An empirical relationship between sea surface temperature and massive stranding of the loggerhead turtle (Caretta caretta) in the Gulf of Ulloa, Mexico

Article *in* Latin American Journal of Aquatic Research · March 2020

DOI: 10.3856/vol48-issue2-fulltext-2348

3 authors:

César A. Salinas Zavala
Centro de Investigaciones Biológicas del Noroeste

María Verónica Morales Zárate
Centro de Investigaciones Biológicas del Noroeste

Raul Octavio Martinez Rincon
Centro de Investigaciones Biológicas del Noroeste

Latin American Journal of Aquatic Research, 48(2): xx-xx, 2020
DOI: 10.3856/vol48-issue2-fulltext-2348

Research Article

An empirical relationship between sea surface temperature and massive stranding of the loggerhead turtle (*Caretta caretta*) in the Gulf of Ulloa, Mexico

César A. Salinas-Zavala[1], María V. Morales-Zárate[1] & Raúl O. Martínez-Rincón[2]
[1]Centro de Investigaciones Biológicas del Noroeste (CIBNOR), La Paz, B.C.S, México
[2]Consejo Nacional de Ciencia y tecnología (CONACyT) comisionado al CIBNOR
La Paz, B.C.S, México
Corresponding author: María V. Morales-Zárate (mzarate04@cibnor.mx)

ABSTRACT. Two mass stranding events of loggerhead sea turtles (*Caretta caretta)* in the vicinity of the Gulf of Ulloa, Baja California Sur, Mexico, were analyzed during 2003-2006 and 2012-2014. Stranding events were related to the accumulation of consecutive days with lower sea surface temperature (SST) series for the corresponding periods using Pearson correlations. Our results showed that in both periods, a significant cross-correlation was observed between mass stranding and accumulation of consecutive days with temperatures below 18, 17, and 16°C, with a time lag of three to five months. Numerical evidence supports the hypothesis that although the loggerhead turtle mortality is caused by multiple factors under extreme cold events, the environment turns markedly unfavorable for these organisms. Side-effects on health and swimming behavior of the species *C. caretta*, compromise their ability to avoid obstacles or flee from predators, thus increasing their vulnerability to sickness or lethargy, and possibly leading to the massive stranding of weakened individuals or dead bodies to the beaches of the Gulf of Ulloa. Hence, while SST may not be the direct cause of turtle mortality, it can be a determining factor for the survival of this species.

Keywords: sea turtle; massive stranding; cold stunning; Pearson correlation; southern California

INTRODUCTION

Frequent mass stranding events of sea turtles on beaches or near the coast have been reported around the world (Davenport, 1997; Tarifeño, 2004; Heithaus *et al*., 2008; Anderson *et al*., 2011; Orsulak, 2014). When these organisms expire, get injured, or weakened, they regularly strand on beaches or in shallow waters. In 2001, a total of 360 sea turtles were stranded off the coast of North Carolina, and in the following year, the number increased to 473 stranded turtles (Orsulak, 2014). A similar phenomenon was observed in the Gulf of Ulloa, on the western coast of the Baja California Peninsula, Mexico, during the periods from 2003-2006 and 2012-2014. Current hypotheses regarding these events indicate that given the overlapping areas used by loggerhead turtles *Caretta caretta* and coastal fishers, coastal fishing may be one of the leading causes of incidental mortality in this species (Peckham *et al*., 2007); however, since loggerhead turtles are ecto-therms and that temperature plays a crucial role in their physiological condition, we suggest that if the environment is unfavorable (low temperatures) for several consecutive days, the turtle's physiological condition will be increasingly vulnerable.

Sea turtles cannot regulate their body temperature and are thus dependent on outside sources for heat. Loggerhead turtles appear not to need to stay close to the sea surface to absorb heat radiation (Sato *et al*., 1995), but they need to stay in warm waters for maintaining their vital functions, which is why they are always moving, looking for water masses with the proper temperature. In general, optimal temperatures for sea turtles range from 18.3-23.8°C; (Davenport, 1997; Polovina *et al*., 2004; Abecassis *et al*., 2013) although they can survive in water temperatures down to 10°C. When the temperature is below the optimum range, their locomotor system becomes deficient, reducing their ability to move (lethargy) considerably and increasing their vulnerability to diseases or attacks by potential predators (Birse & Davenport, 1987; Davenport, 1997; Heithaus *et al*., 2008; Anderson *et al*.,

Corresponding editor: Joanna Alfar

2011). Likewise, if these conditions persist, their immune system tends to become depressed, making them more vulnerable to infections that eventually may lead to health complications, such as pneumonia (Tarifeño, 2004).

According to Birse & Davenport (1987), environments with temperatures close to 20°C impair the ability of these organisms to eat; temperatures below 15°C compromise their mobility, and sustained temperatures below 10°C can result in coma and subsequent death (Davenport, 1997), particularly if the water temperature drops too quickly, "cold-stunning" may occur (Schwartz, 1978; Meylan & Sadove, 1986; Shaver, 1990; Bentivegna *et al*., 2002; Anderson *et al*., 2011). Turtles that are already weakened or dead tend to be dragged by drifting currents towards the coast (Heithaus *et al*., 2008; Anderson *et al*., 2011). Adult individuals are more resistant to these thermal environmental conditions since they possess a particular endothermic ability because of their internal muscle activity, but sub-adult individuals are the most dramatically affected by decreases in temperature (Milton & Lutz, 2002).

Given the previous information and the oceanographic characteristics of the Gulf of Ulloa, mainly defined by seasonal ocean upwelling phenomena (Sverdrup *et al*., 1942; Nelson, 1977; Huyer, 1983; Lynn & Simpson, 1987; Bakun, 1996) that reduce the sea surface temperature to 15°C from April to June (Lynn, 1967), this study conducted a primary analysis based on the physiological theory of thermal control of the reptilian body to establish a possible empirical relationship. This empirical relationship was established between the accumulated number of days over which the sea surface temperature (SST) remained below the reference temperatures (<18, <17 and <16°C) during each month and the number of turtles stranded by month documented during the two periods. The conservative condition of the temperature allowed us to consider that if the cold days persisted, the water temperature would be lower and lower. This situation would lead turtles to unfavorable environments with side effects for health and swimming behavior, decreasing their ability to avoid obstacles or flee from predators, thus increasing their vulnerability to diseases or lethargy and leading to the massive stranding of weakened individuals or dead bodies on the beaches of the Gulf of Ulloa of the Baja California Peninsula. Our approach suggests that although the SST is not the direct cause of death for the turtles, it can be a determining factor for the survival of this species.

