

Article

Hydrometeorological Variability of Olive Ridley Sea Turtle (*Lepidochelys olivacea*) Nesting Beaches: Implications for Conservation Practices

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Abstract: The conservation of the olive ridley turtle (*Lepidochelys olivacea*) is increasingly critical due to declining global populations. This study investigates the influence of hydrometeorological conditions on the nesting season and annual hatchling sex ratios conducted at the Playón de Mismaloya Federal Reserve in Tomatlán, Jalisco, Mexico. The research specifically examines variations in sand temperature at both the beach surface and nesting depths, with extended measurements taken at multiple depths (20, 40, 60, 80, and 100 cm) to analyze the vertical temperature gradient along the beach. Atmospheric parameters were modeled using Newton's Cooling Law and solved with the finite difference method to estimate heat loss rates from beach sand to its surroundings, shedding light on microclimatic effects on incubation and embryonic development. Meteorological data were gathered from an automatic weather station, while sand temperatures were monitored with thermographs. During the warm period (approximately 32 °C), sand temperature showed a negative correlation with depth (20–100 cm), indicating cooler temperatures at greater depths. These conditions were associated with female-biased hatchling production. Conversely, the cold period (approximately 28 °C) led to male-biased hatchling production, with a positive correlation between sand and air temperatures. This study emphasizes the importance of monitoring in situ environmental conditions and extending the protection season until February to avoid the loss of male hatchlings.

Keywords: olive ridley; *Lepidochelys olivacea*; climate variability; measurements of air and sand temperature; nesting variability



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1. Introduction

Sea turtles have the potential to function as bioindicators of ecosystem health [1–3]. There are seven species of sea turtles grouped into two families: Cheloniidae and Dermochelyidae [4,5]. Of these, six species nest on Mexican coasts. Sea turtles are a unique group of reptiles with a distinctive nesting behavior: they spend most of their lives in the ocean, returning to land only during the nesting season to lay eggs on the same beaches

where they were born [6]. Mexico is one of the most important countries for sea turtle conservation [7], with the six occurring marine turtle species protected under both local legislation, such as NOM-059-SEMARNAT-2010 [8], and their conservation status assessed through international protocols, including the Red List of the International Union for Conservation of Nature [9].

Currently, the main intervention tool for sea turtle conservation in Mexico is the establishment of so-called turtle camps. In these spaces, activities such as protection and conservation, research, inspection and surveillance, environmental education, and ongoing community training are carried out [7]. Each day, eggs are relocated from their original nests to on-beach hatcheries due to high rates of natural predation, illegal egg harvesting, and beach erosion. Hatcheries are located in the upper portion of the beach and fenced, and no procedure is practiced to prevent overheating of the nests, such as creating shadows on the surface of the nests or adding water [10].

Although the protection of nesting females and the relocation of nests to hatcheries are thought to have significantly increased sea turtle population sizes, there is no consensus on whether relocating nests to hatcheries or protecting them in situ is more effective in the long term. The former may involve unnecessary manipulation, which can impact hatching success, alter sex ratios, and lead to other phenotypic effects [10].

Sea turtles have a close relationship with their environment [11,12], as their behavior, distribution, and survival are strongly influenced by environmental factors such as temperature, ocean currents, and habitat availability. Nest success on protected beaches depends primarily on seawater inundation [13,14] and the thermal and moisture conditions within the nest chamber [15]. Additionally, sea turtles exhibit temperature-dependent sex determination (TSD) [16,17]. The pivotal temperature producing a 1:1 sex ratio in *L. olivacea* is approximately 30.16 ± 1.9 °C [18]; more males are produced at lower temperatures and more females at higher temperatures, with a lethal incubation threshold around 35 °C [19–21]. Nests located close to the high-water line may experience increased embryonic mortality due to seawater inundation [22] and may also experience significant decreases in incubation temperature [11].

Climate change may pose a particular threat to oviparous species, as eggs cannot thermally regulate incubation or avoid extreme temperatures [11]. Additionally, a warming climate could lead to increasingly female-biased hatchling sex ratios [23]. Tidal and storm overwash inundation events are expected to become more likely for nests located at lower elevations and closer to the high-water line due to wave run-up [11,24].

Generating information on environmental parameters (e.g., air temperature, sand temperature, wind speed and direction, humidity) at nesting beaches is of great importance [25]. This is essential due to the unique life cycle characteristics of sea turtles, such as temperature-dependent sex determination, late maturity, and high migration rates, which make them particularly vulnerable to variations in the ocean-atmosphere system [26–29]. Conservation programs must prioritize the monitoring of oceanic and atmospheric variables, enabling more accurate insights into the relationship between this coupled system and the status of sea turtle populations.

The aim of this study was to investigate the in situ variations in hydrometeorological conditions during the nesting season of the olive ridley turtle (*Lepidochelys olivacea*) and to identify the key factors influencing the variability of sand temperature at both the beach zone and the nesting depths where the turtles lay their eggs. To achieve this, the effects of various atmospheric parameters were investigated through a model based on Newton's Cooling Law, which was solved using the finite difference method. This approach enabled the estimation of heat loss rates from beach sand to its surroundings, providing a key tool

for understanding the influence of microclimatic conditions on incubation processes and embryonic development in this species.

2. Materials and Methods

2.1. Study Area

In the state of Jalisco, olive ridley, hawksbill, and leatherback turtles nest, and in 1986, three beaches were designated as protected areas for sea turtle conservation [30], including El Playón de Mismaloya (East Pacific RMU). The olive ridley (*Lepidochelys olivacea*) is one of the smallest and most abundant sea turtles in the world [25]. However, large-scale industrial exploitation in the 1960s drastically reduced their populations in the Mexican Pacific [31]. The nesting season of the olive ridley turtle (*Lepidochelys olivacea*) spans from July to January. Following significant population declines, the species no longer exhibits the large-scale nesting events known as “arribadas”. The nesting beaches at Playón de Mismaloya are characterized by a dynamic accretion–erosion system typical of high-energy coastal environments, where light-colored sand predominates.

The study area for this research was conducted at the Playón de Mismaloya Federal Reserve in the municipality of Tomatlán, Jalisco, Mexico. The reserve is situated between the coordinates of Punta Ipala ($20^{\circ}14' \text{ N}$, $105^{\circ}36' \text{ W}$) and Roca Negra ($19^{\circ}40' \text{ N}$, $105^{\circ}15' \text{ W}$) (Figure 1). The beach stretches approximately 30 km, with a maximum width of up to 120 m [32]. On the mainland, it is bordered by the Laguna Costera de Agua Dulce coastal lagoon, as well as the El Ermitaño, El Chorro, and Mahuas estuaries. The primary tributaries in the area are the María García and Tomatlán rivers, in addition to small marshes and sections of the mainland. Within this region, the “La Gloria” camp is located, where the data for this study were collected.

