Effect of erosion on the nest depths of sea turtles and its impact on the egg chamber temperature

Alice very alice.very@imbrsea.eu
Supervisor: Nathan Delmas

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Abstract

In Costa Rica every year thousands of female sea turtles emerge onto nesting beaches to lay nests, with their eggs hatching 6-8 weeks later. The impact of erosion is seen throughout the country, on both the Pacific and Caribbean coasts. During the middle trimester of incubation, the temperature inside the nest determines the sex ratio of the offspring. This study aimed to determine if a decrease in nest depth caused by erosion will change the temperature inside the nest, and therefore the sex ratio. Data loggers were buried at green and leatherback nest depths and in the different vegetation zones of Playa Norte beach in Costa Rica. The multiple regression showed that the temperature varies significantly with the depth and the zones, however, only 20% of the variation can be attributed to these variables. Despite this, results and observations in the field clearly showed that the beach was still impacted by erosion, but rather as an all-or-nothing phenomenon. Erosion leads to receding sand cliffs, washing out the eggs in the process, and this is considered to be the real danger of erosion, rather than its impact on nest temperature. This conclusion is positive as it shows the limited impact of erosion on the temperature within the nests. Conservation efforts can still be made to enhance the protection from erosion of the principal nesting beaches all over the world.

Executive summary

Erosion events have a considerable impact on beaches, which are home to sea turtles in search of the best nesting sites. The appearance of cliffs, the washing away of trees and vegetation, and the reduction in beach width, can occur within a few days on certain beaches, such as Playa Norte in Costa Rica. Sea turtles are temperature-dependent in terms of sex ratio of their off-spring. Warmer temperatures will favor a feminization whereas cooler ones will favor a mas-culinization of the offspring. This study aims to assess the impact of erosion on nesting the depth of sea turtles, to see if shallower nests will induce warmer temperatures inside the egg chamber.

To test this hypothesis, fifteen data loggers were buried at nest depths of leatherbacks and green turtles. Data loggers were buried in three zones of the beach, determined by the sunlight supply throughout the day.

Results showed a variation of the temperature through time but explained only at 20% by the depth and different zones. However, a clear change in the topography of the beach was observed through the incubation time proving the impact of erosion on the beach, and the nests within it.

These observations indicate that the real danger of erosion is considered to be the apparition of cliffs taking away the eggs laid, instead of the variation of temperature influencing the sex ratio of the turtle offspring. Differences between the two species were observed and leatherbacks, by the erosion-prone preference in terms of nest selection, are more impacted by this danger. Sus-tainable, easy-to-implement local solutions are beginning to emerge, but more research is needed on that matter.

Introduction

The potential effects of climate change on sea turtles include changes in phenology, reproductive frequency, migration patterns, and feeding conditions (Santidrián Tomillo et al., 2017). Once they reach their nesting beaches, sea turtles face the additional climate-induced problem of beach erosion and its attendant consequences on their nests. Every year, thousands of turtles emerge from the water to nest at Tortuguero Beach on the Atlantic coast of Costa Rica (Segura & Cajade, 2010). During the 2022 turtle nesting season, more than 700 nests were identified on Playa Norte – the portion of the beach surveyed by the volunteers of the Caño Palma Biological Station (COTERC, unpublished data).

The main turtle species coming to Playa Norte to nest is the green turtle, *Chelonia mydas*. With a high natal-beach fidelity (Patrício et al., 2018), encounter turtles are tagged each year and are coming back regularly to nest in the same area (COTERC, unpublished data). Their length varies between 100 and 150 cm with a mean weight of 150 kg. They are found worldwide, primarily in subtropical and temperate regions of the Atlantic, Pacific, and Indian Oceans, and in the Mediterranean Sea (NOAA, 2022). The conservation status of the green turtles is endangered, and decreasing, according to the IUCN (2004). The species nests every 3 years with an average of 3 nests/ a season and, an incubation period of around 55 days (Whitmore & Dutton, 1985). Less frequently, the large leatherback turtles, *Dermochelys coriacea*, can be found, especially at the beginning of the turtle's activity season (Bjorndal & Bolten, 1992). Leatherbacks are the largest and the oldest of the extant marine turtles, believed to be 100 million years old. The particularity of this turtle weighing from 300 to 500 kg and measuring up to 180 cm broad, is the absence of hard carapace. Instead, the carapace is composed of small bones covered in skin and seven ridges along its back, resulting in an adaptation allowing the leatherback to dive up to 1200 meters. Nesting beaches of the leatherbacks are primarily located in tropical latitudes around the world (NOAA, 2023). The conservation status of the leatherbacks is vulnerable, decreasing, according to the IUCN (2013). The species is nesting every 2-3 years only and will lay eggs and smaller yolkless eggs, smaller and around the real eggs, 3 to 7 times a season. The incubation period will last around 65 days (Binckley et al., 1998). The last species that can be encountered at Playa Norte, but not subject to this study, are the Loggerhead turtle, *Caretta caretta*, listed as vulnerable by the IUCN (2015), and the Hawksbill, *Eretmochelys imbricata*, listed as critically endangered, decreasing by the IUCN (2008) mainly due to the poaching of their carapace to make all sorts of objects from it (Witzell & Banner, 1980). Overall, many challenges must be overcome to optimize the hatchlings success rate, among them predation and poaching of eggs. At Playa Norte, the danger of erosion, which is intrinsically linked to flooding, remains an issue for the turtles nesting capacity and cannot yet be diminished by conservation efforts.

Beach profiles can change considerably according to the weather and therefore over the seasons, resulting in a rapid loss of the bare sand portion of the beach and much slower increases (Davis, 2021). Playa Norte has a very dynamic beach profile, changing greatly from one week to another, however, no clear pattern has been seen over the years (COTERC, unpublished data). In some unpublished data collected by students volunteering at the COTERC station, the portion of the beach at Playa Norte has been reported to be increasing since 2017. Based on the observations made during the period of the experiment, the beach of Playa Norte is eroded very suddenly and intensively, and a much slower increase of the beach portion will follow. No clear link between seasons and erosion has been made nor between the amount of rainfall over a given period (COTERC, unpublished data). The reduction of beach quality directly affects turtle nesting success in many ways such as steep escarpments on the beach, restraining females from nesting further on the beach; removal of sand from the beach and creation of a rocky substrate or a shallow layer of sand that prevent nest excavation to a suitable depth; and the washing out of nests that are incubating in the beach can expose eggs to predation and desiccation (Mrosovsky, 1983; Rivas et al., 2016; Spanier, 2010).

In reaction to erosion, several studies have looked at turtles' ability to adjust their nest sites to maintain the most erosion-stable location possible (Rivas et al., 2016; Siqueira et al., 2021; Spanier, 2010). A shift of the nest localisations, by nesting on more suitable beaches, can be one of the results observed to adapt to those changes (Rivas et al., 2016). Those relocations are still not common as it seems to be a quite maladaptive nesting strategy given the erosion-prone nature of leatherback beaches as it would still lead to a relatively high rate of nest loss to erosion (Eckert, 1987). A change in the beach profile can therefore lead to a shift in the turtles' habits. Moreover, a study done at Playa Gandoca, Costa Rica, indicated that the dynamic nature of erosion on nesting beaches used by Leatherbacks has been the explanation for between 35% and 60% of nest loss (Spanier, 2010). At Playa Norte, erosion is thought to be responsible for the declining numbers of leatherback turtles. A clear decrease in the number of leatherback turtles encountered at Playa Norte is observed, as well as a decrease in the number of nests found each year. In 2008, 90 leatherbacks nested at Playa Norte, the busiest of the shown years, whereas, in 2016, only 15 turtles nested in the same area (COTERC, 2008; COTERC, 2016). Unlike the leatherback turtles, throughout the years, no clear pattern is recorded for the green turtle nesting activity at Playa Norte. The number of nests found has increased since a couple of years. During the pandemic, very few conservation efforts took place due to government health restrictions, leading to a very big number of nests being poached (COTERC, unpublished data).

A high percentage of females facing scarps do not go over them, therefore their clutches are being laid below the high tide line (Rivas et al., 2016). Turtles are also less likely to exit the sea in case of an extreme weather event. Nests located in these lower areas are more likely to become wet or flooded by tidal action; eggs are more prone to being washed out (Caut et al., 2010; Eckert, 1987; Patino-Martinez et al., 2014), and the success of hatching may decrease due to the drop of sand temperature (Houghton et al., 2007). High water content in the nest is directly linked to high mortality rates because it limits the oxygen supply needed for the development of the embryos, increases the emergence of disease, and favors bacterial and fungal growth (Patino-Martinez et al., 2014).

Another impact of erosion is the modification, during the incubation time, of nest depth and consequently, the possible modification of the temperature at which the eggs are incubated. According to Refsnider et al., 2013, for species with temperature-dependent sex determination that construct subterranean nests, the depth of the nest may affect incubation temperatures, and thus offspring sex ratio. Indeed, warmer nest temperatures induce a favorable sex ratio towards females whereas cooler ones favor the production of males (Ackerman, 1997; Hays et al., 1995; Morreale et al., 1982). The thermal environment that developing clutches experience varies among species. Bigger species dig deeper nests and, since sand temperatures increase in stability with depth, deeper nests experience more uniform conditions during development (Santidrián Tomillo et al., 2017). Consequently, clutches laid by large species are less likely to be affected by changes in temperature. However, Santidrián Tomillo et al. (2017) noticed that large species with narrow thermal tolerances such as leatherback turtles can still be greatly impacted. Once they have reached their adult size, in the ocean, leatherbacks can withstand a large temperature variation but their eggs, laid in the sand, remain sensitive to temperature changes. In the same study, leatherback hatching rates were lower than those of the smaller green turtles (Santidrián Tomillo et al., 2017). The nest temperature and the degree of its variation according to erosion should therefore be interesting to study between green turtles and leatherback turtles to have a better idea of the consequences of erosion on different species.

According to Bull & Vogt, 1981, and Standora & Spotila, 1985, the middle third of development is the critical phase of the embryo's development, as it determines the sex of the hatchling.