MATERIALS AND METHODS

Study area

According with del Monte Luna *et al*. (2007), the Gulf of Ulloa (GU; Fig. 1) is in the austral edge of the California Current System (CCS). The CCS transports sub-arctic water from the Pacific to the Equator, from around 48°N latitude to 25°N latitude, and presents a mixture of water from the central North Pacific which penetrates to the system from the west. Seasonally, wind-driven upwellings incorporate into the surface nutrient-rich and cold subsurface waters and then are expelled offshore all along the coast.

Sources of information

Monthly records of turtles stranding in the Gulf of Ulloa were analyzed for the periods: January 2003 to December 2006 (Fig. 2a) and April 2012 to November 2014 (Fig. 2b).

Information from the first period was obtained from Lluch-Cota *et al*. (2014). For the second period, stranding records were collected by the Procuraduría Federal de Protección al Ambiente (PROFEPA, Federal Bureau for the Protection of the Environment) in Mexico and the Grupo Tortuguero de las Californias (GTC). Information from April 2012 was comprised of the cumulative data from January-April of that year. Because the data came from those different sources, the periods were analyzed independently.

Daily and monthly SST records were obtained from satellite images using the MODIS-Aqua sensor with a 4 km spatial resolution. The satellite images were obtained from the NASA web server (http://ocean-color.gsfc.nasa.gov/). All satellite images were processed using the raster library (Hijmans, 2019) of the R programming language (R Core Team, 2015). This process consisted of three steps: (1) importing and combining all daily or monthly SST images; (2) cropping all SST images using defined polygons; and (3) averaging all pixels with SST values for each date and polygon. For extracting SST time series, polygons with the highest occurrence of turtles reported by Peckham *et al*. (2007) was used as a reference. According to these authors, 75% of loggerhead turtle (*Caretta caretta*) data occurred in the selected polygons, which were obtained using satellite telemetry on the western coast of Baja California Sur (mainly in the Gulf of Ulloa) during 1996-2005. Our polygons were sorted from north to south as 75.a, 75.b, 75.c, and 75.d.

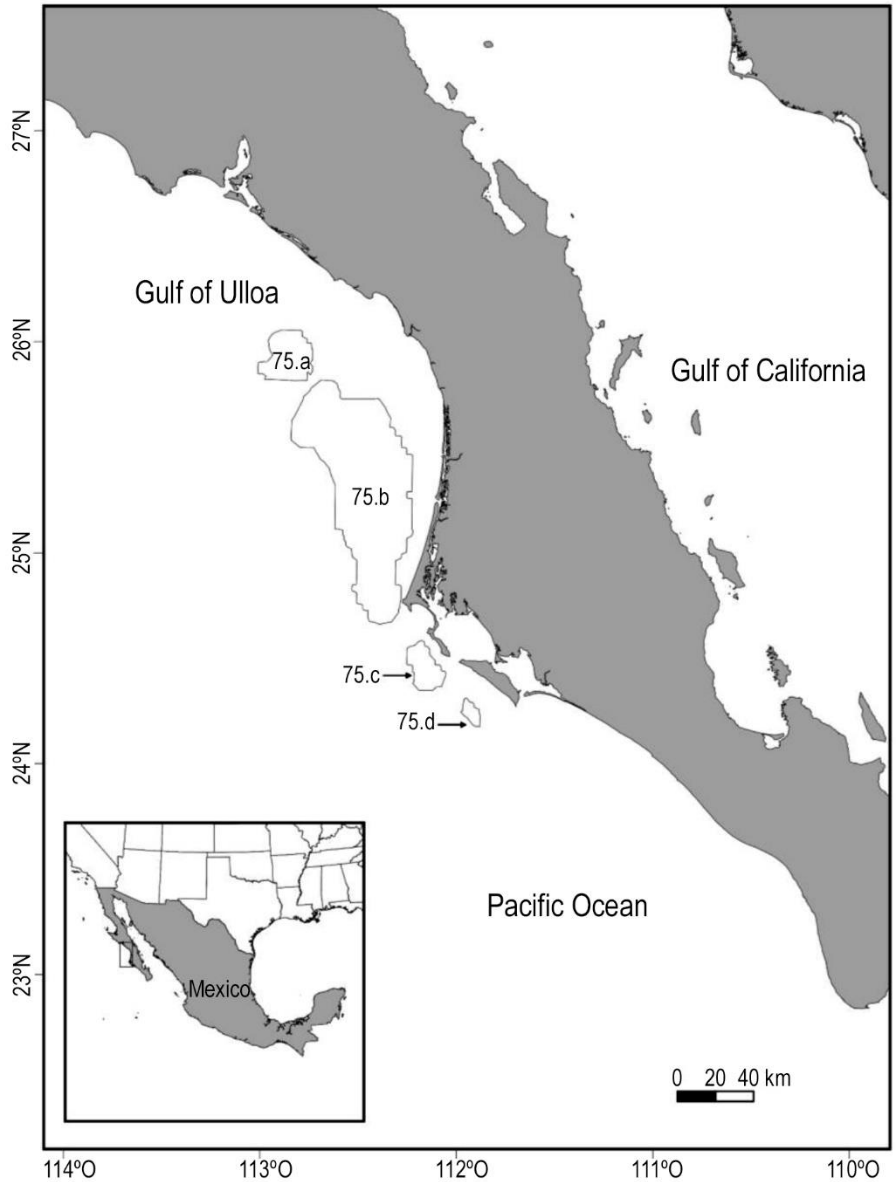

Figure 1. The study area for sea turtle stranding showing referenced polygons used to extract sea surface temperature (SST) series (modified from Peckham *et al.*, 2007). The area in km^2 for each polygon is 717; 5,395; 400 and 104 for the polygons 75.a, 75.b, 75.c and 75.d, respectively.

SST analysis and empirical relationships

From satellite information, primary analysis of monthly average temperature was performed by period, grouped by each polygon concerning the reported stranding events. Subsequently, after considering the optimum SST interval for this species, as reported by different authors (18-23°C; Birse & Davenport 1987; Polovina *et al.*, 2004; Abecassis *et al.*, 2013), the number of days with temperatures lower than the reported limit was calculated for each polygon. Our reference temperatures were <18, <17 and <16°C, for each month of the periods analyzed (2003-2006 and 2012-2014); Pearson cross-correlation tests were performed between the number of days below the reference temperature and the number of stranded turtles for each event using Equation 1.

$$Px, y_i = \frac{\sigma x y_i}{\sigma x \sigma y_i} \quad (1)$$

where Px,y_i is the Pearson correlation of x with reference to y of the month i ($i = 0, 1, 2, \ldots, 6$), σxy_i is the covariance of (x, y_i) and σx σy_i are standard deviations of x and y_i.

