

Saving the Sea Turtles: How Climate Change Affects Loggerhead Populations

Keywords: Temperature dependent sex determination, Loggerhead sea turtle, climate change, heat transfer, computational modeling

BEE 4530

Computer-Aided Engineering: Applications to Biological Processes

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Date Submitted: May 11, 2017

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1.0 EXECUTIVE SUMMARY

An ample amount of research has been conducted on how nest temperatures affect the sex of sea turtle hatchlings, but little has been done on how heat transfer contributes to the temperature. For the purpose of determining if heat transfer could be modeled, Loggerhead sea turtles (*Caretta caretta*) in Southern Florida were examined. Further analysis of nest temperature under conditions associated with climate change can predict potential effects in the future on Loggerhead and other sea turtle populations.

This paper assumes that research and modeling of the heating process can lead to a better understanding of what contributes to nest temperature. The nest was approximated as one spherical homologous domain with weighted egg and air properties, located at 0.35 m below the surface of the sand. Conditions affecting temperature of the nest include solar radiation on the sand, convective heat transfer at the surface of the sand, and metabolic heat generation in the eggs. Hourly weather data from locations in Southern Florida was collected and used to simulate a varying boundary condition at the sand surface from air temperature, wind speed, and solar radiation. Metabolic heat generation from the eggs was based on data from another species of sea turtle. Two-dimensional axisymmetric heat conduction through the sand and nest was modeled using the commercial analysis software COMSOL Multiphysics. The model was validated by comparing the resulting Loggerhead nest temperature over time with experimental data from another location in Florida. Analysis of parameter sensitivity was conducted by varying the density, specific heat, and thermal conductivity of both the egg mass and sand. Changes in all of these parameters by 20% produced negligible effects on nest temperature. Varying the heat transfer coefficient to reflect the minimum and maximum air temperatures found in Southern Florida did not have a noticeable impact on nest temperature. Sensitivity of solar radiation was considered in applying shading conditions. The model was also used to predict potential effects from climate change by varying the top boundary condition.

The model was used to observe how variation of environmental conditions, especially the projected increase of temperature due to climate change, affects the model and destabilizes the ratio between males and females. The results indicated that average nests laid in peak nesting seasons tend to produce a female-dominated clutch. A 1 to 4 °C increase in air temperature, as predicted by global warming trends, could give rise to potentially dangerous nest temperatures and exclusively female clutches. Shading has a drastic effect on nest temperature and can act to stabilize the sex ratio in global warming scenarios.

In a broad sense, any species with temperature dependent sex determination can feel the effects of climate change, making this model especially important for coming years. This study aims to examine the causes of nest temperature variation, and explore viable solutions to potentially harmful effects from climate change. More research and global attention on the harmful consequences of climate change impacting species is critical.

2.0 INTRODUCTION

Loggerhead sea turtles (*Caretta caretta*), like many species of reptiles, experience temperature dependent sex determination (TSD) in their embryonic stage. This means that their sex is determined by the nest temperature. The response to temperature occurs during the middle third of incubation (Hanson et al.

1998). The pivotal temperature for Loggerhead sea turtles, particularly populations in Florida, is 29.2°C (Mrosovsky 1987). Temperatures below this point will produce more males, and temperatures above this point will produce more females. Sex ratios rapidly become more skewed as the temperature moves away from the pivotal point, and nests can become entirely male or entirely female with a change of only a few degrees. In an average fluctuating nest, temperatures reaching above 34 °C have been seen to decrease hatchling success (Read et al. 2013). For these reason, TSD is a particularly important area of research with regards to its potential to be affected by climate change.

Loggerhead nests are typically laid at a depth of .35 m to the top of the nest with a chamber diameter of between .23 and .26 m (Miller et al. 2003). In southeastern U.S., nesting season is between mid-March and late September, with the peak occurring in June and July (SFES 1999). Average clutch size is about 110 eggs (Miller at al. 2003).

Climate change could have detrimental effects on nest temperatures. Global warming of air temperature could lead to an increase in heat flow to the nesting eggs. Exposure to different nesting temperatures could favor one sex over the other, leading to adverse consequences for species populations. There has been some interest in how climate change may affect turtle populations, but most studies focus on recorded temperatures and turtle development (Schwanz et al. 2008). Past studies monitoring the sex ratios of Loggerhead nests in southern Florida have recorded primarily female-based clutches (Hanson et al. 2014).

Laloë et al. (2014) estimated the percentage of male hatchlings as a function of temperature. This sigmoidal curve was used to predict the sex ratio from the resulting average middle third of incubation temperature.