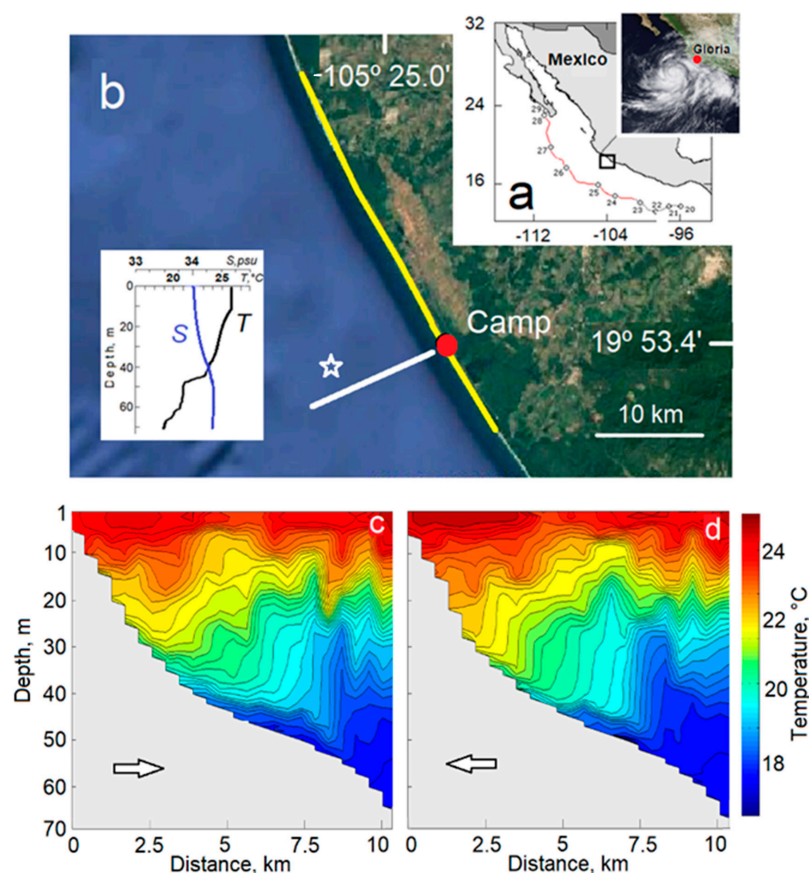


Figure 1. (a) Research area. As an example, the upper right corner of the figure shows the trajectory of tropical hurricane Juliette from 20 September to 1 October 2001 near the study area [32]. (b) The

location of La Gloria camp is marked with a red circle; the thick yellow line shows the section of the ocean beach on which fieldwork was carried out, and the thick white line marks the area of the sea taken by the undulated CTD profiler. The inset shows the temperature and salinity profiles measured at the deepest point of the transect. An asterisk marks the point for which temperature fluctuations in the surface water layer were calculated using the HYCOM model. In the lower boxes are shown vertical–horizontal sections of temperature when moving from the coast (c) and toward the coast (d).

According to García [33], the camp area has a warm, sub-humid climate with an average annual temperature ranging from 26 °C to 28 °C. The warmest months are from June to August, with an average temperature of 28.7 °C, while the coldest months are from December to March, with an average temperature of 24.5 °C. The average annual rainfall is between 700 and 800 mm, with precipitation concentrated in the summer. The rainiest month is September, with 242 mm of rainfall due to the presence of cyclones and tropical storms, while winters are dry, with only 1.5 mm of precipitation in February. The rainy season, corresponding to summer, extends from June to September, characterized by heavy precipitation and increased cyclone activity. The dry season, corresponding to winter, occurs from December to March, with minimal rainfall and cooler temperatures.

The tidal regime in this area is mixed, mostly semi-diurnal, with two high tides and two low tides per tidal day. It becomes diurnal a few days before and after the waxing and waning quarter moons [34,35].

2.2. Sea Surface Temperature Model

In this study, we used surface water temperature data near La Gloria camp obtained from the HYCOM reanalysis product (available at <https://www.hycom.org/dataserver/> accessed on 26 July 2022). The model has a horizontal resolution of 1/12°, 41 vertical layers, and a temporal resolution of 3 h. It uses the Navy Coupled Ocean Data Assimilation (NCODA) system [36] for data assimilation. This system assimilates available altimeter and sea surface temperature (SST) satellite observations, as well as in situ data from XBTs and Argo profiles for temperature and salinity. Additionally, the model uses 1-hourly data from the National Centers for Environmental Prediction (NCEP), the Climate Forecast System Reanalysis (CFSR), and the Climate Forecast System Version 2 (CFSv2) for surface forcing. As a result, a 3-hourly surface temperature time series was obtained for the period from 1 January 2008 to 31 December 2010 at a point as close as possible to La Gloria (−105.44° W, 19.87° N).

2.3. Sand and Coastal Waters Temperature Measurement

Beach sand temperature was measured at four points using HOBO thermographs (HOBO® Water TempProV2, accuracy ± 0.2 °C, time response of 10 min), with a sampling interval of 30 min. One device (HOBO) was buried 20 cm deep in the sand at locations 1, 2, and 4 (see Figure 2). The first thermograph was installed 15 m from the average high-water mark, with the remaining thermographs buried 13 m apart as they moved further from the water, reaching a maximum distance of 54 m. At location 3, which is closer to the hatchery area, five HOBO thermographs were placed at depths of 20, 40, 60, 80, and 100 cm.

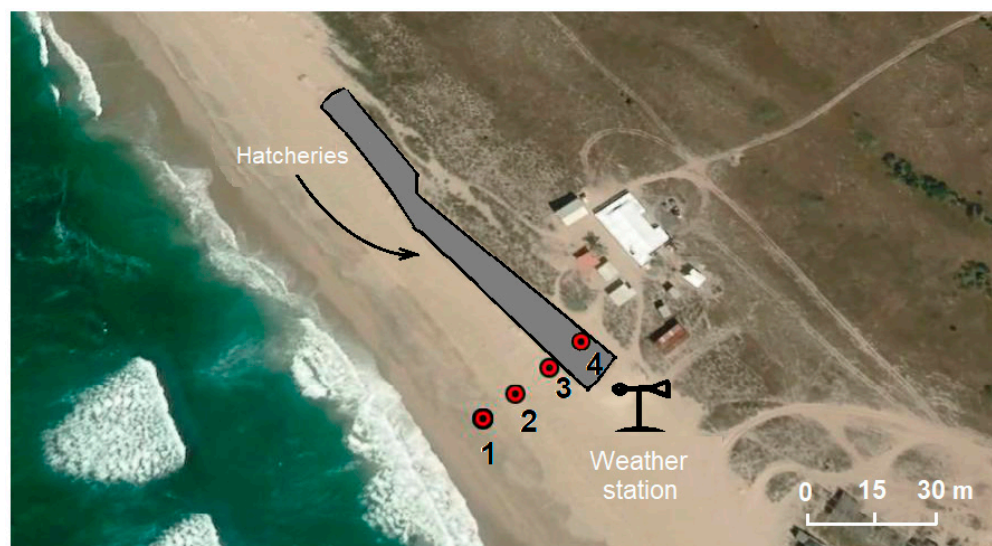


Figure 2. Satellite image of Camp “La Gloria,” showing the outbuildings, weather station, and turtle egg incubation area (hatcheries). The numbered circles (1 to 4) indicate the placement points of the horizontal and vertical antennas of thermographs used to measure the sand temperature.

The temperature structure of the sea was recorded using an undulating autonomous CTD RBR XR-620 (www.rbr-global.com), which was placed in a specially designed hydrodynamic case [37]. The CTD skimmed the surface as the boat moved at its maximum speed of 15 to 20 km/h. When the boat stopped for a cast, the profiler descended freely to a depth determined by the length of the tow rope. The CTD resurfaced once the vessel returned to full speed, continuing this process between stations [38]. The distance between casts was typically 200 m. Navigation data were logged using GPS. The survey could be completed quickly, with a shore-to-shore survey taking nearly two hours and more than 120 casts conducted.