Therefore, the temperature experienced by the embryo during that thermosensitive period will be decisive. Most sea turtles have a pivotal temperature for sex ratio determination, eggs incubated below 29.0 C are 100% male, whereas eggs above 30.0 C gave 100% of female (Binckley et al., 1998). According to numerous studies, the threshold temperature for the transition from the production of one sex to the other (i.e., a sex ratio of 1: 1) is around 28 to 30°C for the four species mentioned in this paper. Standora & Spotila (1985) also observed that in nests incubating at pivotal temperatures, metabolic heating results in female hatchlings at the center of the clutch and male hatchlings along the periphery. The temperature at the center of an egg chamber will increase during the middle third of incubation, exceeding by 2.5°C the adjacent sand temperature. This increase in metabolic heat throughout incubation is found in all the seven sea turtle species, including the green turtles and the leatherbacks (Gammon et al., 2020). On Tortuguero Beach, Standora & Spotila, (1985) observed that green turtles' hatchling sex ratios varied between nest locations. Denser vegetation restricted sunlight and produced zones of nests with lower temperatures. These temperature differences result in differences in sex ratios for nests located in different zones (Standora & Spotila, 1985).

While studies have been interested in the change, in case of erosion, of temperature between artificial and natural nests, there is a lack of studies gathering knowledge about the potential change in temperature within a nest and depending on the depth where incubation takes place. The present study aims to verify the influence of erosion on the nest depths and their consequences on temperature affecting the sex ratio. In other terms, the focus here is to assess the impact of erosion activity, once the turtles have started their incubation, on the temperature, by changing the depth where the eggs are at. Significant variations of temperature, related to the erosion rate should be expected. An increase in temperature at nest depth correlated to a high erosion rate has been hypothesized. Furthermore, a more pronounced increase in temperature should be seen in the nests of green turtles as they are burying eggs at a shallower depth than leatherback turtles.

Material and methods

1. Study site

Figure 1. Map of the study site, at Playa Norte in Costa Rica. The coordinates in purple indicate the markers 0 to 11, where the study took place and the coordinates in red indicate the remaining markers of the Caño Palma Station's transect.

The study was conducted at Playa Norte, Tortuguero in Costa Rica from the 22nd of February until the 2nd of April. Playa Norte's beach is a major nesting ground for the green turtle, *Chelonia mydas*, in the Caribbean Sea. The width of the beach varies with constant erosion and soil deposition. Portions of the sand are littered with logs and other debris, mostly plastic, originating from rivers and along-shore currents. The survey conducted at Playa Norte by the Caño Palma Biological Station includes a 5 km transect ending with the Laguna Cuatro. However, the present study has only been conducted on the first 2 km of the transect, beginning a few dozen meters north of the Tortuguero River mouth and ending at the eleventh marker.

Three zones have been pre-defined, based on the topography of the beach. The open zone extended from the water's edge, including the wet sand below the high tide sand and bare sand after the high tide line. The open zone is exposed to the sun throughout the day (0-50% shading). The border zone starts when the vegetation, principally composed of *Ipomoea pes-caprae*, begins to form a uniform network on the sand and the zone experiences 50-99% shading. The vegetation zone is the last zone before the dense forest and includes the first trees as well as dense vegetation on the ground, and has the sky completely obscured by canopy cover. For all zones, data logger distribution was limited by available space in each zone.

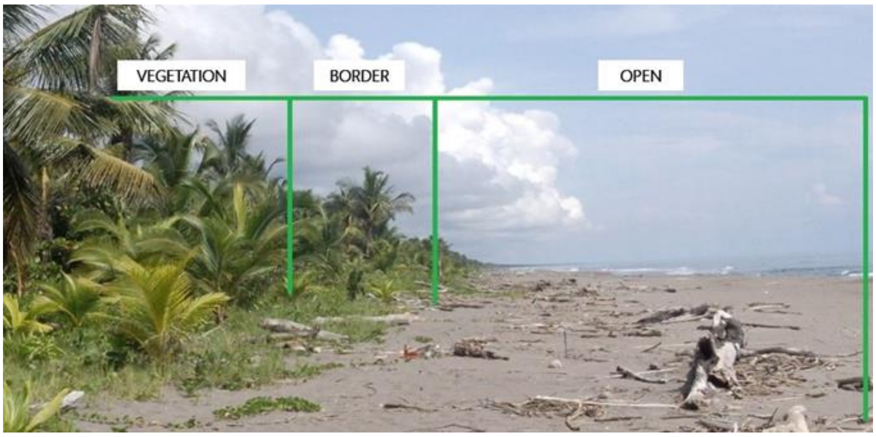

Figure 2. Division of the beach zones at Playa Norte. Open: direct sunlight throughout the day (0-50% shade); Border; 50% - 99% shaded throughout the day; 100% sunlight obstructed by canopy cover (COTERC).

2. Erosion and data collection

The Beach profile was surveyed over the year to assess the impacts of erosion. One of the measurements taken for the beach profile is the distance from the high tide to the tree line and from the vegetation line and the tree line. At the tree line, trees are painted to indicate markers, and half markers are spaced 200 meters apart and placed in alternation in the way that markers, numbered from 0 to 25 are in between half markers. The slope of the beach is also calculated with a clinometer and the number of cliffs in front and behind the high tide line is noted but those measures have not been used in this study.

The erosion rate was calculated by burying plastic bottles at a certain depth and measuring the decrease in depth over time. In total, 30 plastic bottles were buried, with 15 of them containing temperature data loggers. The plastic bottles were buried every 200m over 2 kilometers. In total, 11 different markers were used as an indicator of where the plastic bottles were buried. In each marker, 3 plastic bottles have been buried, in the three different zones previously cited. A line of 3 empty plastic bottles was buried, with the same methodology, in between lines of plastic bottles containing data loggers.

Every plastic bottle was tied with a rope and, using a measuring tape, a node was made at every 10 cm. Sand loss above each bottle was determined by observing the amount of rope exposed at the surface. A mark made by a nail polish indicated at which depth the bottle was first buried. In addition, the distance between the nail polish and the end of the rope out of the sand has also been calculated, before being buried, in case the red nail polish could not be found.

The erosion rate was measured every two to four days for nine weeks. Temperature data loggers were used to observe the changes in temperature at nest depth. The depth of the data loggers corresponds to the average depth of the bottom of the nest for the two species of turtles studied Two different depths were recreated, the green turtle's average nest depth, of 55cm, and the leatherback turtle's average nest depth, of 75cm. After 30 days of the first set of measurements, the 15 bottles containing the data loggers separated by two different depths were unburied and reburied, reversing their initial depth. This way, after 60 days of incubation, each data logger contained data for the two different depths, increasing the number of replicates. During the second burying phase, the bottles were buried considering the topography of the actual beach and not the topography of the beach during the first burying phase. This way, if the beach was wider after one month, the bottles have been buried more spaced out from each other.

Controls of data loggers were placed at three different locations at the surface, corresponding to three different degrees of sun expositions: in complete shade, in partial shade and in absence of shade. The data logger in partial shade was stolen halfway through the experiment and the data from this device has not been recovered. The first period of incubation took place between the 21st of February to the 21st of march and the second period of incubation took place between 23rd of march and the 2nd of April. The second period of incubation was shortened by half, to avoid theft of additional data loggers, as data loggers were in limited supply. Moreover, the loss of a data logger would have resulted in the loss of both sets of measurements. The data loggers have been buried at markers 3, 5, 7, 9 and 11 whereas the empty bottles were buried at markers 0, 2, 4, 6 and 8. No data loggers were put at marker 1 due to a high erosion rate, reducing the beach to only a few meters.

The temperature at nest depth has been collected with Fresh Tag 1, single-use type data loggers commercialized by Freshliance. A led was indicating every 30 seconds that the device was still recording. The device can record data for a total of 120 days. The temperature supported by the loggers is in the range of - 30°C ~ + 70°C. The data were uploaded in a computer by the USB port of the loggers. The outcome gave a PDF containing a graph and a table with the temperature recorded every 5 minutes during the incubation period. For each measure of the erosion rate taken on the beach, all the recorded data 12 hours before the measure and 12 hours after were collected from the PDF and put in an excel file to obtain an average temperature over 24 hours.

3. Statistical analysis

The following statistical analyses were performed using the R studio software (R version 4.1.2 of 2021-11-01).

A modified Mann-Kendall test was performed to determine whether or not a trend was observed for the high tide line data, through time and at each marker where data loggers were buried. The modified version of the test takes into account autocorrelation where HTL at time (0) is correlated to HTL at time (1), assuming that subsequent data points aren't independent but correlated. It is a non-parametric test, therefore no underlying assumption was made about the normality of the data. From the test, a graph was obtained to visualize the trend. A data visualization of the erosion impacting the beach profile was realized and a graph was obtained showing the condition of the beach at random times during the fieldwork period. The ggplot2 package in R studio was used to visualize the dataset. A multiple linear regression was performed to estimate the relationship between the depth (independent variable), the different zones of the beach (independent variable), and the temperature (dependent variable) recorded inside the nests. A two-samples t-test was used to determine whether or not the means of the temperature, recorded between the different nest depths, are equal. Other two-sample t-tests were realized to determine whether or not the means of the temperature, recorded between the controls and the data loggers are equal. The control left in the sun at all times was tested against one of the data loggers buried in the open zone, and the control left in the shade at all times was tested against one of the data loggers buried in the vegetation.

Data have been collected, from the yearly turtle reports, found on the COTERC website, to assess the evolution of the number of turtles encountered, depending on the species. A graphic was realized in Excel out of a table collecting, for each of the two species in the study, the total number of turtles encountered and the total number of nests and half-moons every year.

Results

1. Evolution of the beach profile at Playa Norte

An analysis of the beach profile was realized through statistical tests and graphics to show how the erosion was impacting Playa Norte during the incubation period of the data loggers.

A. B.

Figure 3. Erosion of the beach is shown by pictures taken at Playa Norte in the same location, spaced out by 6 days.

The first picture is facing south and was taken on the 28th of January. The second picture was taken on the 4th of February, further meters southward and facing north. The back of a sign can be seen at the end of the palm tree, bottom right of the first image. The blue front of the sign can be seen on the left of the second image. A cliff has been formed within days and a clear progress towards the vegetation zone can be seen, taking away the vegetation of the border zone.

C.

D.

Figure 4. Erosion of the beach, on the 5th of March at the same location, Playa Norte.

The blue sign was taken out a few hours after this picture was taken, to avoid losing it in the sea. The cliff-forming in picture B is way bigger in picture C, reaching 1m50 and the border zone of the beach is almost gone. Palm trees in the surrounding have been washed out as seen in D.

