation, which is difficult to separate from the climatic impact (Parmesan, 2006).

We note that the rate associated to phenomenological changes found in our work is very high compared with other measurements in terrestrial ecosystems. We cite, for example, lengthening of the growing season by 1.1–4.9 days/decade in Europe (Menzel et al., 2003), the migrant birds that have advanced their passage by 0.5–2.8 days/decade in the U.K. (Huppop and Huppop, 2003), and the advance of mean laying date of the first clutches in the U.K. by 3.7 days/decade (Crick et al., 1997). Our estimation of time advance of marine turtle nest is approximately five times greater than that of these cited works. We may understand the discrepancy by the insufficient statistics. Indeed, the cited works have at least three times larger time samples than our current work, but our work is focused on marine ecosystems that are understudied (Parmesan, 2006).

Regarding the observed delay in oviposition, the tendency of shifting periods to adapt to climate change is widespread. A global meta-analysis has found a mean advance of 2.3 days/decade among 677 species averaged over the past 4 decades (Parmesan and Gary, 2003). Otherwise, the present trend of species' responses to change in climatic conditions should not be linearly extrapolated to future years. Indeed, at a certain point, some saturation effect should appear (Walther et al., 2002). In fact, there is some evidence and theoretical predictions that a combination of intrinsic processes of the ecosystem as well as abiotic processes result in nonlinearities that should affect the linear trend (Stenseth et al., 2002).

The warming SST trend in the studied Hawksbill Turtle nesting area was observed in a recent study that investigated the effect of global warming in the oceans' coasts (Varela et al., 2018). Varela et al. (2018) compared the SST of the past 30 yr and pointed out a warming in this coastal region. We call attention that two tendencies were simultaneously observed in our study: the SST warming and the shift of the peak of maximal temperatures from March to April. These two results seem to be correlated with the later nesting of the Hawksbill Turtle in the area.

Beyond the climatic context, our results are relevant in a conservation perspective. Considerable effort is being carried out in the conservation of marine turtles worldwide (Marcovaldi and Marcovaldi, 1999). In particular, the Hawksbill Turtle is an endangered species that has an important nesting site in northeastern Brazil (Santos et al., 2013). Several groups, such as nongovernmental organizations, patrol and monitor beaches to help marine turtles to maximize their offspring. To optimize their work in patrolling beaches, the stakeholders are interested in the time of the year when marine turtles are in the beach; this knowledge will potentially save time and labor in conservation efforts.

Acknowledgments.—Created 35 yr ago, PROJETO TAMAR results from the sum of efforts of Fundação Pro-TAMAR and Centro TAMAR ICMBio and is officially sponsored by Petrobras. Data collection was authorized by ICMBio, through special license number 14122, issued by Biodiversity Authorization and Information (SISBIO). We thank the Pipa Ecological Sanctuary and all the field volunteers for their help. We also gratefully acknowledge the financial support of Conselho Nacional de Desenvolvimento Científico e Tecnologico, Brazil.

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Accepted: 11 April 2020.
Published online: 4 November 2020.