The Pearson tests helped determine whether a delayed relationship existed between the number of days

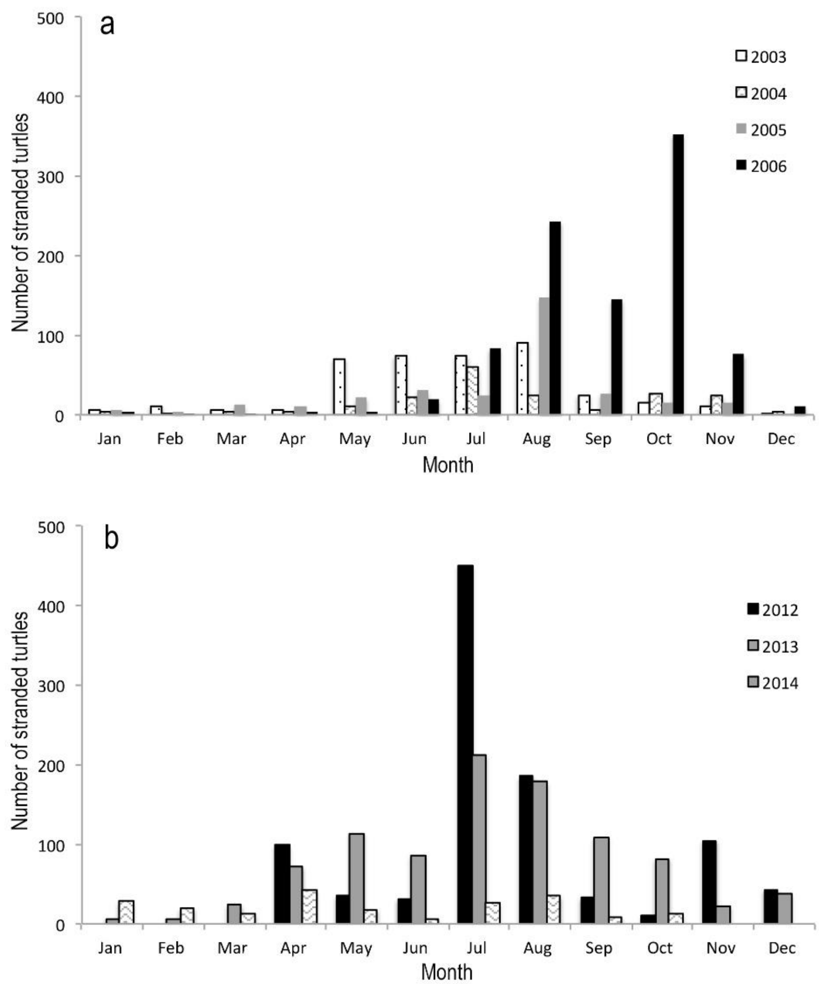

Figure 2. Loggerhead sea turtle *Caretta caretta* stranded. Stranding events recorded in the vicinity of the Gulf of Ulloa, Mexico from a) 2003 to 2006, and b) 2012 to 2014.

below the reference temperature and the number of stranded turtles; in case a relationship was found, the most significant delays could be determined for each case. Negative delays were not considered due to a lack of biological significance.

Exponential correlations between the variables were performed to obtain the coefficient of determination and the proportion of variation of the results that could be explained. The independent variable was the number of days with temperatures below the reference temperatures <18, <17 and <16°C), and the dependent variable was the number of stranded turtles (with the delay of the highest significance found with Pearson cross-correlation tests). The exponential function was chosen because the behavior of the postulated empirical relationship had a limit on the abscissa. For the first period (2003-2006) the limit was 48 months, and 36 months for the second period (2012-2014).

Moreover, temperature anomalies in the area were calculated to evaluate periods of sustained low temperature using the following equation:

$$SSTa_{ij} = SST_{ij} - \overline{SST_i} \quad (2)$$

where $SSTa_{ij}$ represents temperature anomalies of the month *i* in year *j*, SST_{ij} is the average temperature value of month *i* in year *j* and $\overline{SST_i}$ is the average temperature value of month *i*. This difference in measurement represents the variation in Celsius degrees of the SST observed for the monthly average for each period 2003-2006 and 2012-2014.

RESULTS

We obtained the time series of the number of stranded turtles recorded in the Gulf of Ulloa compared with the SST monthly average for the study area for 2003-2006 (Fig. 3a) and 2012-2014 (Fig. 3b). While the relation-