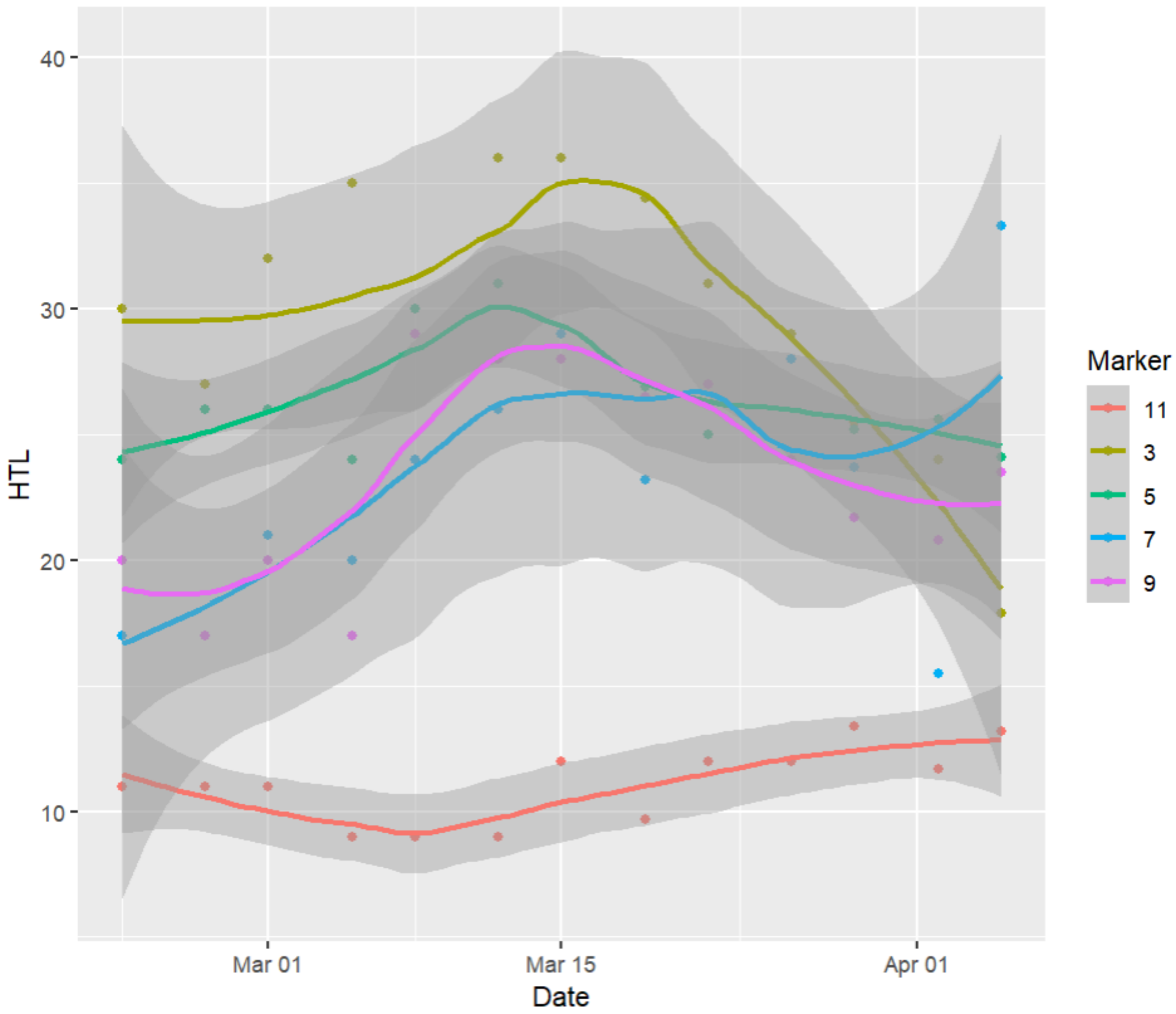

Figure 5. Evolution of the high tide line at Playa Norte, for all the markers containing data loggers, throughout the incubation time.

A modified Mann-Kendall test was realized for all the markers containing data loggers. A trend was observed through time for the markers 3, 7 and 11 with respective p-values of 0.0250, 0.0015 and 0.0462, which is lower than 0.05. The p-values obtained for the markers 5 and 9 were respectively equal to 0.7661 and 0.7491, which is greater than 0.05, meaning that no trend was observed in the data of those of those markers. However, the graph shows a clear evolution of the high tide line through time for all the markers. Marker 11 was the only one showing a decrease in the width of the beach, from 11 meters wide to 9 meters, followed by an increase going up 13.4 meters. The other markers showed the opposite pattern, with an increase followed by a decrease.

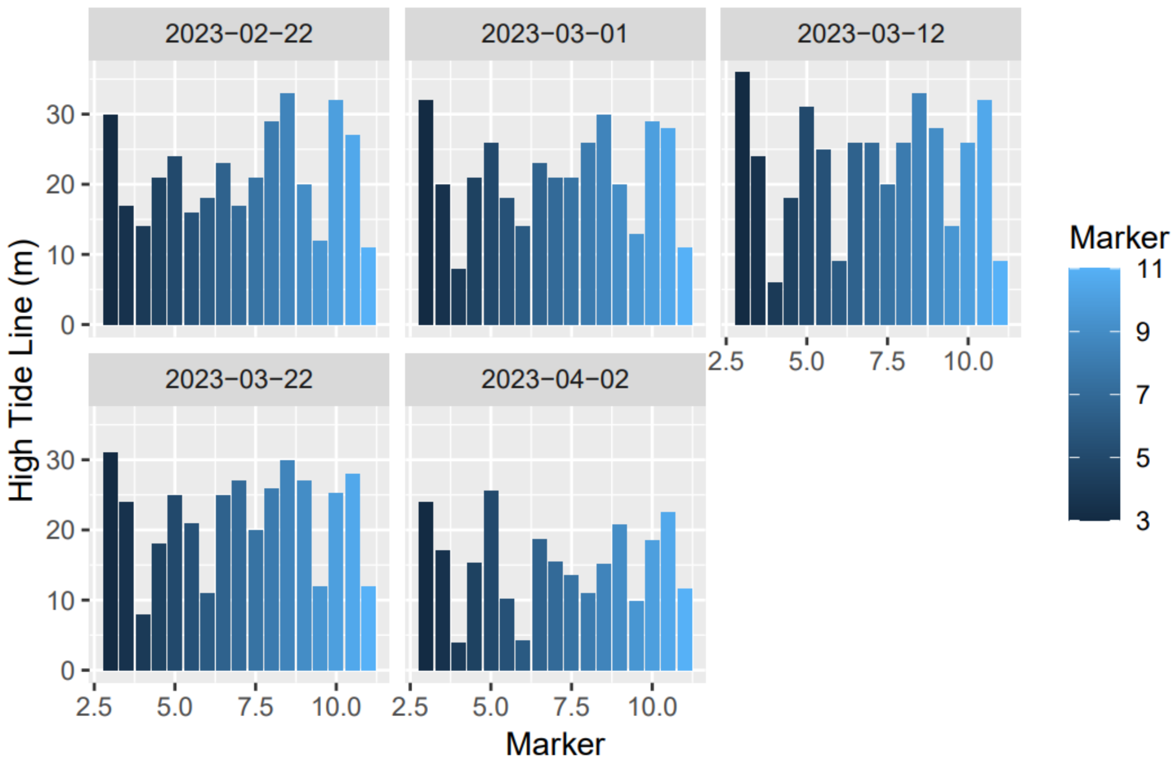

Figure 6. Bar charts representing the high tide lines at the markers included between 0 and 11. Each graph represents the high tide lines at a specific time of the incubation period in order to illustrate the change of beach profile through time.

From one graphic to another, a change in the high tide lines for all the markers can be observed, with, on average, a high tide line measuring respectively 21.47 m, 21.24 m, 22.88 m, 21.78 m and 15.16 m. Over the five periods chosen, the 12th of March corresponds to the time when the beach was the widest and the 2nd of April corresponds to the time when the beach was the narrowest. A high bar in the graph indicates a wide beach whereas a small bar indicates a narrow beach.

Table 1. Maximum erosion rate at every bottle without data loggers.

Marker	Tag	Max erosion rate
0	EBV0	0
	EBB0	washed out
	EBO0	washed out
2	EBV2	-3
	EBB2	-5
	EBO2	-2.5
4	EBV4	-13
	EBB4	washed out
	EBO4	washed out
6	EBV6	0
	EBB6	washed out
	EBO6	washed out
8	EBV8	0
	EBB8	-12
	EBO8	-15

EB corresponds to the empty bottles and V, B and O indicate the zones of the beach, respectively vegetation, border and open. Among the bottles without data logger, 6 of the 15 were washed out by the waves during intense erosion. The bottles that have been washed out by the waves were in the open and border zones of the beach, at markers 0, 4 and 6. The maximum of erosion rate recorded for the bottle without a data logger is -15cm, corresponding to the open zone of marker 8, followed by the empty bottle buried in the open zone of marker 8 with an erosion of -12 cm.

Table 2. Maximum erosion rate at every bottle containing a data logger.

Marker	Tag	Max. erosion rate	
		1st set	2nd set
3	DLV3	-3	0
	DLB3	0	-2
	DLO3	-4	-12
5	DLV5	-1	-2
	DLB5	-2	-2.5
	DLO5	-2	-2.5
7	DLV7	-3	-2
	DLB7	0	-2
	DLO7	0	-3
9	DLV9	-6	-5
	DLB9	-10	0
	DLO9	-8	-1.5
11	DLV11	-4	-4
	DLB11	-6	-3
	DLO11	-6	-3

DL corresponds to the bottles containing data loggers and V, B and O indicate the zones of the beach, respectively vegetation, border and open. The maximum of sand retrieved above a buried logger is 12cm, corresponding to the data logger buried at marker 3, in the open zone (closest to the sea).

2. Evolution of turtle activity at Playa Norte

An analysis of the turtle activities at Playa Norte has been realized to assess the importance of the beach in terms of nesting sites for the two species studied.