It is true that water temperature can vary monthly and annually. However, since the thermal structure in the coastal zone of the Pacific Ocean has been well studied in previous research [34,39], we decided to conduct the temperature survey only once, on 24 July 2008, along a line perpendicular to the coast (Figure 1c,d), using a panga-type boat and a CTD. The total measurement time for both sections was 2 h and 55 min. Although seasonal and annual variations in temperature are likely, the data obtained during this survey allowed us to observe the thermal characteristics at a specific point in time and to detect phenomena such as intense internal waves in the coastal zone of the shelf. These waves move toward the coast and collapse as a result of the disintegration of tidal internal waves near the shelf edge (10–15 km from the coast) [34,40]. The periods of these waves near the coast typically range from 20 to 30 min, with amplitudes not exceeding 10–20 m, wavelengths of 200–500 m, and phase velocities of 20–30 cm/s.

2.4. Meteorological Measurements

An autonomous weather station (Croweather Davis Instrument Corp. system) was installed at a height of 3 m above sea level, 50 m from the shore (Figure 2). The station recorded various meteorological parameters, including air temperature, humidity, atmospheric pressure, wind speed, and wind direction every 30 min. To understand the dynamics of meteorological processes in the beach area and how these processes affect the temperature regime in the sand column, we used a series of observations collected from July 2008 to June 2010 at the meteorological station located near the hatcheries.

To compute the temporal variability of wind, air temperature, and sand temperature at depths of 20, 40, 60, 80, and 100 cm, the meteorological data were presented in the

form of two-dimensional matrices. The auto- and cross-spectral functions were calculated using the Fourier transform, followed by smoothing of the periodograms in the frequency domain. The spectra were computed to explore the periods and amplitudes of the dominant oscillations, as well as the coherence and phase difference between them (e.g., [34,41,42]). This analysis allowed us to determine the rate and depth of the vertical penetration of diurnal thermal waves in the sand.

2.5. Collecting and Transplanting Turtle Eggs

Every morning, camp collaborators circled the beach, digging up turtle egg nests and transporting them to the hatchery area for further incubation (as shown in Figure 2). The eggs from the relocated nests are placed in holes drilled at a depth of 40–60 cm in the sand, which mimic the size and shape of the turtles' natural egg chambers. The technique of relocating nests to a protected area for incubation includes the procedure of reducing stocking sizes. This means that the collected nest, depending on the size of the clutch, is divided into 2 or 3 sub-nests or is not divided at all. This method is widely used in Malaysia, Costa Rica, and Mexico to increase the total hatching rate of sub-nests [10,43–49].

To analyze the spatial patterns of beach nesting, we used GPS technology to record the position of each nest laid by turtles on a daily basis. The distance from each nest to the water's edge was determined from the average position of the wave-breaking zone along the coastline using Google Maps images.

The sex ratio of the nests was estimated using a maximum likelihood model proposed by Girondot [50], which is defined by a logistic function (Hill equation) and has also been utilized by Gammon et al. [51], Vinicius et al. [52], and Suganthan et al. [53] for similar analyses.

Ethics Statement

During our study, we did not handle sea turtle eggs nor participate in the process of relocating nests from in situ nesting areas to on-beach hatcheries. Our work was strictly limited to the installation of sensors in the beach sand and a meteorological station near the hatcheries without interfering with the routine conservation activities of the turtle camp. Data retrieval from the data loggers was carried out periodically, in some cases, by personnel from the turtle camp itself. Data regarding the clutch size and the nesting locations on the beach were provided by the camp headquarters. It is important to note that our study on the coastal and marine environmental dynamics of the turtle camp aligns with the research priorities of SEMARNAT (the official federal agency responsible for sea turtle conservation in Mexico), thus eliminating the need for a specific research permit for this study [54].

2.6. Energy Spectrum Analysis

Cross-spectral analysis is applied to pairs of time series from random processes, $x(t)$ and $y(t)$ [55]. This approach allows for determining the degree of interaction between these processes. The coherence function, derived from the auto-spectra and cross-spectra of these processes, is used as described below:

$$\left\{ \begin{array}{l} C_x(\omega) = \int_{-\infty}^{\infty} [x(t) \cdot \cos 2\pi\omega t - ix(t) \cdot \sin 2\pi\omega t] dt, \\ C_y^*(\omega) = \int_{-\infty}^{\infty} [y(t) \cdot \cos 2\pi\omega t + iy(t) \cdot \sin 2\pi\omega t] dt, \end{array} \right\} \quad (1)$$

The following expressions are introduced for the amplitude spectra:

$$S_{xy}(\omega) = \frac{1}{T} (a_x(\omega) - ib_x(\omega))(a_y(\omega) + ib_y(\omega)) \quad (2)$$

From here,

$$S_{xy}(\omega) = P_{xy}(\omega) - iQ_{xy}(\omega), \quad (3)$$

and finally, coherence function is found from the following relation:

$$C_0^2(\omega) = \frac{|S_{xy}(\omega)|^2}{S_{xx}(\omega) \cdot S_{yy}(\omega)} = \frac{P_{xy}^2(\omega) + Q_{xy}^2(\omega)}{S_{xx}(\omega) \cdot S_{yy}(\omega)} \quad (4)$$

If $C_0^2(\omega) = 0$, then it is considered that there is no linear relationship between the processes x and y ; if $C_0^2 = 1$, then it is considered that there is a linear relationship between the processes at the frequency ω with the following phase difference:

$$\Delta\phi_{xy}(\omega) = \arctg\left(\frac{Q_{xy}(\omega)}{P_{xy}(\omega)}\right). \quad (5)$$

2.7. Modeling Sand Temperature

To model sand temperature using air temperature data, a variation of the model employed by Narasimhan [56] was developed. This model is based on the combination of the heat conduction equation and Newton's Law of Cooling. The heat conduction equation is used to describe how temperature propagates deep into the sand, while Newton's Cooling Law models the heat transfer between the sand surface and the surrounding air. This combination of approaches allows for the estimation of sand temperature as a function of air temperature and other relevant parameters.

In the initial phase, we define the heat conduction equation, a fundamental tool for characterizing heat propagation within the sand medium. It is expressed as follows:

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T \quad (6)$$

where ρ is the density of the sand (kg/m^3), c is the heat capacity of the sand ($\text{J}/(\text{kg K})$), k is the thermal conductivity of the sand ($\text{W}/(\text{mK})$), and T is the temperature of the sand at depth (K).

Therefore, in order to comprehend the variations in the surface temperature of sand resulting from its interaction with air temperature, we will employ the equation of Newton's Cooling Law, expressed as follows:

$$\frac{\partial T_s}{\partial t} = h(T_a - T_s) \quad (7)$$

where T_a is the air temperature (K), and T_s is the sand temperature (K) and h is the convective heat transfer coefficient ($\text{W}/(\text{m}^2 \text{K})$).

To solve both equations, we applied the heat conduction equation at a depth of 40 cm. Subsequently, we employed the equation corresponding to Newton's Law of Cooling at the surface to conduct a comprehensive analysis of the process. This methodology allowed for a detailed evaluation of the temperature variation in the system, providing a deeper understanding of the thermal phenomena involved.