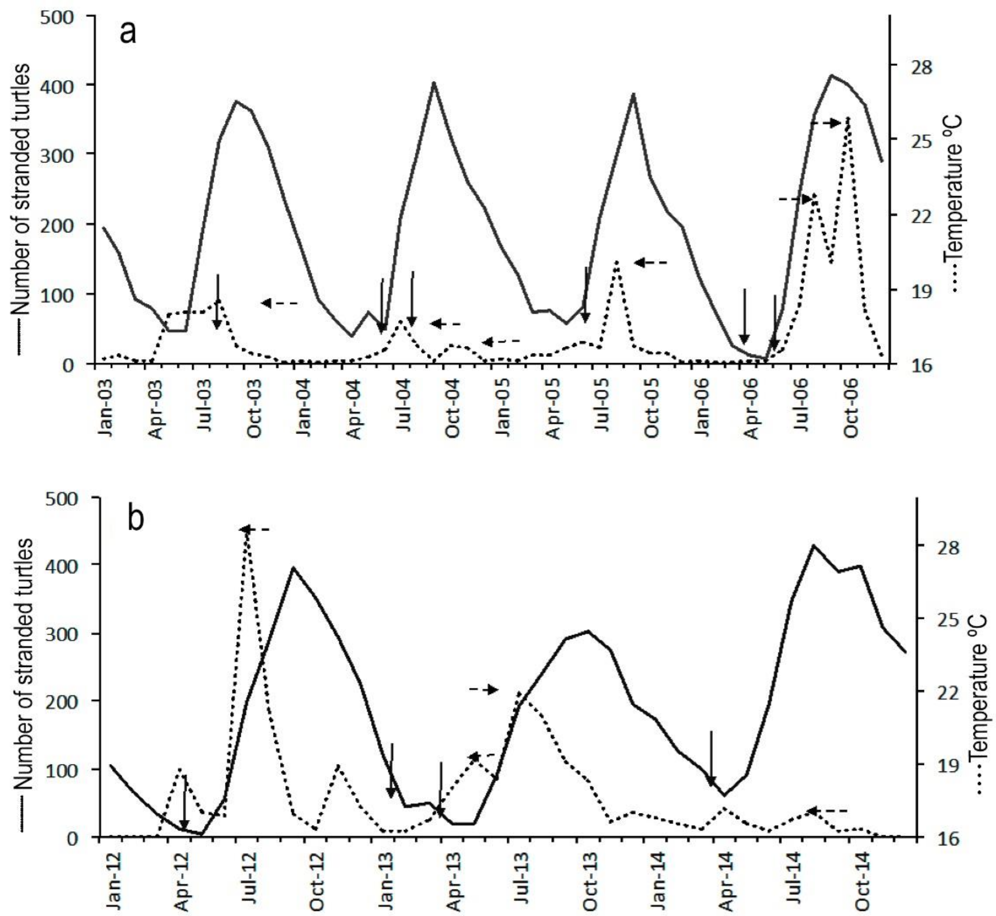

Figure 3. Average monthly temperature *vs.* loggerhead sea turtle *Caretta caretta* stranding around the Gulf of Ulloa. Vertical arrows indicate the conditions of lower temperature, while the horizontal arrows indicate stranding values corresponding to the previous thermal conditions, suggesting a three to five-month delay; a) 2003 to 2006 period, and b) 2012-2014 period.

ship between the maximum number of sea turtle stranding and the temperature values was not clear, a possible correspondence was observed between the maximum number of stranding events and prior sustained low temperatures. As such, SST from March-June for both periods had the lowest values compared with other periods of the year. The periods of maximum stranding corresponded to those of sustained cooling, which was particularly evident during the first period in 2006 and the second of 2012, with a consistent delay from three to five months for both cases. During the 2003-2006 period, a higher number of stranding events was reported than in 2012-2014 (Figs. 3a-b).

For the first period, observed in Table 1, the maximum percentage of days with temperatures lower than 18°C corresponded to May 2006, with percentages higher than 80% in polygons 75.a and 75.b, and with percentages higher than 70% in polygons 75.c and 75.d. These conditions were sustained from April of the same year for the entire area and from March for 75.a, 75.b and 75.c, with 2006 being the coldest year of the period. The only year with a high percentage of days with SST <16°C was 2006, during April and May in polygon 75.a, and May for polygons 75.c and 75.d. For previous years (2003-2005), the coldest months were May and June (Table 1).

Table 2 shows that the percentage of days with SST <18°C was the highest during April 2012 for all four polygons, with values of ≥60% of days with temperatures <18°C. It is also worth noting that during the previous month (March), these same conditions prevailed in polygons 75.a, 75.b and 75.c, of which polygon 75.b (the largest) was cold for almost the entire month (90%) having temperatures <18°C. Cold conditions were persistent in polygons 75.a and 75.b, with more than 50% of days with SST <17°C and with more than 30% in all polygons during March and April, while the percentage of days with SST <16°C was even

Table 1. Percentage of days with temperatures below the reference temperature (<18, <17 and <16°C) for each polygon within the study area during 2003-2006. Underline and bold numbers ≥50; only underline numbers ≥30%. The months that had zero days for the whole period were omitted.

	Year	2003				2004				2005				2006			
	Polygon	75.a	75.b	75.c	75.d	75.a	75.b	75.c	75.d	75.a	75.b	75.c	75.d	75.a	75.b	75.c	75.d
<18°C	Jan	0	0	0	0	0	0	0	0	6	3	0	0	13	16	0	0
	Feb	4	0	0	0	46	32	18	11	0	4	0	0	**68**	43	36	11
	Mar	35	23	19	16	**58**	**52**	42	32	42	32	**55**	32	**68**	**71**	**65**	48
	Apr	47	**50**	10	10	**60**	**67**	40	47	**50**	**53**	13	10	**70**	**73**	**67**	**60**
	May	**68**	**61**	**65**	**65**	45	23	**58**	**58**	**61**	**58**	45	42	**81**	**81**	**74**	**71**
	Jun	**87**	**57**	43	**53**	**77**	33	**80**	**80**	**63**	23	30	43	27	17	**50**	47
<17°C	Jan	0	0	0	0	0	0	0	0	3	3	0	0	3	3	0	0
	Feb	4	0	0	0	18	4	7	7	0	0	0	0	32	21	4	0
	Mar	13	3	6	3	32	23	3	13	13	6	16	3	**61**	**65**	42	19
	Apr	27	27	0	0	40	37	27	20	30	13	0	0	**63**	**60**	**50**	**50**
	May	48	23	19	19	35	3	16	29	39	23	6	13	**65**	39	**68**	**71**
	Jun	**63**	13	40	40	37	13	43	40	27	7	17	23	3	7	37	30
<16°C	Jan	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
	Feb	0	0	0	0	4	0	0	7	0	0	0	0	18	4	4	0
	Mar	3	0	3	0	3	3	0	3	3	0	3	0	29	29	16	3
	Apr	7	10	0	0	17	10	0	10	7	7	0	0	**57**	17	20	23
	May	3	6	3	0	13	3	0	3	3	3	0	3	32	13	45	**61**
	Jun	0	7	10	0	7	10	7	7	7	0	10	7	3	3	20	17

Table 2. Percentage of days with temperatures below the reference temperature (<18, <17 and <16°C) for each polygon within the study area during 2012-2014. Underline and bold numbers ≥50; only underline numbers ≥30%. The months that had zero days for the whole period were omitted.

	Year	2012				2013				2014			
	Polygon	75.a	75.b	75.c	75.d	75.a	75.b	75.c	75.d	75.a	75.b	75.c	75.d
<18°C	Jan	26	19	10	3	32	42	3	6	10	0	0	3
	Feb	**61**	**61**	32	32	**57**	**64**	29	29	4	4	7	4
	Mar	**77**	**90**	**61**	48	45	**68**	29	32	32	23	3	0
	Apr	**70**	**73**	**60**	**50**	**70**	**83**	37	40	**50**	43	37	37
	May	45	**55**	32	29	**65**	**55**	32	29	**55**	19	39	13
	Jun	43	37	23	10	30	27	13	3	0	0	0	0
<17°C	Jan	10	6	0	3	6	16	3	6	0	0	0	3
	Feb	32	21	18	21	39	43	7	11	4	4	0	4
	Mar	**71**	**71**	48	19	35	48	13	3	13	10	0	0
	Apr	**70**	**63**	37	43	**53**	**60**	27	30	27	13	13	23
	May	45	39	29	29	48	23	32	29	26	0	6	3
	Jun	27	20	10	3	17	7	3	3	0	0	0	0
<16°C	Jan	0	3	0	0	3	6	3	0	0	0	0	0
	Feb	14	0	4	0	7	18	7	7	0	0	0	0
	Mar	45	19	19	3	3	6	0	0	6	3	0	0
	Apr	37	7	10	27	17	23	7	13	10	3	0	3
	May	39	6	13	16	16	6	6	10	3	0	3	0
	Jun	20	3	0	3	0	0	0	0	0	0	0	0

observed for polygon 75.a (northernmost) from March to May 2012.