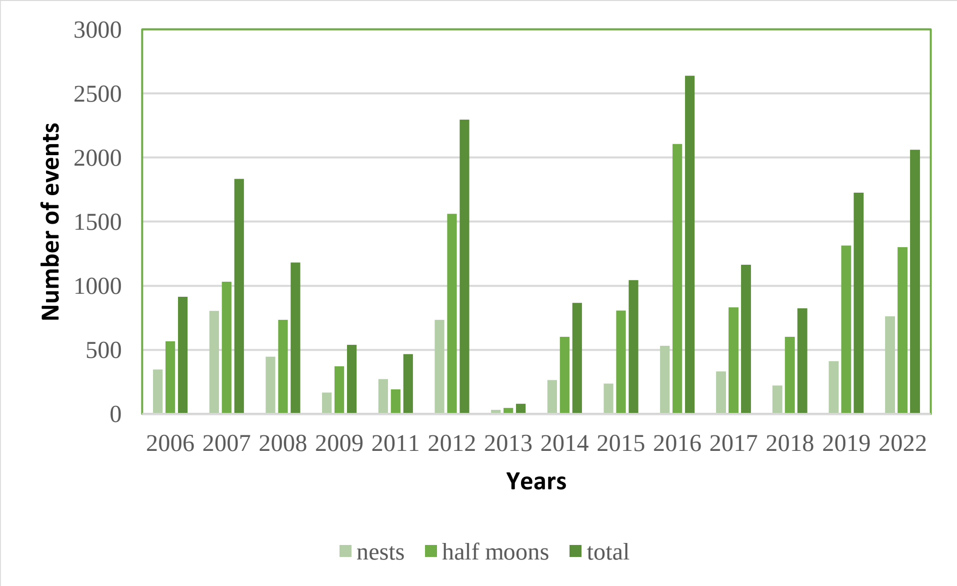

Figure 7. Evolution of the Green turtle's activity at Playa Norte, from 2006 to 2022. Activities recorded by the Caño Palma Biological Station, in a 5km transect starting at Tortuguero river's mouth and finishing at the Laguna Cuatro.

Throughout the years, no clear pattern can be observed but it seems that the number of green turtles, coming to the beach every year, increases for a couple of years in a row and decreases sensibly over the same number of years. No data has been recorded for the years 2020 and 2021 due to Covid restrictions but an increase in turtle nests and half-moons is recorded since 2019. The years 2007, 2022, and 2012 have recorded the highest number of nests with a total number of nests amounting respectively to 803, 762, and 735. The year 2003 was the lowest year in terms of nests and half moons found with a total of 80 events recorded.

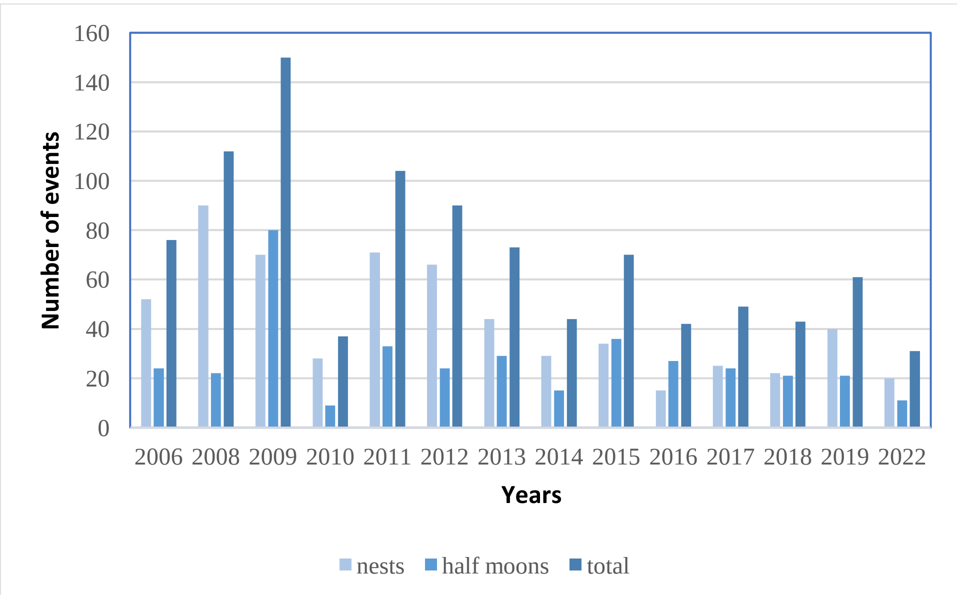

Figure 8. Evolution of the Leatherback turtles' activity at Playa Norte, from 2006 to 2022. Activities recorded by the Caño Palma Biological Station, in a 5km transect starting at Tortuguero river's mouth and finishing at the Laguna Cuatro.

Over the recorded years, a decrease in the number of leatherback turtles coming at Playa Norte can be observed. No data has been recorded for the years 2020 and 2021 due to Covid restrictions. In 2008, 90 nests were recorded at Playa Norte, with a total of 112 turtle events observed, and the following year the number of nests passed to 70 in total, but the total of activities increased to 150. Those years were the busiest in terms of leatherbacks activity whereas 2016 and 2022 were the slowest ones with respectively 15 nests on a total of 42 events recorded, and 20 nests and a total of 31 events recorded.

3. Temperature variation inside the nests

Tests have been realized with the temperatures obtained from 15 data loggers, buried two times over a 6 weeks period, at Playa Norte, in a 2km transect after the Tortuguero river mouth.

A two samples T-test was realized between the data recorded by the data logger used as a control in the vegetation zone, corresponding to a shade covering of 100% during the day, and the data recorded by one of the data loggers buried in the same beach zone. The aim of the test was to see if a difference was observed between the mean temperatures of the two data loggers. The choice of the data logger was random between all the data loggers buried in the vegetation zone and ended up being the one at marker 9. The p-value obtained for this t-test is 2.2e-16. For a t-test, a p-value < 0.05 rejected the null hypothesis by stating that the probability of observing the results by chance is less than 5%. Moreover, the difference between the means of the two groups is equal to 0.87977. The result stated therefore that the difference in temperature recorded between the two data loggers is significant.

A t-test was realized between the data recorded by the data logger used as a control in the open zone, corresponding to a shade covering of 0% during the day, and the data recorded by one of the data loggers buried in the same beach zone. The aim of the test was to see if a difference was observed between the mean temperatures of the two data loggers. The choice of the data logger was random between all the data loggers buried in the vegetation zone and ended up being the one at marker 5. The p-value obtained for this t-test is 2.2e-16. For a t-test, a p-value < 0.05 rejected the null hypothesis by stating that the probability of observing the results by chance is less than 5%. Moreover, the difference between the means of the two groups is equal to 2.82151. The result stated therefore that the difference in temperature recorded between the two data loggers is significant.

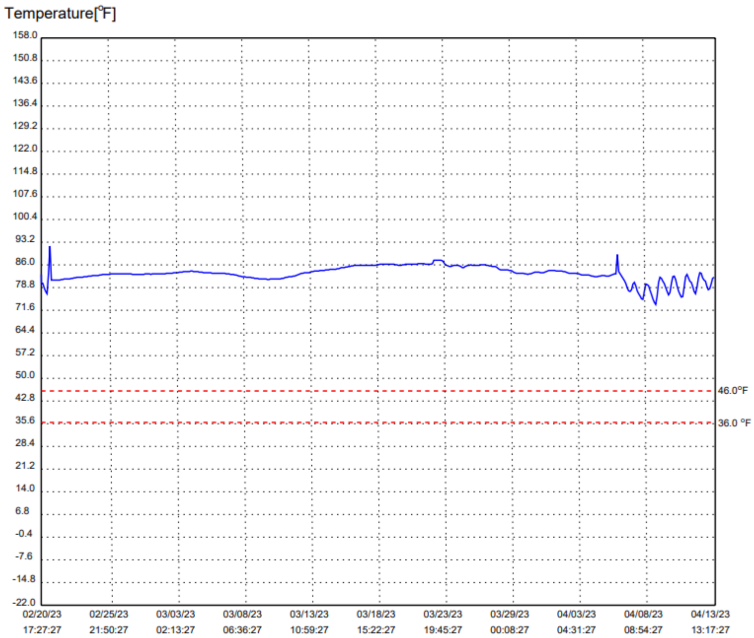

Figure 9. Variation of the temperature through time for the data logger placed at marker 11, in the open zone.

Before the 22nd of February and after the 2nd of April, the data logger was stocked at the station, causing the variations observed. On the 22nd of March, the data logger has been unburied and reburied in the middle of the open zone observed at the time. Compared to the data logger left at the surface, as a control, no important variation is observed when the data logger is buried in the sand. The mean temperature for the first set of measurements is equal to 82.68 Fahrenheit (or 28.16°C) and the mean temperature for the 2nd set of measurements is equal to 83.85.

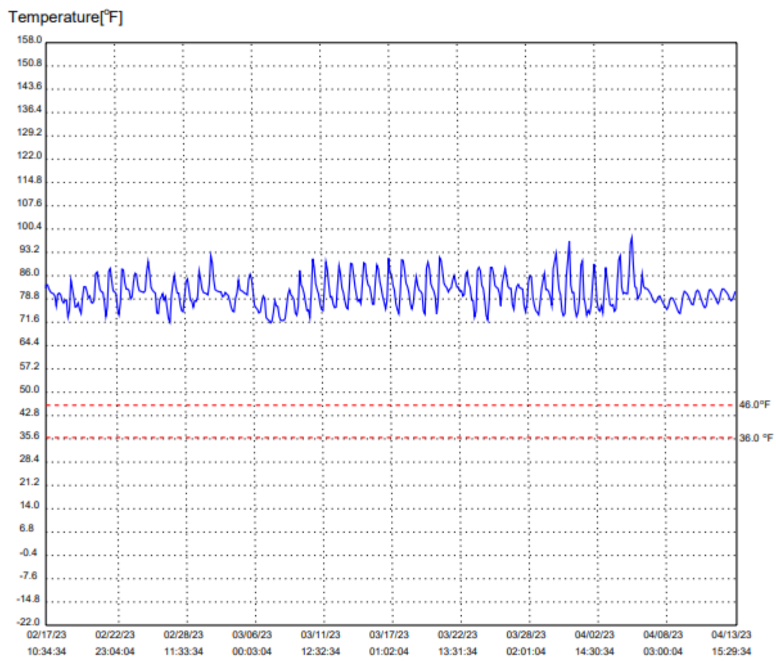

Figure 10. Variation of the temperature through time for the data logger placed as a control, with constant exposition to the sunlight.