The temperature of the sand at depth (40 cm) is the following:

$$\rho c \frac{\partial T_{40}}{\partial t} = k \nabla^2 T \quad (8)$$

The temperature of the sand at the surface is the following:

$$\frac{\partial T_s}{\partial t} = h(T_a - T_s) \quad (9)$$

The solution to the system of equations was achieved through the application of the finite difference method. This method was implemented using the collected air temperature data and considering the initial condition, which encompasses the first recorded temperature value in the sand obtained from the sensors.

During the resolution process, the following parameter values were utilized: $\rho = 150 \text{ kg/m}^3$, $c = 830 \text{ J/(kgK)}$, $k = 0.25 \text{ W/(mK)}$, and $T_0 = 29.165 \text{ }^\circ\text{C}$. These parameters are fundamental for establishing the initial conditions and the thermophysical properties of the medium under analysis. The mean square error (MSE) to quantify the disparity between the simulated and observed sand temperature values was estimated. The outcome revealed a value of $1.47 \text{ }^\circ\text{C}$, indicating a reasonable level of accuracy in our model's capacity to replicate the thermal conditions within the studied system. This metric serves as a valuable indicator of simulation quality and affirms the utility of our mathematical approach in the realm of hydrometeorology and thermal modeling. The correlation between sand and air temperatures was calculated using the standard statistical method [55].

3. Results

3.1. Meteorological Analysis

3.1.1. Wind Variability

Throughout the year, at night, starting around 20:00 and continuing until about 10:00 the next morning, wind speeds generally remain low, not exceeding 1–2 m/s. After this period, the wind gradually intensifies, typically reaching 10–15 m/s by 14:00–15:00, with a direction near the shore ($270\text{--}300^\circ$). During certain periods, especially with the passage of tropical cyclones, wind speeds can increase to 20–25 m/s while generally maintaining the same directional trend. From 9 to 12 October 2008 (Figure S1), tropical storm Odile [57] passed near the campsite, with the storm's center moving parallel to the coast at a distance of only 50–70 km. On these days, the meteorological station recorded wind speeds at the study site of nearly 29 m/s, with atmospheric pressure dropping to 997 mb.

The wind data were processed to highlight key temporal characteristics of the wind field structure. Hourly measurements were averaged over the entire observation period and by month to capture both daily and seasonal variations, producing a 2D matrix that illustrates wind variability across times of day and throughout the year (Figure 3c). Histograms for wind speed and direction (Figure 3a,b) showed that maximum wind speeds were infrequent, with typical averages around 5–6 m/s observed between 10:00 and 17:00. For the rest of the day, winds were weak, generally not exceeding 0.1–1 m/s. During the day, the wind direction remained oriented to the north and northeast (toward the coast, Figure 3c), likely linked to a strong daytime coastal breeze and the absence of a nighttime breeze due to the nearby mountain range, located 20–25 km inland. Two seasonal patterns were identified: during the rainy season (June–September), the wind direction is consistently northerly in the morning (10:00–15:00), shifting northwest by afternoon (16:00–18:00); in the dry season (October–April), the midday and early evening winds (12:00–18:00) predominantly come from the west.

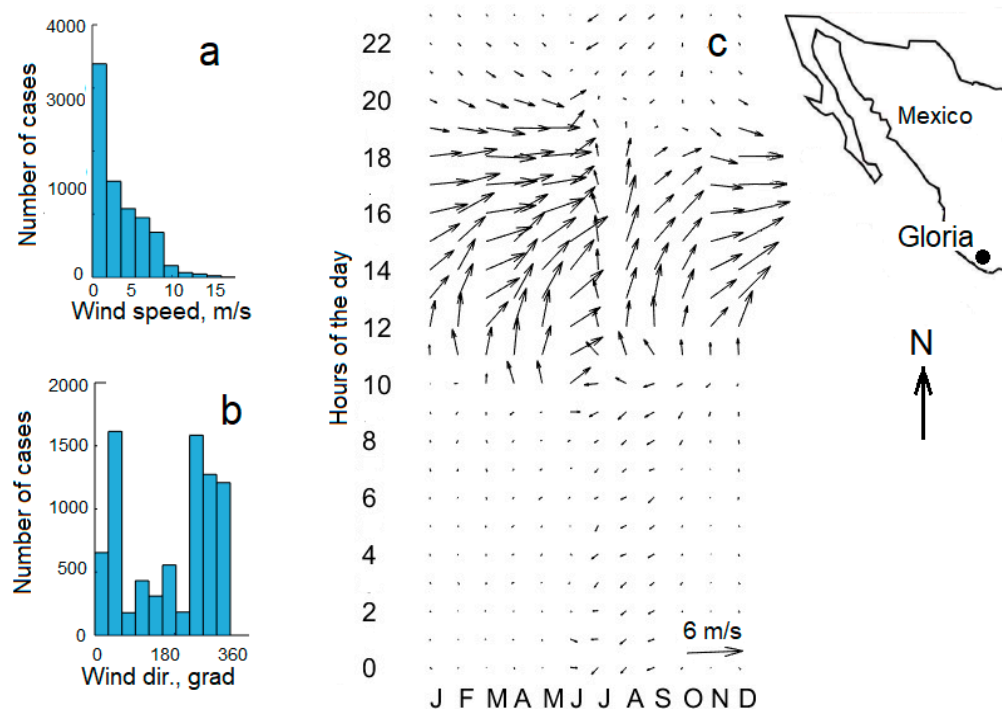


Figure 3. Histograms of wind speed (a) and direction (b) according to observations at the meteorological station in 2008–2009. (c) Hourly and monthly dynamics of wind speed and direction vectors.

3.1.2. Air Temperature

The air temperature at the camp throughout the year exhibited a diurnal variation, significantly moderated by the breeze circulation. During the summer months, daytime temperatures reached 30–32 °C, while nighttime temperatures dropped to 25–26 °C. In the winter months, daytime maximums did not exceed 25 °C, with nighttime temperatures ranging from 18–19 °C, reaching their minimum around 06:00 h.

3.2. Sand Temperature Variability on the Beach

The sand temperature, measured at a depth of 20 cm with the horizontal antenna of HOBO thermographs, and the air temperature are shown in Figure 4. Air temperature and sand temperature (at 20 cm depth) are highly correlated ($r = 0.956$, $p < 0.01$). The sand temperature curve on the beach generally follows the air temperature pattern but is, on average, 6.7 °C higher. We identified three distinct periods in the horizontal distribution of sand temperature. The first period, from early May to the end of June, is characterized by higher temperatures further from the high tide line (Figure 4c). In the second period, until the end of October, the sand temperature remained relatively constant on average. Finally, during the third period (November–January), an inversion occurred, with higher temperatures observed closer to the water and the wave-breaking zone rather than at the point furthest from the water.

The temperature difference between the sensor closest to the beach (first sensor) and the sensor furthest from the beach (fourth sensor) was almost 2 °C during the rainy season; however, this difference decreased to only 1 °C during the dry season. Sand temperature fluctuates significantly over time, with the main short-term variations being caused by rain events. For example, the passage of tropical depressions and hurricanes near the camp caused significant cooling effects on sand temperature, with a maximum decrease of up to 6.5 °C observed. Furthermore, rainfall has a homogenizing effect on the horizontal distribution of sand temperature. The magnitude and duration of the cooling effect depend

on the amount and duration of the rainfall, with heavier and longer-lasting rains leading to more significant and prolonged temperature decreases.