For 2013, the maximum number of days with SST values <18°C also occurred in April, with a similar pattern as 2012 but with a lower percentage of days per month, with the percentage of days that had SST values of <16°C not exceeding 23%. April had the highest percentage of days lower than 18°C for 2014; finally, in May, the percentage of days less than 16° and 17°C was lower with 10%, while the maximum was 27% for polygon 75.a.

The Pearson cross-correlation tests were used to determine whether a correlation was found between the independent variable (number of days with temperature <18, <17 and <16°C by polygon) and the dependent variable (monthly accumulated sea turtle stranding record), showing a statistically significant correlation (SSC, $P < 0.05$) between both variables, with delays ranging from two to six months (Figs. 4a-b) and consistent for both periods analyzed. For the 2003-2006 period (Fig. 4a), the highest frequency of maximum SSC could be observed with a five-month delay for SST <16°C, except for polygon 75.a, which had its most SSC value with a six-month delay between low SST conditions and turtle stranding records. For the second period, the highest SSC was a four-month delay, apart from polygon 75.d for SST conditions <17°C and <16°C, which had higher SSC values with a three-month delay. These results indicated that for both periods, peak stranding events occurred four or five months (on average) after the region showed sustained low temperatures.

Figures 5a and 5b show the exponential relationship analyzed between the number of days with low SST (<18, <17 and <16°C) and the number of stranded loggerheads (*Caretta caretta*) recorded for the 2003-2006 and 2012-2014 periods in the Gulf of Ulloa, considering delays corresponding to the best cross-correlation coefficient value. This relationship showed that the coefficient values of determination (R^2) were significant (Figs. 5a-b). In other words, loggerhead stranding in the Gulf of Ulloa could be explained by the number of days with sea surface temperatures <18, <17 and <16°C, with a delay from four to five months. It is worth to point out that as the number of days with SST below these temperatures increased, the higher the probability of loggerhead stranding occurred four or five months later along nearby coasts.

DISCUSSION

Because physiological parameters are directly related to persistence in the conditions of any environmental variable, temperature, in particular, is one of the environmental factors with the most significant influence on marine life, as it determines the rates of all biological processes, accelerating the rate of biochemical reactions as temperature increases or delaying them if the temperature decreases. Based on reports in the literature, turtles are mostly affected by a sudden shift to low temperatures, *e.g.*, a rapid drop on orders from 5 to 10°C would be fatal for turtles to remain under such conditions for prolonged periods (Tarifeño, 2004).

As shown in Tables 1 and 2, the number of days with SST values less than 18°C was higher during 2006 and 2012 from February to June. During 2006, in particular, this thermally unfavorable condition for loggerheads represented more than 60% of the period analyzed (February-June). Likewise, the same pattern was observed in 2012 with unfavorable low-temperature conditions sustained during more than 60% of the period (February-June 2012).

The result of exponential relationships (Figs. 5a-b) is particularly important given that in marine animals, the effects of temperature changes are more drastic than in terrestrial animals due to the physical characteristics of water (high heat capacity and greater density). Supporting this information, the Multivariate ENSO Index (MEI) from the National Oceanic and Atmospheric Administration (NOAA) suggested a moderate La Niña conditions during most of 2014 in the eastern Pacific Ocean; according to the same source, 2005-2006 and 2011-2012 were La Niña years, so it could be presumed that in those years, turtles in the Gulf of Ulloa experienced abnormally colder conditions than those prevailing in normal years, increases the chances of stranding.

For sea turtles, which are ectothermic animals, any heat generated by their metabolic activity (endogenously) is permanently transferred by water conduction, cooling their body until it reaches thermal equilibrium with the aquatic environment. When an individual detects a change in the environment, the type of adaptive response depends on the intensity and the duration of the change; intensity refers to the absolute difference between the pre-existing and new condition and duration corresponding to the time the change lasts either short term (acute effect) or long term (chronic effects; Tarifeño, 2004). The speed with which individuals respond to environmental changes (response rate) is also important, and it refers to the speed at which the organism can respond to change through either movement or physiological compensation. Environmental changes are generally found to be more stressful if they occur rapidly (abrupt change) and if the individual's response rate is low (limited locomotion or low metabolism), compared with gradual changes that take more time so that the individual can adapt to the new environmental conditions (Tarifeño, 2004).

Because this study was done based on data from sea turtle stranding reported by two different sources, no information was obtained concerning turtle's body conditions in which the remains of stranded turtles were found; however, in the study of Lluch-Cota *et al.* (2014),