Before the 22nd of February and after the 2nd of April, the data logger was stocked at the station, causing the variations observed. The variations observed follow the dial cycle and therefore the temperature increase strongly during the day and drop during the night. The variations in the increases during the day are due to the weather like the presence of clouds, rain, or even storms.

A multiple linear regression was used to test if the depth and the different zones of the beach (open, border, and vegetation) significantly predicted the variation in temperature. The fitted regression model was: [fitted regression equation] x = 86.093105 – 0.030333* -2.061437* -1.184690*. The p-values of the depth and the different zones were statistically significant with the p-values respectively equal to 0.00228 (depth), 2.23e-13 (vegetation), and 1.31e-05 (border). However, the adjusted R-squared obtained is equal to 0.2015. The multiple regression showed that the temperature varies significantly with the depth and the zones, however, only 20% of the variation can be attributed to these variables. Thus, 80% of the variation of the temperature isn't explained by the depth or the zones, which makes the relationship between the variables of the regression quite small. Based on the small negative correlation in this test, it can be concluded that depth plays a small role in regulating temperature.

A t-test was realized to compare the means of the temperatures recorded from data loggers buried at 55cm, the average nest depth of a green turtle, versus the ones buried at 75cm, the average nest depth of a leatherback. The p-value obtained for this t-test is 0.01611. For a t-test, a p-value < 0.05 rejected the null hypothesis by stating that the probability of observing the results by chance is less than 5%. However, the difference between the means of the two groups is equal to 0.58493. The p-value observed signifies that the difference in temperature recorded between the two data loggers is significant, but the difference in the means is very low. No real difference in temperature between the two depths can be concluded.

Discussion

I – Erosion at Playa Norte

Playa Norte, and its prolongation towards Tortuguero, is considered as one of the most important beaches for green turtle nesting sites (Spotila et al., 1987; Standora & Spotila, 1985). The beach also hosts an interesting diversity of species, with leatherbacks, hawksbills, and occasionally, loggerhead turtles, taking advantage of this beach to nest, which made it an ideal location to investigate the impact of the erosion rate on the temperature inside the nest of different turtle's species.

The data loggers were buried in three different zones of the beach, in function of the quantity of shade received throughout the day. Thus, three zones were determined with the vegetation zone receiving the most shade, followed by the border zone, and finally the open zone with direct sunlight at any time of the day. The assumption made was that the data loggers buried in the vegetation zone will have the coolest temperature throughout the day whereas the open zone will have the warmest temperature throughout the day, as the sun will heat the sand around the egg chamber (Patrício et al., 2018; Staines et al., 2020). The multiple regression showed a p-value of <2e-16, corresponding to a significant variation between the three zones of the beach. However, the adjusted r-squared of 0.2015, illustrates that the variation in the temperature is explained by the zones and the depth only at 20%. Because less than 20% of the variation is explained by the different zones of the beach, no strong relationship is observed, and no significant outcome can be concluded. However, a study conducted by Standora and Spotila (1985) in Tortuguero Beach, located in the north of the Playa norte, observed a highly significant difference in the temperatures of the three same zones of the beach. The border zone temperatures were the highest and vegetation temperatures were the lowest. In terms of sex ratio, the nests in the vegetation produced predominantly males while the two remaining zones contained nests producing mostly females (Standora & Spotila, 1985). The first hypothesis matches the results found in studies but does not concord with the results obtained, perhaps due to the limited amount of data loggers buried. Another supposition is that Playa Norte, during the time of the study was too narrow to bury the data loggers with enough distance between them, showing therefore less variations.

Prior to the beginning of the fieldwork, a hypothesis stipulated that the nests would get eroded gradually, removing a few centimeters of sand at each measurement, depending on the importance of the erosion from one given time to another. This way, during an episode of a high-intensity period of erosion, the eggs chamber, represented by the data loggers in this study, will get closer to the surface as the sand will get removed by the waves passing on it. Looking at the results, it has been observed that the erosion rate above the nest, corresponding to the amount of sand retrieved from the original depth dug by the turtles, is very slow, with a maximum of 15 cm retrieved from the original depth (*Table 1*). Those observations can be compared to the literature that describes heavy rains and stormy seas greatly accelerating the normal erosion process (Fowler, 1979) as well as short-term erosion, defined by Recinos Brizuela (2019) caused by storm surges and high waves eroding the beach with strength and speed. Those observations in other studies concord with the absence of gradual erosion observed on the field.

Moreover, prior to putting data loggers in plastic bottles, at nest depth, 15 empty bottles have been placed, alternating with the future data loggers on the transect selected for the project. Unlike the buried data loggers, the empty bottles were left in the sand, even if a high cliff was forming close to them. This way the bottles could have been washed out by the cliffs passing through it, illustrating the same process seen with the egg chambers. Looking at the *Table 1*, out of the 15 buried empty bottles, 6 of them have been washed out, corresponding to the ones from the border and open zones of markers 0, 2, 4 and 6. Those markers have been subjected to high erosion prior to and during the experiment. Even if some of the results of the Mann-Kendall tests didn't show a clear trend, the graphics associated show an important change through time in terms of beach profile. An erosion process is observed in all markers with 4 of the 5 presenting the same curve corresponding to an episode of erosion followed by the augmentation of the beach zone (*Figure 5*). The same results are seen with the *Figure 6*, where the high tide line is clearly changing from one observation to another. Those results, together with the bottles getting washed out (*Table 1*), clearly show the dynamism of Playa Norte and are very important to put in comparison with the erosion rate measured above the recreated nests and the beach profile. The impact of erosion on the beach and therefore the nests was obvious, even with a limited amount of sand retrieved above the artificial nests. Indeed, this apparent absence of erosion does not correspond to an absence of erosion but shows that it does not impact the nest by reducing its depth in a constant way through time. Instead, the beach is impacted by the cliffs formed resulting from the erosion process. With an increase in the strength of the waves, the high tide line will go higher up the beach and will sometimes result in the formation of cliffs as seen in the pictures A, B and C of the *Figure 3.* and *Figure 4*, as well as destruction of the tree line as seen in the *Figure 4*. D. The pictures clearly show an intense event of erosion with a cliff forming within days and meters of beach lost over a month. The cliffs will be formed with different speeds and different highs which tend to make their formations very difficult to predict from one day to another. The formation of cliffs on the beach will have a great impact on the sea turtles trying to nest. Literature together with observations made at the Caño Palma Biological Station showed that if the cliff is too high, the turtle will not go over the cliff and instead of nesting, halfmoons will be seen on the sand (Carpio Camargo et al., 2020; Rivas et al., 2016). Halfmoons will occur if the location, once the turtle emerges from the water, is not suitable for nesting (Garnier et al., n.d.). Even if the turtles manage to go up to cliffs after few trials, the effort made will be important and the turtle may not be able to nest very far away from the high tide line and the nest site may not be optimal.

Given the erosion-prone characteristic of the Playa Norte beach, the high dynamism of the process together with the high fidelity of the turtle species for this beach, it was critical to know the impact of the erosion on the development of the turtle's eggs.

II – Impact of the erosion rate on the temperature inside a nest

To assess the impact of the erosion rate on the temperature, a multiple regression has been realized. Results observed showed a variation in temperature related to the change of nest depth through time (p-value <2e-16). However, observing the adjusted r-squared, the variation in temperature is only explained at 20% by the change in depth and the different zones (with an adjusted r-squared equal to 0.2015), meaning that even if a relationship is observed between the temperature inside the nest and its depth, no conclusive link can be drawn. An assumption made was that the reduction of the depth caused by the erosion would favor an increase in the temperature inside the eggs chamber, as it will be closer to the surface and therefore more likely to be heated by the sun during the day. In the same way, the egg chamber should be more inclined to have temperature variation within 24h, following the drop of temperature at night and the relative increase during daylight depending on the weather and the location on the beach (Gammon et al., 2020). The results obtained show that the sand's capacity to buffer the variation of temperature is high, to the point that even with a lot of sun, or during a change of temperature corresponding to the dial cycle, the temperature will remain stable at the depth of the eggs chamber. Moreover, by field observation, together with the graphs obtained, it has been seen that the data logger located in the open zone at Marker 11 remained stable through the incubation time, as seen in the *Figure 9*. Even if the maximum of erosion registered was 6 cm above the egg chamber, the data logger was very close to a cliff, up to only 20 cm away from it, meaning that the sun was heating the sand on the side of the nest, which could have influenced the temperature inside the egg chamber, but no conclusive increase of the temperature has been observed.

In terms of consequences on the sex ratio, a feminization of the hatchlings was expected together with an increase in the temperature, which would have impacted the survival of species in the long term (Laloë et al., 2014, Laloë et al., 2017). The incubation temperature that produces 50% of each sex is defined as the pivotal temperature or threshold (Ackerman, 1997). An increase in the temperature during the middle third of the development of the embryo, when the sex of the turtles is defined, can favor a sex ratio towards females if the threshold is exceeded (Segura & Cajade, 2010). Therefore, even a small increase in the temperature during the middle third of the development of the embryo will have a huge impact on the sex ratio of the offspring. The results obtained illustrate rather an all-or-nothing event where the turtle's nests will not be affected by a change in the temperature inside their eggs chamber until it gets completely eroded by the ocean.

The absence of concrete variation in the temperature in the results shows that there is no impact of erosion itself on the nests concerning the variation in temperature. However, erosion is often linked to an increase in flooded nests, as an extreme weather event comes with a reduction of the beach portion (Martins et al., 2022; Pike & Stiner, 2007). Following the nest check protocol of the Caño Palma Station, a nest is considered wet when the high tide line reaches the nest, but the eggs still have a chance to dry out. A nest is considered natural when no new activity has been recorded since its first discovery. A nest will be eroded when a cliff higher than the nest's depth goes through the nest, washing out the chamber containing the eggs. Finally, a nest constantly in contact with water, either under the low tide line or with a puddle of water present above it, is noted as flooded (COTERC, unpublished data). The flooding of the nests will put the eggs in contact with constant water, and while some studies observed that it increases the risk of diseases, bacteria, and fungus emergence, it can also favor a decrease in the temperature (Martins et al., 2022; Patino-Martinez et al., 2012). With increasing sand water content, a decrease in the hatching success and the emergence success can be seen. During the development of the embryos, an exchange in the respiratory gases and water occurs with the surroundings, and an excess in water content in the nest may form a protective layer that blocks gas exchange, leading to asphyxiation and embryo mortality (Martins et al., 2022). Moreover, an increase in moisture content can induce a decrease in the sand temperature, reducing embryo metabolism and overall embryonic development and with it, the incubation duration. Studies found out that clutches recorded under lower temperatures were observed to have longer incubation duration compared to clutches experiencing warmer temperatures (Martins et al., 2022). Erosion together with flooding events causes multiple damages to the topography of the beach and decreases the hatching success of sea turtles with high erosion-prone beach fidelity. However, not every turtle specie is impacted the same way by those events and understanding the difference in their impacts is therefore necessary in terms of conservation strategies.