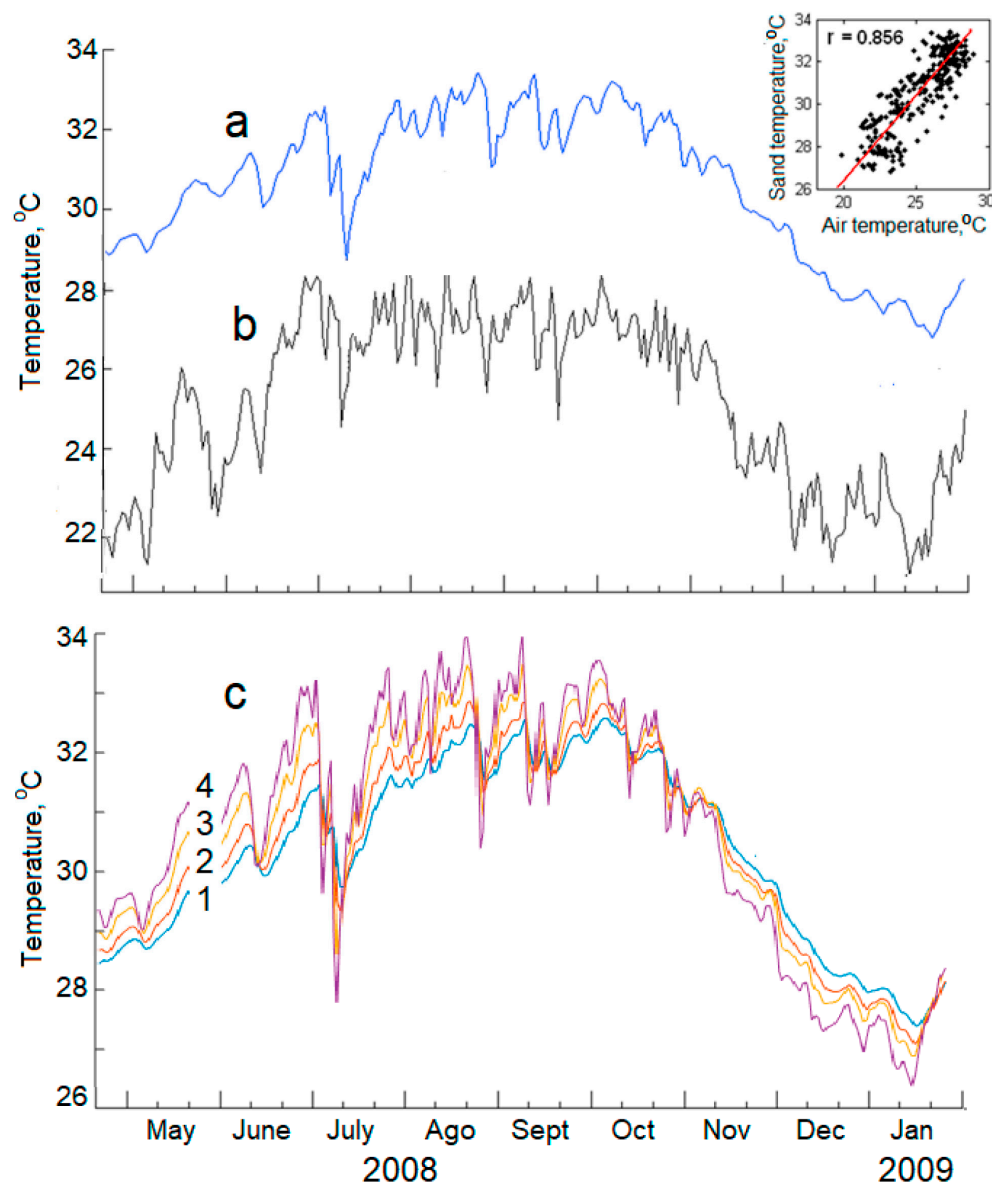


Figure 4. (a) Daily average sand temperatures at a depth of 20 cm, averaged across the four sampling zones where thermographs were placed. (b) Air temperature at a height of 2 m above the sand during the summer-autumn season of 2008 at the La Gloria camp. The inset in the upper right corner shows the graphical relationship between air and sand temperatures at the camp (point 3; 0.6 m depth). (c) Average daily sand temperature across the beach at a depth of 20 cm, recorded by thermographs distributed at four positions from the wave breaking line toward the land (see Figure 2). Thermograph numbers are indicated in Arabic numerals.

The highlight of the entire 2008 tropical cyclone season was the passage of Hurricane Elida, which occurred from 12–18 July. This category 2 hurricane (on the Saffir–Simpson Hurricane Scale) did not make landfall. On July 16, the wind speed in the storm reached 38.6 m/s, and the atmospheric pressure in its center dropped to 980 mb. During this period, the sand temperature dropped from 33 °C to 26.5 °C (Figure 5). Before Hurricane Elida, the area had already experienced the passage of two other significant weather disturbances: tropical storm Douglas and depression Five-E, occurring on 5–7 July. These events brought wind speeds exceeding 18 m/s and approximately 15.4 m/s, respectively. As a result, the weather scenario for the camp area was highly complex and potentially impactful.

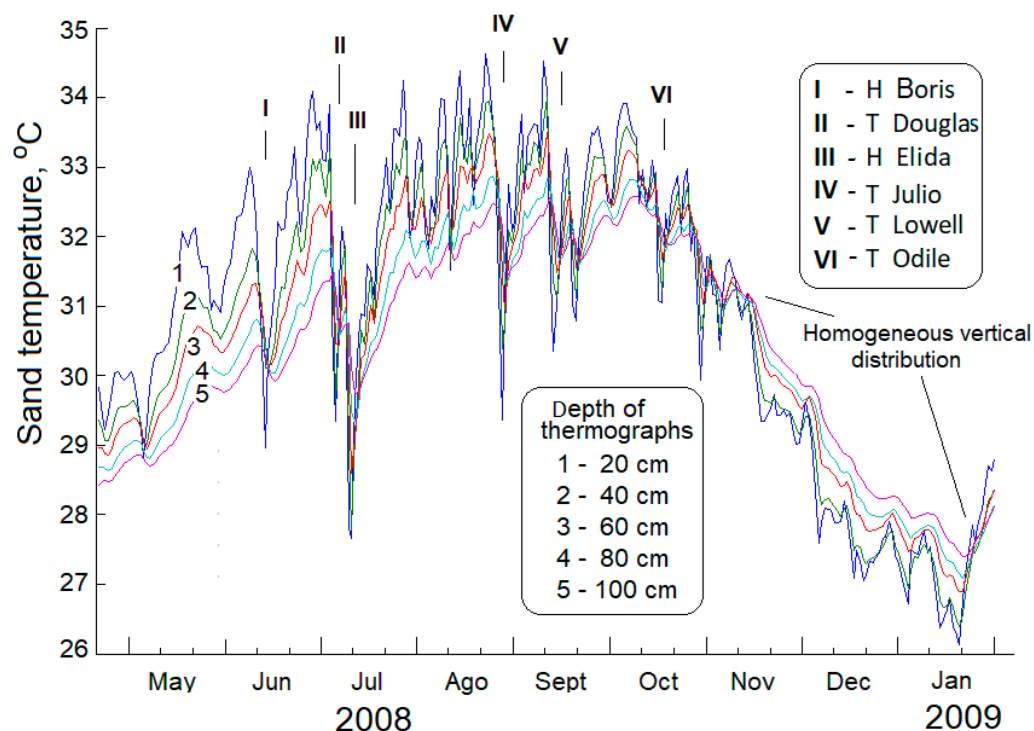


Figure 5. A vertical antenna of five thermographs was located at point 3, approximately 30 m from the wave-breaking zone. The figure shows the mean daily sand temperatures during the summer-autumn season of 2008, measured at depths ranging from 20 to 100 cm in the sand at the La Gloria camp area. Roman numerals indicate the moments when tropical cyclones (T) and hurricanes (H) passed near the camp, along with their respective names.