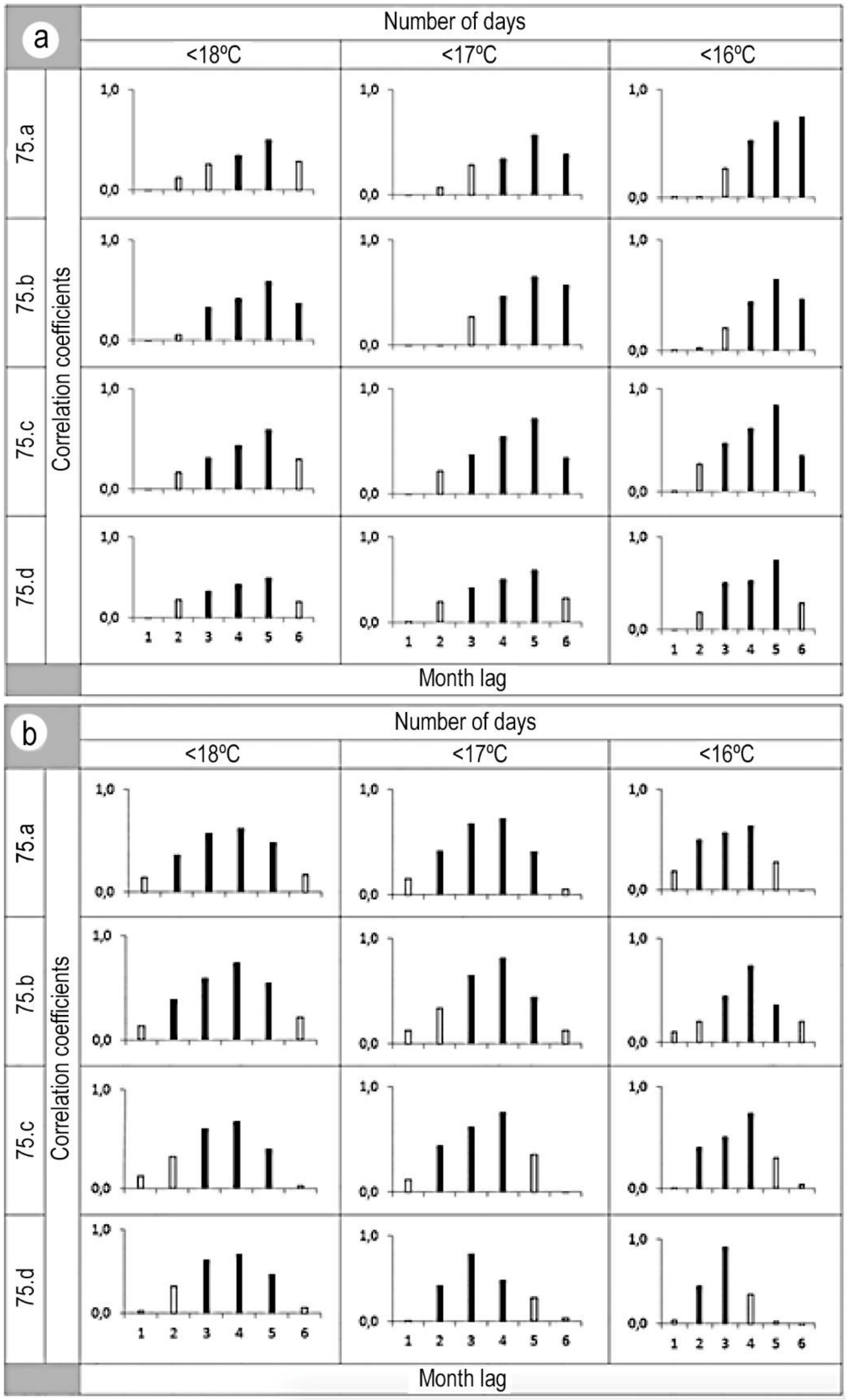

Figure 4. Pearson correlation coefficient (cross-correlation) values for each combination of reference temperature (<18, <17 and <16°C) by polygon (75.a, 75.b, 75.c, 75.d) for the a) 2003 to 2006 and, b) 2012 to 2014 periods. Black bars indicate significant values of $P < 0.05$, while white bars indicate values of $P > 0.05$.

authors reported that during 2013-2014 monitoring, they were able to perform necropsies to seven organisms of *Caretta caretta*, one of which was found floating 45 nautical miles north of the Gulf of Ulloa and

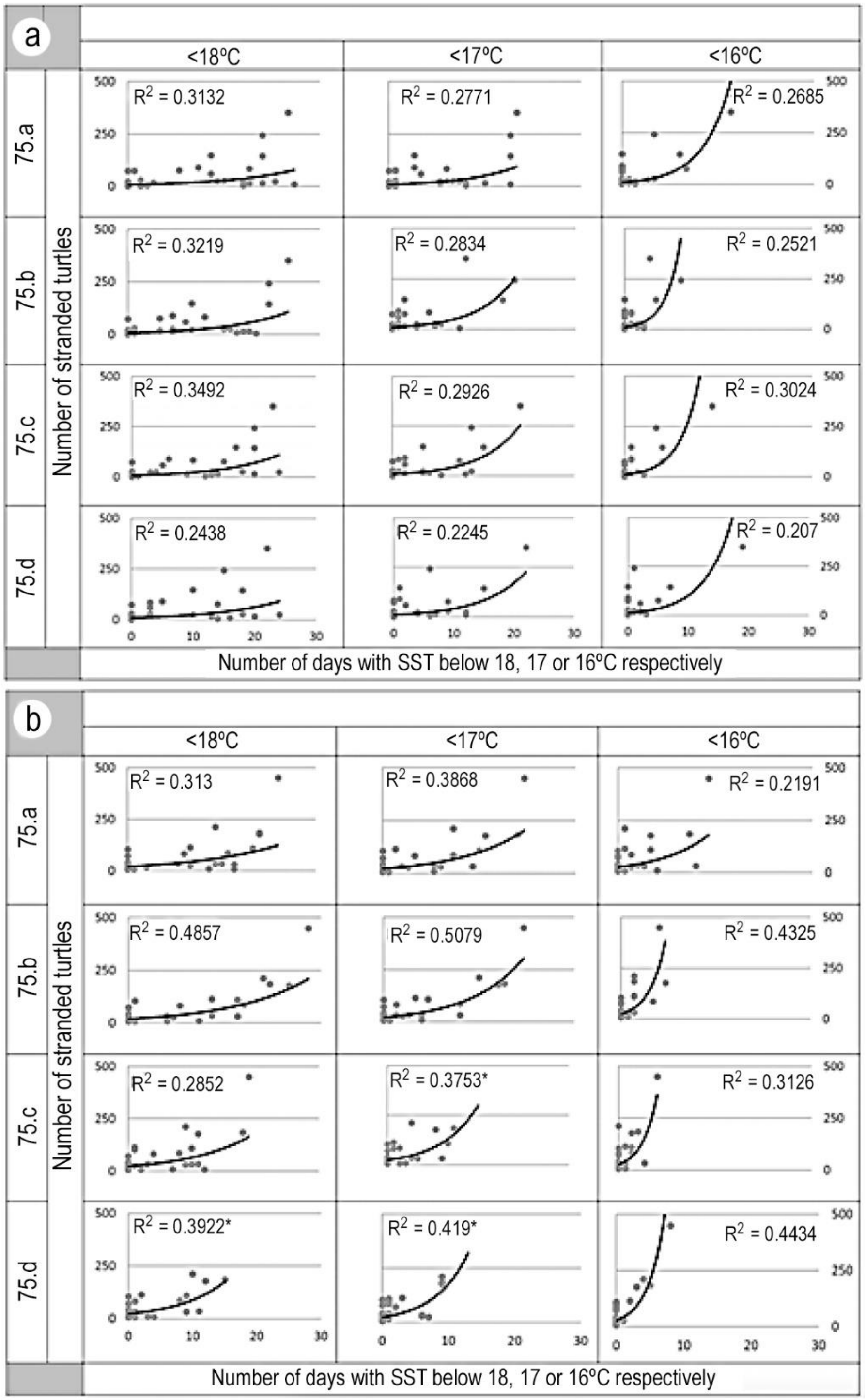

Figure 5. Exponential correlation between the number of days below each reference temperature (<18, <17 and <16°C) and loggerhead sea turtle *Caretta caretta* stranding considering the month with the most significant lag determined with Pearson correlations for a) 2003-2006 and, b) 2012-2014 periods, by polygon (75.a, 75.b, 75.c, 75.d). The determination (R^2) value for each case is shown.