III – Inter species comparison

Whether the temperature varies or not inside a nest with a change of depth will influence nesting strategies of sea turtles. The two species that are the subject of the study, green and leatherback turtles, have different nesting strategies (Davenport, 1997; Mrosovsky, 1983). Focusing on the way the nests are formed, the leatherbacks will dig deeper nests, with an average depth being 75cm, while greens will dig shallower nests, with an average nest depth of 55cm (Whitmore & Dutton, 1985). According to the literature, the increase of the nest depth will increase the stability of the nest, therefore it has been presumed that the nests of the green turtles, shallower, will experience a greater variety of temperatures in case of erosion (Heredero Saura et al., 2022; Whitmore & Dutton, 1985). A 2 samples t-test has been realized in addition to the multiple regression, comparing the mean temperatures of the two nest depths. A p-value of 0.01611 was obtained. Even with a significant p-value, concurring with the multiple regression, the difference in means between the two groups is only 0.58493 Fahrenheit or 0.32488 Celsius degrees. This difference in temperature is a very small variation compared to the increase averaging around 2.5◦C caused by the metabolic heat at the end of the development of the embryos (Gammon et al., 2020). This increase varies within and between species with metabolic heat in the final semester ranging from 1.2◦C in loggerhead nests to 4–8◦C in leatherback nests (Gammon et al., 2020). With an augmentation up to 8◦C in leatherback nests, a variation of 0.3◦C can be considered as minimal and won't be the cause of the change in the sex ratio.

Multiple studies (Jourdan & Fuentes, 2015; Santidrián Tomillo et al., 2017; Van De Merwe et al., 2006) observed cooler temperatures in the nests 75 cm deep than in the nests 55cm deep. They have also observed that deeper nests experience more stable conditions with less variation in their temperature throughout the entire incubation time (Booth & Astill, 2001). Those observations are very interesting to contrast with the nest locations of the two species. According to Mrosovsky (1982), leatherbacks move slower on the sand than green turtles and follow a less straight path. Therefore, nesting far from the sea will put them in difficulties once they need to return to the sea after nesting and will also expose their offspring to the same difficulties. Moreover, leatherback offspring, lacking the imposing stature of their progenitor, will have higher chances to be predated when the distance to cover increases. Following this finding, multiple articles, and the data from the COTERC station, observed that leatherbacks tend to nest closer to the high tide line, mainly on the open zone of the beach, exposing their nests to a bigger danger of erosion (COTERC, unpublished data; Kamel & Mrosovsky, 2004; Mrosovsky, 1983). A pattern of nest site selection can therefore be observed where the disadvantages of nesting too low on the beach or too high form pressures forcing the leatherbacks to nest in a restrained part of the beach, prone to erosion (Kamel & Mrosovsky, 2004; Mrosovsky, 1983).

In comparison, according to Bjornal and Boltern (1992) as well as the data recorded by the COTERC station, the green turtles are nesting in equal proportion in the open and border zones of the beach (COTERC, unpublished data). Within a season, individual green turtles that will nest multiple times are more likely to lay eggs in more than one zone of the beach. They are also more likely to follow the population's pattern of the year in term of nest distribution than to maintain their own individual pattern through the years (Bjorndal & Bolten, 1992). The Caño Palma biological station has reported, for the 2022 season, that green turtles will preferentially nest in the open zone with 54.8 % of the nests found in this zone, followed by the border zone (42.2%) and finally, the vegetation zone (3%) (COTERC, green turtles report 2022). According to Whitmore and Dutton (1985), the hatching success of green turtle nests is similar in the sand and border zones, which may be the result of an adaptation to limit the competition with leatherbacks for nest sites in the sand zone by selecting sites further back on the beach, in the border zone. Moreover, green turtle nests are shallower than leatherbacks' and are more likely to be destroyed by leatherbacks trying to dig a nest in the same zone (Whitmore & Dutton, 1985). This hypothesis of competition between greens and leatherbacks on the nest selection does not seem to affect other species like Hawksbill, nesting sensibly at the same time and on the same beaches, like Playa Norte or Tortuguero beach, located further south of it. The nest's depth of Hawksbill is shallower; however, no avoidance behavior is reported for this species (Bjorndal & Bolten, 1992). Hawksbill turtles will nest in the three zones, studies have reported that Hawksbill nest as often in the open as in the border zone (Bjorndal & Bolten, 1992), whereas nests are also found in the vegetation zone at Playa Norte (COTERC, unpublished data). Therefore, the shallower depth of the nests in green turtles may be the reason to nest further away from the high tide line. Indeed, shallower nests are more likely to be eroded and as green turtles are moving faster in the sand, their interest in nesting further from the high tide line is greater.

In addition, the dynamic structure of Playa Norte allows the open zone of the beach to be free of any vegetation. Indeed, the erosion cycles remove and then replace the sand between nesting seasons, effectively cleaning the sand of each year's nest debris and vegetation (COTERC, unpublished data). This way, the erosion normally prohibits the seaward spread of Ipomoea pes-caprae a fast-growing vine spreading along the beach surface, tolerating extreme temperatures, direct sunlight, high salinity, and nutritionally impoverished soil (Devall, 1992). I. pes-caprae plays an important role in beach stabilization with its roots, penetrating more than one meter, vertically into the substrate and remaining dormant even when the surface vegetation dies. The plant will anchor in the substrate, limiting the erosion impact and allowing the apparition of other types of vegetation like bushes and trees. However, Conrad et all. (2011) found out, in controlled experiments that Ipomoea pes-caprae decreased nest productivity by reducing leatherback hatching and emergence success rates. The plant obstructs nest construction (Bustard & Greenham, 1968; Chen et al., 2007) and potentially dries out the sand, which can result in egg chamber collapsing during nest excavation (Bustard & Greenham, 1968). Those discoveries concord with the erosion-prone preference of the leatherbacks in terms of nest selection, searching for a zone free of vegetation. (Conrad et al., 2011).

Future studies may observe a change in the tendency, with sea turtles wanting to nest away from the sea to protect the eggs from flooding and thus maximizing their hatchling success. With an increase of flooding and erosion events, the pressure of predation and vegetation spread may not be high enough to stop green and leatherback turtles from nesting on the border and the vegetation zones. Because the roots of I. pes-caprae do not seem to disrupt the hatchling success of the green turtles (Conrad et al., 2011), they will be able to nest further away, mainly in the border zone, with a proportionate part of the remaining nests in both open and vegetation. Leatherbacks will probably have no choice but to nest in nest in the open and the border zones, areas that are composed mainly of I. pes-caprae, reducing their hatchling success but avoiding the complete loss of the egg chamber by the erosion process (Conrad et al., 2011). The two species may as well start digging deeper nests to limit the same risks, even if this adaptation will be limited as the cliffs seen at Playa Norte are usually very high and will wash out an egg chamber located deeper in the sand.

IV –Towards the prospects of adapted responses to erosion

Finding solutions to limit the effects of erosion is primordial but very difficult to introduce knowing its unpredictable nature, even at a local level. Coastal management, storm frequency, mismanaged protection project and rise of the sea level are factors that can vary greatly on a large and small scale (Davis, n.d.). Therefore, it is essential to know and take into consideration the impact of erosion on vital nesting beaches to better inform and prioritize conservation actions. Coastal erosion and shoreline management plans are often implemented in reaction to an extreme event and not as a preventive action. Hard engineering structures such as groins, seawalls, revetments, gabions, and breakwaters, are structures usually used in those cases, but their implantation will often cause negative impacts for the ecosystem of the coast (Gracia et al., 2018). This approach is therefore limited and not very sustainable nor adapted to coasts with rich ecosystems. An evolution to smarter coastal protection strategies is needed that are also economically viable to restrain the predicted and unpredicted issues of erosion. According to Gracia et al. (2018), an evolution toward an ecosystem-based approach is a necessary step. This approach is based on the creation and restoration of coastal ecosystems, such as wetlands (e.g. mangroves), biogenic reef structures (e.g. corals, oysters, and mussels), seagrass beds and dune vegetation can offer optimal natural alternatives to help solve coastal erosion (Gracia et al., 2018). The self-repair and recovery of coastal ecosystems provide a significant advantage over traditional hard engineering solutions and reduce the impact on coastal communities of hazards of erosion by their multiple functions in processes, including sediment capture, system roughness, and thus attenuation of wave energy (Gracia et al., 2018).

The options put forward by the author are, in idea, interesting but need to correspond to the beach topography of Playa Norte. Concrete solutions are needed that are feasible for the Caño Palma station and its volunteers. The Costa Rican Ministry of Environment and Energy is focused on the conservation of beaches as well as their biodiversity and is aware of the danger of the erosion of Costa Rican beaches. However, it is very unlikely that a budget will be released for Playa Norte, to implement a system and reduce the risks associated with flooding and erosion processes, despite its importance for sea turtle populations (Davis, n.d.). If some solutions, using the present ecosystem can be locally applied, they present disadvantages for some turtle species. Thus, studies like (Neto et al., 2006), are using the Ipomoea pes-caprae in dune rehabilitation projects, given its ability to limit erosion and cliff formation. The vegetation cover traps and holds wind blown sand and stabilizes beaches and dunes (Neto et al., 2006). The loss of vegetation makes the beach and dunes more susceptible to wind and water erosion, thus inhibiting their recovery from storms. On another hand, the eradication of the Ipomoea pes-caprae's spread has been studied by (Conrad et al., 2011) to free up more nesting sites for the leatherback turtles. Neither mechanical removal nor herbicidal treatments were successful in managing their roots. They then proposed clearing small sections of surface vegetation and completely removing roots to create small nest relocation sites. This option could take place when the seaward spread on nesting beaches is large and nest relocation is necessary (Conrad et al., 2011). Adapting this solution at Playa Norte is technically feasible but will require a lot of work, which is difficult to envisage given that the turtle season already requires a lot of volunteers. Moreover, big nesting beaches are usually female biased probably due to the higher frequency of reproduction for the males compared to females (Sieg et al., 2011). The bias observed is therefore very important for the survival of the turtle's species. This bias is affected when relocalization is taking place. According to the literature, the translocation of eggs chambers that don't have any survival chance prior to it is needed but lessens the female bias of those eggs (Sieg et al., 2011).