The goal for this project is to model heat flow through sand and eggs in order to better understand how temperature affects the sex of Loggerhead sea turtles. Applying this knowledge, the increase in air temperature due to global warming will indicate the change in nest temperature and subsequent risk to turtle sex ratio and survival. Through analysis of the environmental factors leading to altered sex ratios, this study will give insight into possible preventative techniques for turtles populations as well as for other species.

2.1 Problem Statement

The objective of this study is to determine what effect climate change will have on the sex ratio of Loggerhead turtle egg clutches in Southern Florida.

2.2 Design Objective

The goal for this project is twofold:

- 1) To accurately model the temperature variation within and around the egg chamber of a nest, using real weather and climate data for Southern Florida.
- 2) To use this model to investigate the potential impact of climate change on the sex distribution of Loggerhead turtle populations.

3.0 METHODS

3.1 Schematic

The geometry of the model and boundary conditions are shown in Figure 1. The two domains in the model are the sand and nest.

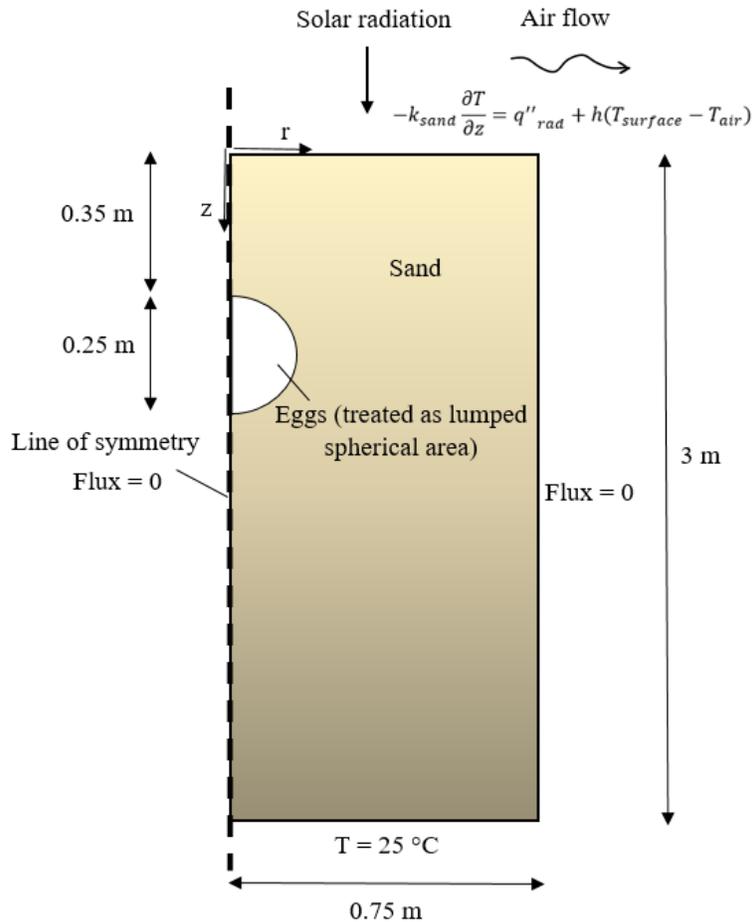


Fig. 1: Problem schematic. The eggs are contained in a spherical egg chamber buried below the beach surface. The sand is treated as a semi-infinite domain surrounding the eggs, which are modeled as a single axisymmetric region.

The sand has a top boundary condition specified by solar radiation and convective air flow. The bottom boundary is considered to be held at a constant temperature of 25 °C. The right boundary, as well as the left boundary at the axis, are insulated with zero heat flux moving across. The nest was approximated as one spherical homologous domain 0.35 m below the surface of the sand, consisting of egg and air, with a diameter of 0.25 m.

3.2 Governing Equations

The physics of the model is heat transfer via conduction through a solid domain, with the sand and the egg area making up two subdomains. Our model includes the transient temperature term to account for

changing conditions above the surface, and the eggs produce an increasing amount of metabolic heat during the course of their incubation. The governing equations for the egg and sand domain are given below in Equations 1 and 2.

Egg domain:

$$\frac{k_{eggs}}{\rho_{eggs}c_{p_{eggs}}}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}\right]+\frac{Q_{metabolic}}{\rho_{eggs}c_{p_{eggs}}}=\frac{\partial T}{\partial t} \quad (1)$$

Where the thermal properties k_{eggs} , $c_{p_{eggs}}$, and ρ_{eggs} are the thermal conductivity, specific heat, and density of the eggs, respectively, T is the temperature of the eggs, r is the distance from the left boundary axis, z is the distance from the surface of the sand, and $Q_{metabolic}$ is the metabolic heat generated by the eggs.