In the months following Hurricane Elida, tropical storms and hurricanes continued to affect the weather and cause sand temperature fluctuations through November. However, these fluctuations were not as dramatic as those described above, as the storms moved at considerable distances from the coast and did not have a significant effect on the temperature dynamics along the coastline.

Temporal patterns in the vertical distribution of sand temperature revealed three distinct periods (Figure 5). In the first period (May to June), all sensors showed an increasing temperature trend, with the highest temperatures in the surface layer decreasing progressively with depth. During the second period (late June to October), sand temperatures reached their highest values, maintaining the same vertical stratification. In the third period (10 November to the end of January 2009), an inversion of the sand temperature profile occurred: the temperature at 20 cm depth was the lowest due to autumn–winter cooling, while the highest temperatures were recorded at 100 cm depth. Tropical storms and hurricanes disrupted these patterns across the three periods, temporarily reducing sand temperatures and homogenizing the vertical profile. The correlation between air temperature and sand temperature at various depths weakened with depth, though it remained statistically significant in all cases ($p < 0.01$).

Comparing Figure 6a,b, we observe that the HYCOM model’s calculated temperatures generally capture the annual variability in surface water temperature near the camp. However, the model lacks the resolution to reveal finer details of sea dynamics associated with tropical cyclone passages, both near and at a distance from the camp, likely due to the model’s relatively coarse temporal resolution (3-h intervals). To evaluate the reliability of the coherence values obtained (Table 1), we applied the algorithm by Thomson and Emery [55]. A 95% confidence interval for coherence was calculated based on spectral characteristics smoothed over five independent values (resulting in 10 equivalent degrees

of freedom), yielding a threshold of 0.283. All coherence estimates exceeded this threshold, indicating significant reliability.

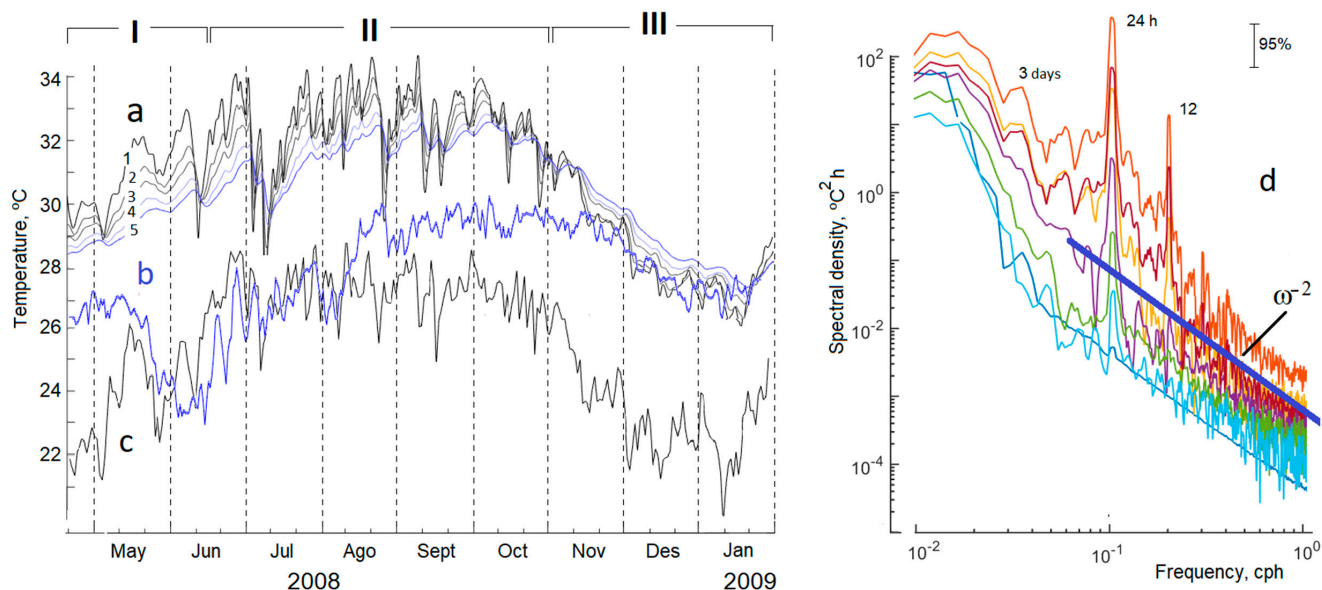


Figure 6. (a) Time series of sand temperature at five depths (20 to 100 cm) measured at hatchery locations from late April 2008 to January 2009. (b) Daily average sea surface temperature at the location marked by an asterisk in Figure 1b. (c) Air temperature at a height of 2 m above the sand during the summer–autumn season of 2008 at the La Gloria camp. (d) The top curve shows the air temperature spectrum; below are the sand temperature spectra at various depths. The vertical line indicates the 95% confidence interval, and the thick line represents the decay of spectral density with frequency.

Table 1. Spectral characteristics of air temperature and its relationship with sea surface temperature (SST) and sand temperature.

Temperature	Corr.	Coherence	Air Temperature Phase Dif.	Coherence Between
SST	0.956	0.853	2.9	−0.504
Sand (20 cm)	0.907	0.85	7.7	−0.439
Sand (40 cm)	0.856	0.761	12.5	−0.365 main egg-laying
Sand (60 cm)	0.819	0.73	19.1	−0.295
Sand (80 cm)	0.767	0.654	22.7	−0.212
Sand (100 cm)	0.956	0.853	2.9	−0.504

In the present study, only the spectra from time series measurements in interval 2 are examined (intervals I and III were not considered due to the non-linear behavior of the measured variables; see Figure 6a). The spectra reveal peaks at periods of 24 and 12 h, which correspond to the daily variation of air temperature, and a peak at a period of 3 days, likely associated with synoptic variability. Additionally, cross-correlation analysis between air temperature and sand temperature at a depth of 40–60 cm in sea turtle nests revealed a significant positive correlation of 0.856 between these variables (Figure 6). This high correlation indicates a strong association between ambient air temperature and sand temperature at this depth.

In Figure 7, the simulated sand temperature distribution within the 40 cm deep sand layer is presented alongside the actual temperature measurements taken at the same depth. Despite some noise contamination inherent in the measurement process, it is evident that the overall trend closely aligns with the experimentally recorded temperature. This ob-

servation underscores a notable concordance between the simulation and observed data. To quantify the relationship between the modeled sand temperature and the recorded temperature, the correlation coefficient was computed. The results show a significant correlation coefficient of 0.83, confirming the robustness of our model in accurately representing thermal variations in the sand layer at that depth. This correlation further reinforces the validity and utility of our mathematical approach for predicting and modeling temperatures in hydrometeorology.