This situation illustrates the complexity of the ecosystem and the intrinsic relationships of each of its components, with the deep roots of the Ipomoea pes-caprae providing stability to the beaches and dunes but creating a disadvantage when it comes to leatherback nests, forcing them to restrict themselves to the part of the beach without vegetation, the most prone to erosion.

V - Study bias

Overall, the initial questions were all answered, and the following inconveniences did not interfere strongly with the running of the study. The main obstacle was to let the data loggers at the view of everyone passing on the beach, and two of them have been taken away. To avoid the loss of additional data loggers, the second set was shortened. Therefore, the second set lacks measurements and the reliability could have been increased if the data loggers had stayed longer in the sand. Because the data loggers have not been buried in real nests, the temperature recorded during the experience does not take into consideration the actual temperature inside a nest with the metabolic heat occurring during the embryos' development. The budget allowed for this study is limited, only 15 data loggers have been buried at 5 different markers and each time, in the three different zones. To remedy this, the data loggers, with a total recording length of 120 days, have been buried at first for 1 month, prior to being unburied and reburied again for a second set of measurements. Finally, the extremely dynamic profile of the beach made the placement of the data loggers in the different zones of the beach difficult, due to the change in the width of the beach from one day to the next. When burying the data loggers, at some markers, no open zone was observed, causing the data loggers to be buried at the edge of the border one. This situation made the results more difficult to interpret, as the zones were not as clearly defined as desired.

Conclusion

With a variation of the temperature that is not clearly linked to the depth nor the different zones of the beach, it has been concluded that the real threat for the eggs inside the chamber isn't the feminization of their nest due to the augmentation of the temperature but the complete loss of the eggs, being washed out when erosion is occurring. In other terms, following an all-or-nothing event, the nest won't be affected by erosion unless a cliff comes. The cliff needs, however, to be high enough to take the eggs chamber as it progresses further away from the sea, On the conservation aspect, the results are positive as they reduce the list of factors impacting the success of hatching. The fact that the results indicate a very little variation of the temperature from one area of the beach to another also suggests that it may be possible to relocate the turtle nests most likely to be eroded through the passage of a cliff without changing the outcome of the sex-ratio. However, as the study hasn't been conducted in real nests, the results cannot be taken at face value.

Further studies will need to be realized to see the difference in temperature in real nests for the three zones at Playa Norte specifically, to take appropriate and sustainable conservation measures. Studies that link the variation of rainfall through the seasons with the degree of erosion should also be interesting to develop, given the known correlation between the weather and erosion events (Faivre et al., 2011; Naylor et al., 2017)**.** Moreover, it seems that the amount of rainfall during a season influences the nesting behavior of the turtles. In a study realized by (Bjorndal & Bolten, 1992), at Tortuguero beach in Costa Rica, a year drier than the surroundings year will force the green turtles to avoid the open zone, because of the sand, too dry, and therefore collapsing on the sides of the nest chamber. They will attempt to nest further up until they reach greater sand moisture at the border or the vegetation zones to be able to dig a proper egg chamber.

Increasing the research, made on the beaches that host a high number and diversity of turtles every year, is crucial to better understanding the processes affecting them. Huge efforts are yet to be made to protect sea turtles and other marine species to avoid their complete extinction.

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Annexes

Table 3. Number of nests, halfmoons and total green turtle events through the years. Activities recorded by the Caño Palma Biological Station from 2006 to 2022, in a 5km transect beginning at Tortuguero river's mouth and finishing at the Laguna Cuatro.

Year	Nbr of nests	Nbr of half moons	Total of turtles activity
2006	347	567	914
2007	803	1031	1834
2008	446	735	1181
2009	168	372	540
2011	273	193	466
2012	735	1560	2295
2013	33	47	80
2014	265	602	867
2015	238	807	1045
2016	532	2105	2637
2017	333	832	1165
2018	221	602	823
2019	411	1314	1725
2022	762	1300	2062

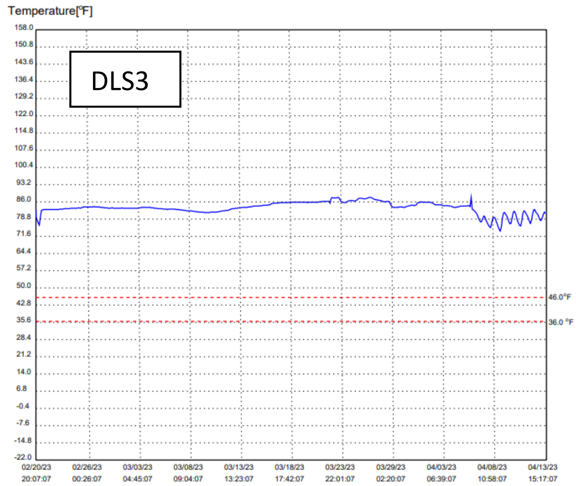
Table 4. Number of nests, halfmoons and total leatherback turtle events through the years. Activities recorded by the Caño Palma Biological Station from 2006 to 2022, in a 5km transect beginning at Tortuguero river's mouth and finishing at the Laguna Cuatro.

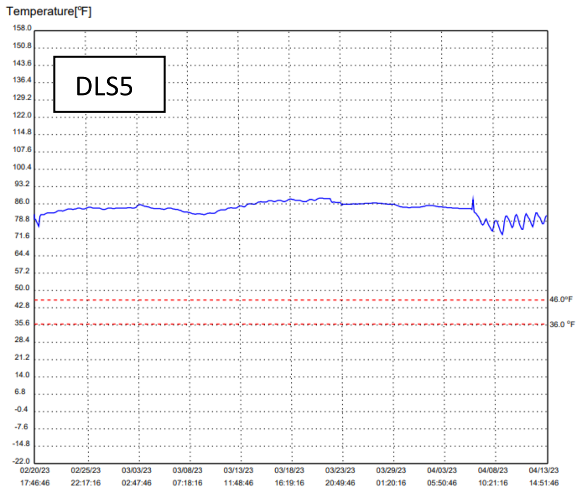
Year	Nbr of nests	Nbr of half moons	Total of turtles activity
2006	52	24	76
2008	90	22	112
2009	70	80	150
2010	28	9	37
2011	71	33	104
2012	66	24	90
2013	44	29	73
2014	29	15	44
2015	34	36	70
2016	15	27	42
2017	25	24	49

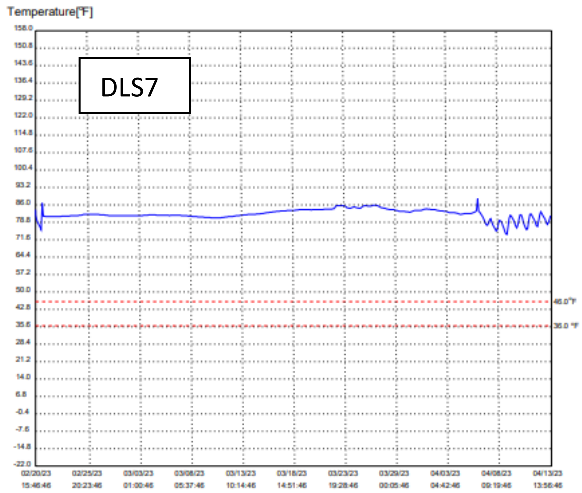
2018	22	21	43
2019	40	21	61
2022	20	11	31

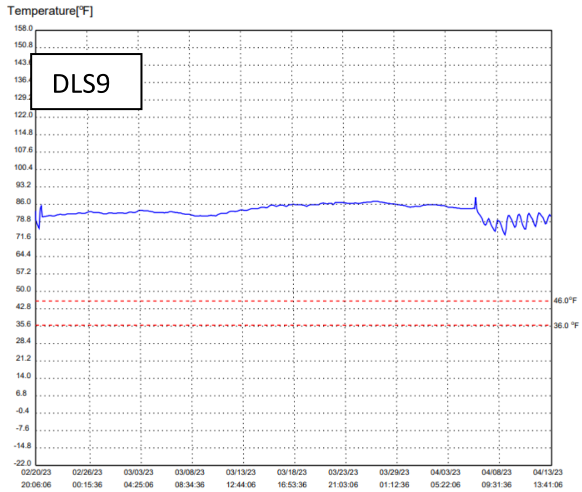
Table 5. Mean of temperatures for every data logger and separated by the different zones of the beach. The data were collected between February and April 2023, in Playa Norte, Costa Rica.