the other six were found stranded on the beach. No fishing-gear damage was determined. For the organism that was floating, its death was determined from drowning. Nonetheless, the triggering factor could not be defined, so the authors considered that any disease not causing a sudden death could cause drowning. Con-

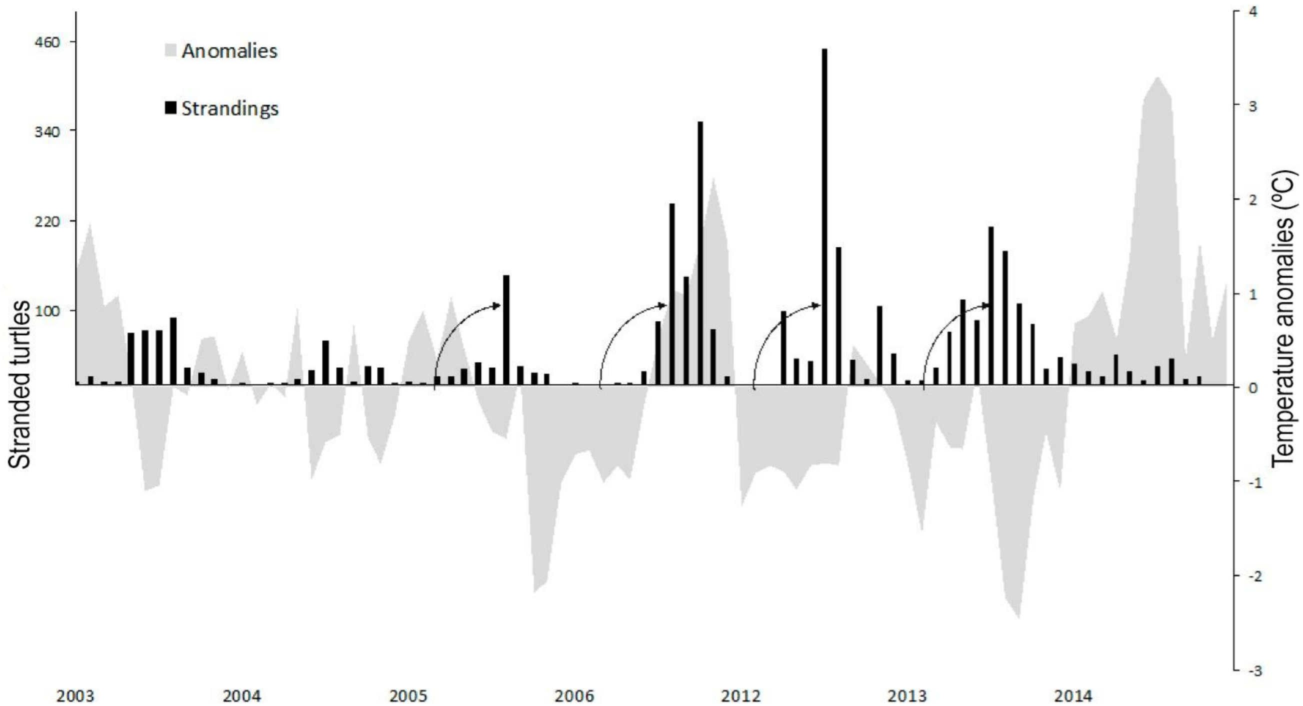

Figure 6. A theoretical model of the relationship between extremely low and sustained sea surface temperature (SST) and sea turtle stranding in the Gulf of Ulloa, Mexico. Curved arrows show the maximum turtle stranding events held after abnormally cold temperatures (five month-lag on average). Gray graphs denote anomalies of temperature, and black bars denote the number of stranded turtles.

cerning the other six-stranded turtles, five were partially eaten by scavengers, so a full necropsy was only performed on the last one, which led to results of death by cold temperature; nevertheless, the histopathological results showed multiple etiologies, so the authors concluded that the cause of death of the analyzed organism was multifactorial. Although this information was based on very few observations, it supports the hypothesis proposed in or study.

CONCLUSIONS

The number of days below the thermal optimum of 18-23°C for the population of juvenile sea turtles inhabiting the Gulf of Ulloa region represents, on average, more than 60% for both periods analyzed.

The empirical relationship between the number of days where the SST was below 18, 17 and even 16°C recorded stranding events in the vicinity of the Gulf of Ulloa, showing a statistically significant exponential correlation. The cross-correlation analysis showed that the relationship was most reliable with an SST delay from four to five months. This behavior is strongly related to the seasonal pattern of SST and the presence of oceanic upwelling events in the region (Lynn, 1967; Bakun & Nelson, 1977; Lynn & Simpson, 1987; Bakun, 1996). Based on the above, this study suggests that abnormally cold conditions from March to June each year may cause a progressive weakening of the sea turtles in the area. This situation puts them at high risk increasing their vulnerability to infectious and parasitic diseases and lethargy, which impede their ability to avoid obstacles during swimming movements, as well as being detrimental to their ability to escape from predators. These results are an alternative and complementary explanation to that offered by Peckham *et al*. (2007), who established that the leading cause of loggerhead turtle *Caretta caretta* mortality was coastal fishing in the Gulf of Ulloa, supported by the possible effect that drift nets have on *C. caretta* individuals inhabiting that oceanic region. To date, no conclusive scientific evidence has been found regarding the leading cause of mortality of sea turtles at this site. Therefore, this study infers that the cause of sea turtle stranding is multifactorial (greater vulnerability to disease, predation, reduced swimming ability and movement, lethargy, and inability to avoid obstacles, including fishing gear while swimming, among others). Sea turtles are regulated by thermal oceanic environmental conditions in the region, corresponding to higher mortality during the prevalence of cooler SSTs

(<18°C) for more than 15 days (>60% monthly) four months before stranding occurs. The graphical model of this empirical relationship based on the theory of the thermoregulation of marine ectotherms is shown (Fig. 6).