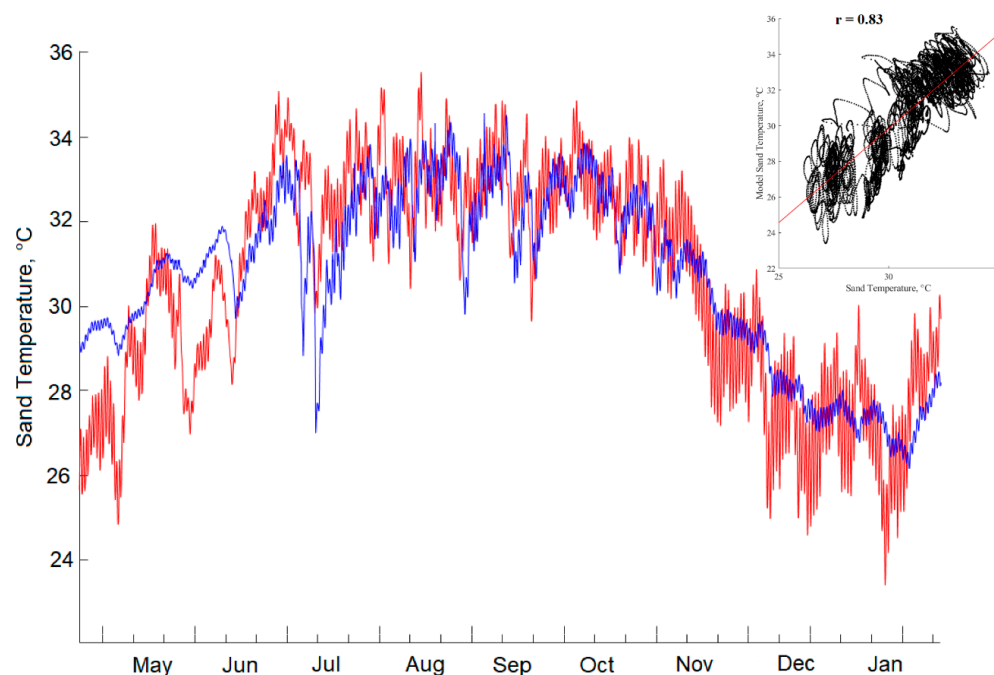


Figure 7. Mean daily sand temperatures during the summer-autumn season of 2008, represented by measurements (blue) and modeling (red) at a depth of 40 cm on the beach near La Gloria camp. At the top of the figure, a correlation chart illustrates the comparison between sand temperature measurements and modeling.

The average sand temperatures during the thermosensitive period of sex differentiation for each protected nest are shown in Figure 8. The parameters used to estimate the female proportions of the nests incubated in hatcheries included temperatures during the middle third of nesting, which ranged from 28.2 °C to 33.8 °C, with 33.8 °C being the highest temperature recorded. These measurements were obtained using HOBO thermographs installed at depths of 20, 40, 60, 80, and 100 cm in the incubation area, providing a detailed temperature profile of the nests. The pivotal temperature was 30.0 °C, consistent with values reported by Morales Mérida et al. [58] and Abreu-Grobois, Morales-Mérida, Hart, Guillon, Godfrey, Navarro, and Girondot [18], and the increase due to metabolic heat during the critical period of sexual differentiation was 1.1 °C, as reported by Hays et al. [59], Hawkes et al. [60], and Hanson et al. [61]. Considering the seasonal pattern of sand temperatures in hatcheries and the temporal distribution of nesting abundance, and given that there were no temporal or spatial differences in mortality across hatchery areas, a clear bias in the sex ratio toward females can be observed. Higher nesting abundance occurred when sand temperatures exceeded 30 °C (June–October), noticeably higher than temperatures from November to January (below 30 °C). The estimated female proportion for the entire nesting season was 91.3% and 93.4% if the nests were incubated at 40 cm or 60 cm, respectively.

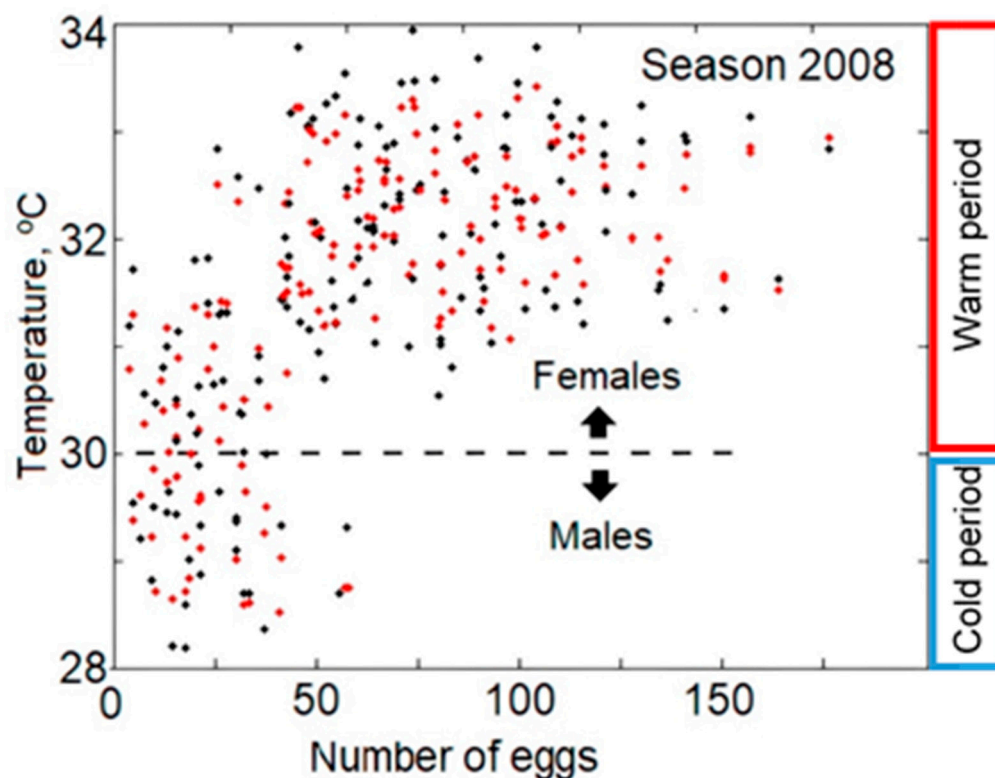


Figure 8. The average temperature of the middle third of the incubation period of the nests protected in hatcheries during 2008. The black dots indicate the nests if they had been incubated at a depth of 40 cm and the red dots if they had been incubated at 60 cm.

4. Discussion

Historical sea surface temperature (SST) or air temperature can be used to predict historical sand temperatures at nest depths with accuracy [62]. Developing mathematical functions to relate sand temperature with other environmental variables could help clarify the mechanisms that control population sex ratios and allow for forecasts of the effects of climate change. We were unable to establish a significant relationship between SST data and sand temperature (40–60 cm), likely due to the recording frequency of our data. A higher temporal resolution of the data series (e.g., weekly or monthly averages) could better capture the relationship between these variables over long time series [62,63].

The variable that best explained sand temperature variability (0–100 cm) was the in situ air temperature. Similar results were obtained by Stokes et al. [64] and Laloë et al. [65], who also suggest including moisture data to improve the explanation of sand temperature variability.

Our model, which uses the time of day and local air temperature, achieved a high correlation value of $r = 0.83$, whereas other similar models reported correlation values of $r < 0.7$ [59,63,65,66]. As air temperature rises during the day due to solar radiation, heat is transferred to the sand surface layer by direct contact. Through thermal conduction, this heat gradually penetrates deeper sand layers, sustaining a positive relationship between air and sand temperature at these depths. This heat transfer process is essential for maintaining suitable thermal conditions for the embryonic development of sea turtle eggs.