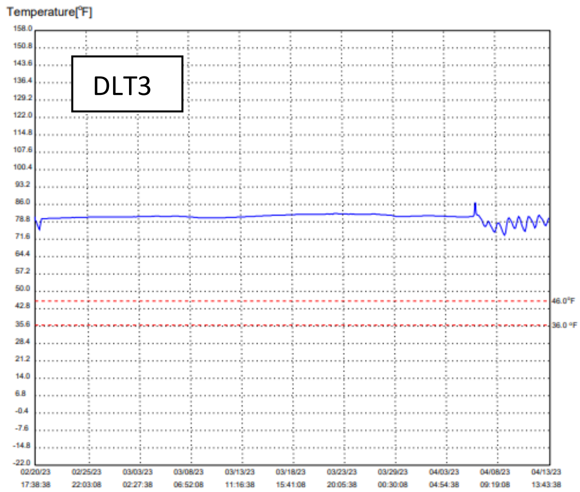
Zone	Tag	Mean 1st set	Mean 2^{nd} set	Mean zone
Open	DLO3	**83.8665767**	**85.7613218**	**84.1763201**
	DLO5	**84.9860057**	**85.4610345**	
	DLO7	**82.2245402**	**84.2922989**	
	DLO9	**83.5073563**	**86.0713218**	
	DLO11	**83.828046**	**84.6452874**	
Border	DLB3	**79.7034483**	**80.4757471**	**82.9820547**
	DLB5	**84.6924425**	**85.256092**	
	DLB7	**82.1439943**	**84.2531034**	
	DLB9	**84.2025**	**84.1438506**	
	DLB11	**82.751092**	**83.8512069**	
Vegetation	DLV3	**81.108565**	**81.5577586**	**82.1074174**
	DLV5	**83.1382759**	**84.1067816**	
	DLV7	**81.3992529**	**82.2483333**	
	DLV9	**81.9945977**	**82.6547126**	
	DLV11	**81.4753161**	**83.0485057**	

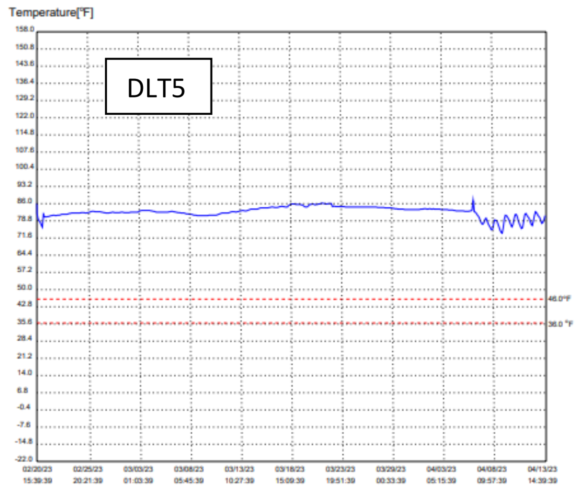

DLS3
Temperature[°F]
46.0°F
36.0 °F

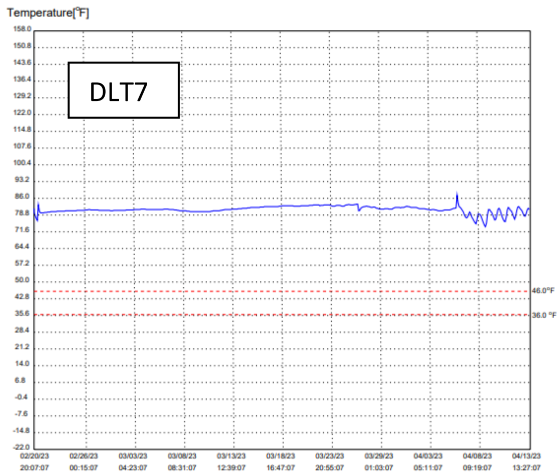

DLS5
Temperature[°F]
46.0°F
36.0 °F

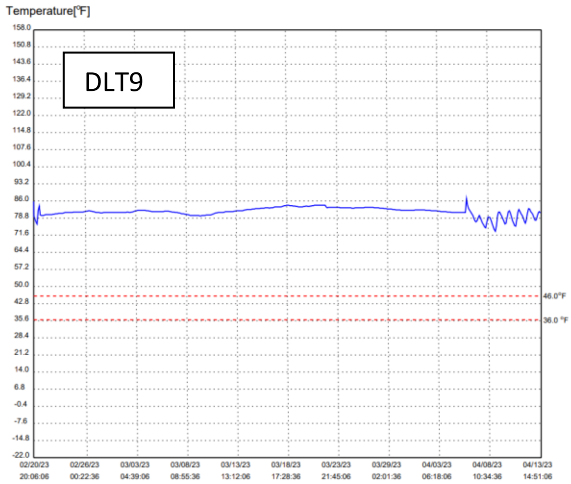

DLS7
Temperature[°F]
46.0°F
36.0 °F

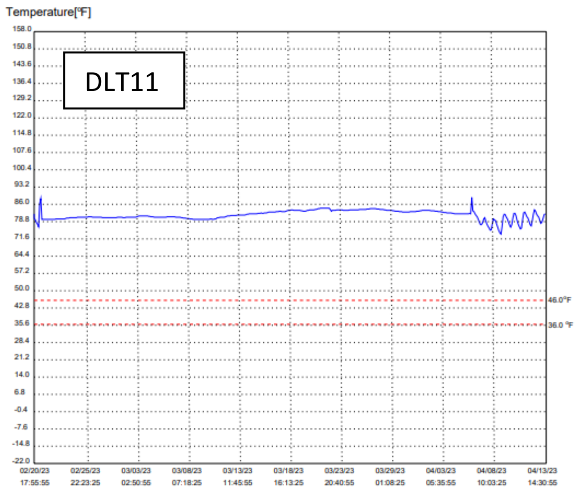

DLS9
Temperature[°F]
46.0°F
36.0 °F

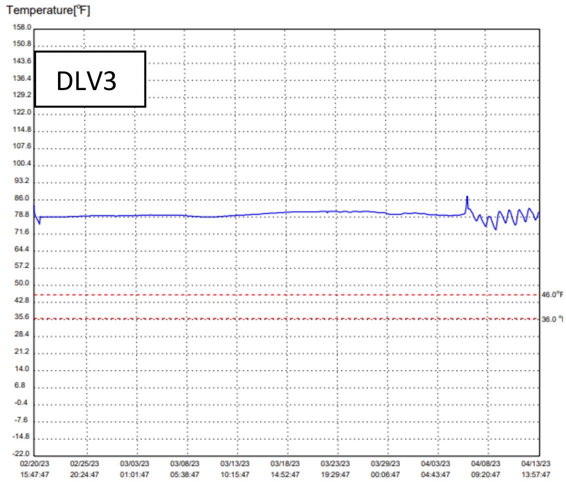

DLT3
Temperature[°F]
46.0°F
36.0 °F

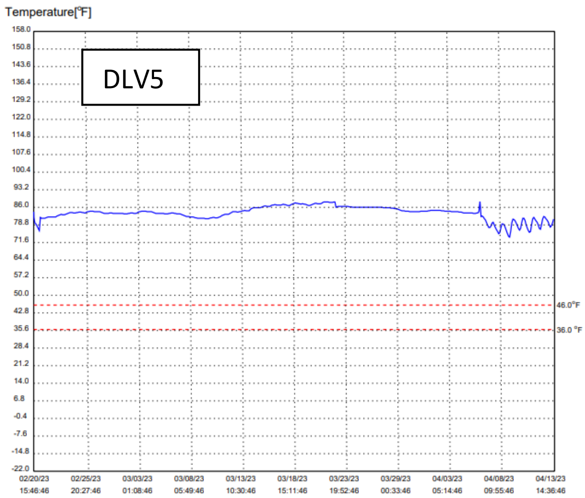

DLT5
Temperature[°F]
46.0°F
36.0 °F

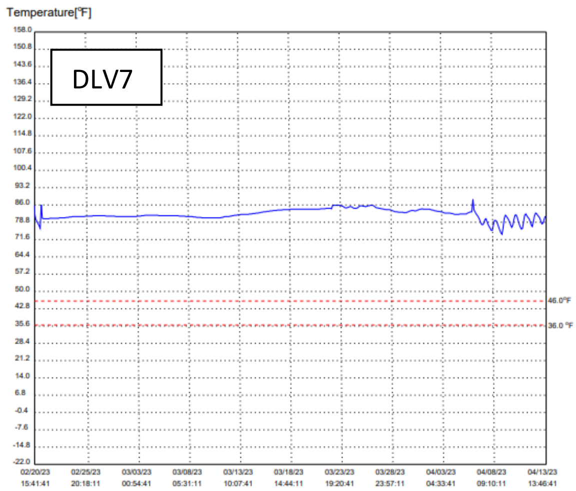

Temperature[°F]
DLT7
46.0°F
36.0 °F


Temperature[°F]
DLT9
46.0°F
36.0 °F


Temperature[°F]
DLT11
46.0°F
36.0 °F


Temperature[°F]
DLV3
46.0°F


Temperature[°F]
DLV5
46.0°F
36.0 °F


Temperature[°F]
DLV7
46.0°F
36.0 °F

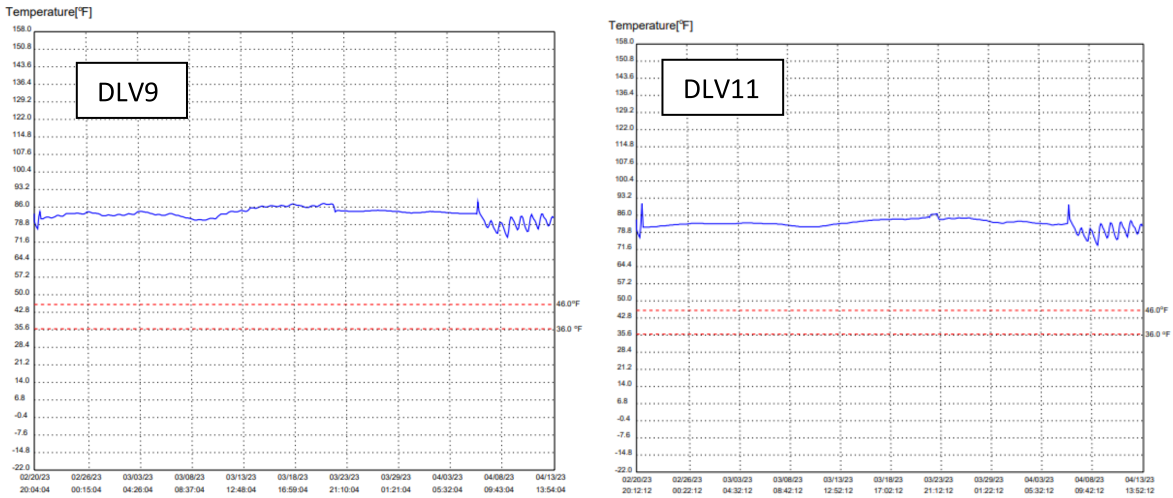


Figure 7. Graphics of the temperature for all the data loggers that don't appear in the results section.

DL is an abreviation for data logger, and V, B and O stand for the different zones of the beach, respectively Vegetation, Border and Open. The variations observed before the 22nd of February and after the 2nd of April correspond to the period where the data loggers were kept unburied at the station. A pic on the 22nd of March correspond to the moment where the data loggers have been unburied and reburied.