ACKNOWLEDGMENTS

The authors are grateful to the technical staff of the Observatory of Seas and Coasts for the facilities to acquire satellite imagery; to Carlos Armando Pacheco-Ayub and Gerardo R. Hernández-García for figure editing; to the Comisión Nacional de Aquacultura y Pesca (CONAPESCA), and the Procuradoría Federal de Protección al Ambiente (PROFEPA) and D. Fischer for final English edition.

REFERENCES

Abecassis, M., Senina, I., Lehodey, P., Gaspar, P., Parker, D., Balazs, G. & Polovina, J. 2013. A model of loggerhead sea turtle (*Caretta caretta*) habitat and movement in the oceanic north Pacific. Plos One, 8(9), e73274.

Anderson, E.T., Harms, C.A., Stringer, E.M. & Cluse, W.M. 2011. Evaluation of hematology and serum biochemistry of cold-stunned green sea turtles (*Chelonia mydas*) in North Carolina, USA. Journal of Zoo and Wildlife Medicine, 42: 247-255.

Bakun, A. 1996. Patterns in the ocean: ocean processes and marine population dynamics. California Sea Grant, California.

Bakun, A. & Nelson, C.S. 1977. Climatology of upwelling related processes off Baja California. California Cooperative Oceanic Fisheries Investigations Report, 19: 107-127. [http://www.esrl. noaa.gov/psd/enso/mei/]. Reviewed: April 10, 2014.

Bentivegna, F., Breber, P. & Hochscheid, S. 2002. Cold-stunned loggerhead turtles in the south Adriatic Sea. Marine Turtle Newsletter, 97: 1-3.

Birse, R. & Davenport, J. 1987. Gut action in young loggerhead turtles *Caretta caretta* L. at various temperatures. Herpetology Journal, 1: 170-175.

Davenport, J. 1997. Temperature and the life-history strategies of sea turtles. Journal of Thermal Biology, 22: 479-488.

Del Monte-Luna, P., Arreguín-Sánchez, F. and Lluch-Belda, D. 2007. Marine ecosystem analyses in the Gulf of Ulloa, Mexico: BAC meets Ecopath. In: INCOFISH ecosystem models: transiting from Ecopath to Ecospace, Edition: Fisheries Centre Research Reports 15(6), Publisher: Fisheries Centre, University of British Columbia, pp.114-133.

Heithaus, M.R., Wirsing, A.J., Thomson, J.A. & Burkholder, D.A. 2008. A review of lethal and non-lethal effects of predators on adult marine turtles. Journal of Experimental Marine Biology and Ecology, 356: 43-51.

Hijmans, R.J. 2019. Raster: Geographic data analysis and modeling. R package version 2.8-19. [https://CRAN.R-project.org/package=raster]. Reviewed: April 10, 2014.

Huyer, A. 1983. Coastal upwelling in the California current system. Progress in Oceanography, 12: 259-284.

Lluch-Cota, S.E., Cordero-Tapia, A., Melo-Barrera, F.N., Gómez-Gallardo-Unzueta, E.A., González-Rodríguez, E., Riosmena-Rodríguez, R., Lara-Uc, M.M., Salvadeo, C., Ramírez-Orduña, J.M. & Ramírez-Orduña R. 2014. Estudio sobre las causas de muerte de la tortuga amarilla (*Caretta caretta*) en la costa occidental de Baja California Sur (Golfo de Ulloa). Informe Final, UABCS-CICIMAR-CIBNOR, 25 pp.

Lynn, R.J. 1967. Seasonal variation of temperature and salinity at 10 m in the California Current. California Cooperative Oceanic Fisheries Investigations Report, 11: 157-186.

Lynn, R.J. & Simpson, J.J. 1987. The California Current System: the seasonal variability of its physical characteristics. Journal of Geophysical Research, 92: 947-966.

Meylan, A. & Sadove, S. 1986. Cold-stunning in Long Island Sound, New York. Marine Turtle Newsletter, 37: 7-8.

Milton, S. & Lutz, P. 2002. Physiological and genetic responses to environmental stress. In: Lutz, P.L. (Ed.). The biology of sea turtle. CRC Press, Florida, pp. 163-197.

Nelson, C.S. 1977. Wind stress and wind stress curl over the California Current. U.S. Department of Commerce. National Oceanic and Atmospheric Administration Technical Report, 714: 87 pp.

Orsulak, J. 2014. Outer banks sea turtles. Field report. [http://www.fieldtripearth.org/article.xml?id=1805]. Reviewed: April 15, 2014.

Peckham, S.H., Diaz, D.M., Walli, A., Ruiz, G., Crowder, L.B. & Nichols, W.J. 2007. Small-scale fisheries bycatch jeopardizes endangered Pacific loggerhead turtles. Plos One, 2(10): e1041.

Polovina, J.J., Balazs, G.H., Howell, E.A., Parker, D.M., Seki, M.P. & Dutton, P.H. 2004. Forage and migration habitat of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central north Pacific Ocean. Fisheries Oceanography, 13(1): 36-51.

R Core Team. 2015. R: A language and environment for statistical computing [Software]. Vienna: R Foundation for Statistical Computing. [http://www.r-project.org/].

Sato, K., Sakamoto, W., Matsuzawa, Y., Tanaka, H., Minamikawa, S. & Naito, Y. 1995. Body temperature independence of solar radiation in free-ranging loggerhead turtles, *Caretta caretta*, during internesting periods. Marine Biology, 123: 197-205.

Schwartz, F. 1978. Behavioral and tolerance responses to cold water temperatures by three species of sea turtles (Reptilia, Cheloniidae) in North Carolina. Florida Marine Research Publications, 33: 16-18.

Shaver, D.J. 1990. Hypothermic stunning of sea turtles in Texas. Marine Turtle Newsletter, 48: 25-27.

Received: 24 April 2019; Accepted: 26 September 2019

Sverdrup, H.V., Johnson, M.W. & Fleming, R.H. 1942. The oceans: their physics, chemistry, and general biology. Prentice-Hall, New Jersey.

Tarifeño, E. 2004. Adaptaciones fisiológicas de animales marinos. In: Werlinger, C. (Ed.). Biología marina y oceanografía: conceptos y procesos. Revisar Editorial.