Wind is a factor rarely considered when studying the thermal dynamics of sand on nesting beaches. Sand beaches are often viewed as heat storage, with wind acting as a heat dissipator [67]. We found that the highest wind intensity aligns with the hours of peak sand surface temperature, and its direction consistently flows from the sea toward the beach, varying both throughout the day and seasonally. Wind-driven sand movement

contributes to shaping beach morphology [68], which could alter nest depth during the incubation period. Due to climate change, significant alterations in coastal wind patterns are expected [69].

The incubation temperature of a nest determines not only the sex ratio of hatchlings but also influences mortality under extreme temperatures [70], as well as the phenotype and survival of hatchlings [71]. Detailed recording of hatchery temperatures at egg incubation depth can help infer hatchling sex ratios by nesting season. The sex ratio of an annual cohort depends on the thermal regime of the beach, which may be influenced by distinct periods within the nesting season [72,73]. However, on a regional scale, local environmental variability during years with typical environmental conditions can result in significant differences in hatchling sex ratios for *L. olivacea* [74].

The sea turtle nesting season in the Mexican Pacific occurs during summer and autumn, coinciding with both the highest temperatures and the rainy season [75]. The nesting season of *L. olivacea* at Playón de Mismaloya runs from July to December, and our results indicate that 30 °C (the pivotal temperature for temperature-dependent sex determination, or TSD) is not a temperature maintained for extended periods. Instead, it represents an intermediate value between the average temperatures characterizing two distinct thermal periods. During the warm period (approximately 32 °C, July–October), 100% females would likely be produced, with mixed sex ratios only possible during intense rainfall events, which can lower sand temperatures for hours or days (<30 °C). In the cold period (approximately 28 °C, November–January), only male hatchlings are likely produced, with no expectation of mixed-sex nests, as no environmental factors would raise temperatures above 30 °C [75]. Sandoval, Gómez-Muñoz, and Porta-Gándara [73] found that males are primarily produced in two periods—at the beginning (June–July) and end of the season (December–January). However, due to low nesting abundance in these periods, the overall male percentage for the entire season was only 28%.

The seasonal pattern of sex production may be the primary mechanism defining the sex ratio of the annual cohort, with rainfall highlighted as a key factor that significantly lowers sand temperature. This effect on nest sex ratios occurs only during the warm period, as rainfall during the cold period would reinforce the male-biased conditions typical of that season. According to Porter et al. [76], when eggs are incubated at temperatures above 30 °C and sudden temperature drops below the pivotal threshold occur for several days (3–7), a certain proportion of males may be produced if this happens during the critical sex-determination phase. We observed that significant drops in sand temperature (40–60 cm), lasting between 3 and 5 days during the warm period (above 30 °C), were only associated with intense rainfall from hurricanes. Lighter rains caused temperature declines lasting only a few hours. Rainfall has been suggested as a factor that may help prevent the complete feminization of turtle populations as climate warming continues [63]. However, high sand moisture during embryonic development can affect hatchling survival, morphology, and performance [77].

We observed that on Playón de Mismaloya beach, *L. olivacea* predominantly nested at distances ranging from 18 to 25 m from the sea, while the designated protected hatchery area is situated farther away, approximately 40 to 60 m from the shoreline. The natural thermal conditions of nest incubation, which result from the selection of nesting sites, have long been altered by conservation practices involving nest relocation to hatchery areas and, in some cases, to artificial nests [71]. During the peak nesting season (feminizing period), beach areas farther from the shoreline recorded higher sand temperatures, while lower temperatures were observed from November to January (masculinizing period).

The primary rationale for relocating turtle nests to protected areas at Playón de Mismaloya remains the prevention of predation, illegal egg collection, loss due to sand

erosion, and high tides. Additionally, hatchery temperatures do not typically reach critical or sublethal levels. García et al. [78] found no significant differences in the sex ratios of *L. olivacea* hatchlings produced in natural nests versus on-beach hatcheries at a nearby beach. However, incubating *L. olivacea* nests in protected hatcheries could lead to adverse effects, such as altered sex ratios and decreased hatchling survival or fitness, if the selected hatchery site has substantially higher temperature values than natural nesting sites [71].

Management strategies, such as nest shading and irrigation, have been proposed to mitigate the impact of high temperatures on eggs and hatchling sex ratios [20,79]. While nest cooling could be justified to reduce mortality, attempts to modify the sex ratio should be approached cautiously, as there is currently no clear evidence of the primary sex ratio for sea turtle hatchlings [80].

Efforts should be increased to understand the relationship between rainfall volume, the corresponding drop in sand temperature, and the duration of that cooling effect. In particular, further research is needed on the mechanisms of sexual differentiation that operate near pivotal temperatures, as current sex ratio models assume constant temperatures [18]. It is also necessary to study how sudden temperature drops from rain events influence sexual differentiation in this range.

Evidence suggests a non-linear effect of temperatures above the pivotal temperature [76], which complicates sex ratio estimations under fluctuating incubation temperatures. Georges [81] and Georges et al. [82] found that brief, daily bursts of high temperatures during incubation can result in an unusually high proportion of females.

Protection of sea turtle nests at conservation camps in developing countries often depends on volunteer availability and financial resources. Frequently, the protection season is shortened to cover just over half of the nesting season, leaving late-season nests unprotected. These unprotected nests may primarily produce male hatchlings [75]. Additionally, since nests laid in December would hatch around February, male hatchlings from these nests are left vulnerable, potentially worsening the risk of population over-feminization.

5. Conclusions

Air temperature and rainfall are the primary environmental drivers affecting nest incubation and the sex ratio of sea turtle hatchlings. In situ air temperature provides a better explanation for sand temperature variations than sea surface temperature (SST). The incubation temperature in on-beach hatcheries fluctuates between 26.5 °C and 34 °C. Two main environmental periods influence nesting abundance and hatchling sex ratios:

- Warm period: During July to October, with an average nest chamber temperature of 32 °C and minimal rainfall, conditions favor the production of female hatchlings only (feminizing period);
- Cold period: From November to January, with nest temperatures averaging 28 °C, conditions favor 100% male production (masculinizing period).

A negative correlation was observed between air temperature and sand temperature at depths of 20–100 cm during the warm period. Inversion of the sand temperature profile occurred, with sand temperature showing a direct correlation with air temperature during the cold period (November–February). Rain events homogenized the vertical sand temperature profile within a 1-m depth range.

Overall, the estimated sex ratio for the annual cohort was strongly biased toward females, with a percentage exceeding 90%.

Seasonal thermal variation has been identified as a key factor influencing sand temperatures modulating their behavior over time. This highlights the importance of considering these patterns when analyzing thermal dynamics in nesting habitats. However, severe

weather events, such as hurricanes, can disrupt environmental conditions and lower nest temperatures. It is necessary to know the relationship between rainfall (quantity and duration) and humidity in the sand and its effect on the temperature at the incubation depth of the nests.

To ensure effective research and conservation of these species, it is essential to adopt an integrated approach that accounts for both seasonal thermal variations and climatic changes. Such an approach is crucial for understanding the factors that impact survival rates and population sex ratios.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/geosciences15010011/s1>. Figure S1. Hourly variability of wind speed (a) and wind direction (b) at the meteorological station in 2008–2009. The initial data were averaged with a sliding filter over 2 days for each hour of the day.

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