Sand domain:

$$\frac{k_{sand}}{\rho_{sand}c_{p_{sand}}}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}\right]=\frac{\partial T}{\partial t} \quad (2)$$

Where the thermal properties k_{sand} , $c_{p_{sand}}$, and ρ_{sand} are the thermal conductivity, specific heat, and density of the sand, respectively. These values are dependent on the moisture content of the sand, which in turn varies with depth, which is accounted for later in the COMSOL implementation. T is the temperature of the sand, r is the distance from the left boundary axis, and z is the distance from the surface of the sand.

Sex determination occurs during the middle third of embryonic development. Incubation time is dependent on temperature, with nest development occurring more quickly at increased temperatures. For simplicity, our model assumes incubation time to be 50 days (1200 hours). Assuming that thermal sensitive period as the middle third of development, the nest was examined between Hour 400 and Hour 800. To find the sex ratio, a sigmoidal curve developed by Laloe et al. (2014) was used:

$$sr(T) = \frac{1}{1 + e^{\left(\frac{1}{S}\right)(\ln(P+K) - \ln(T+K))}} \quad (3)$$

Where $sr(T)$ is sex ratio (proportion male) at a temperature T (in °C), S equals -0.033621 and defines the shape of the temperature transition, P is the pivotal temperature (29.2 °C for Florida loggerheads), and K is a coefficient equal to 0.1. This equation is visualized in Figure 2.

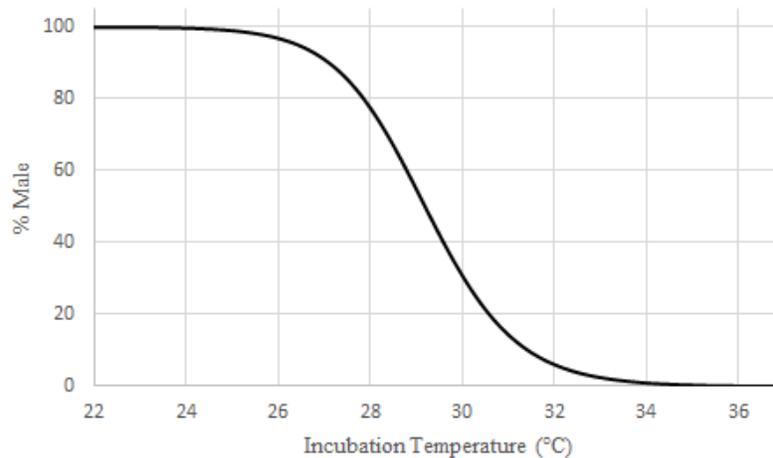


Fig. 2: Plot of sex ratio of the nest versus incubation temperature.

The sex distribution follows a sigmoidal curve with a pivotal temperature of 29.2°, where the nest is 50% male. Temperature fluctuations near this pivotal point can have a large effect on the sex ratio of the nest. The average temperature of the nest during the thermal sensitive period is used as a constant temperature equivalent for the purposes of sex determination.

3.3 Boundary Conditions

There are four boundary conditions necessary for the model. The 2D axisymmetric model allows for a zero flux boundary condition at the left boundary, along the line of symmetry. Heat conduction from the surface was assumed to occur downward only, allowing for a zero flux boundary at the right edge, which was defined at a sufficient distance from the nest to be unaffected by any lateral heat transfer due to metabolic heating. The top boundary represents the surface of the sand, which has both radiative heat flow from sunlight and convective heat transfer due to air flow. Because temperature remains relatively constant at large depths, a constant boundary condition of $T = 25\text{ }^{\circ}\text{C}$ has been applied for the bottom boundary. This value is consistent with literature values for ground temperatures in Florida (EPA 2001), and the boundary depth of 3m is consistent with depths at which very little temperature variation occurs (Florides).

3.4 Model Implementation

The implementation of the full model used 2D axisymmetric transient heat transfer via conduction through two domains: the sand and the egg mass. Air temperature, wind, and radiation data was imported into COMSOL using empirical data for Southern Florida (see Appendix). Since loggerhead nests are typically laid near the vegetation line (Hays et al. 1995), many nests receive shading during at least part of the day. To account for this, shading was approximated by implementing a shading coefficient in front of the radiative flux boundary condition. The heat created by the metabolism of the eggs was also accounted for in this model using empirical data. The problem was run for 50 days, or 1200 hours, choosing midnight on July 1st, which is during peak nesting season (Hanson et al. 1998), as a starting point. The problem was implemented in COMSOL using the physics for heat transfer in solids. Radiation, ambient air temperature, and wind speed were defined as functions of the imported data.

4.0 RESULTS AND DISCUSSION

The baseline model represents an average nest laid during peak nesting season in Southern Florida. Figure 3 shows the temperature distributions. Cut points were taken at the top, bottom, and center of the nest to examine spatial variation. A cut point was also taken in the adjacent sand at the edge of the domain to visualize the metabolic heating of the nest in comparison to the surrounding sand.

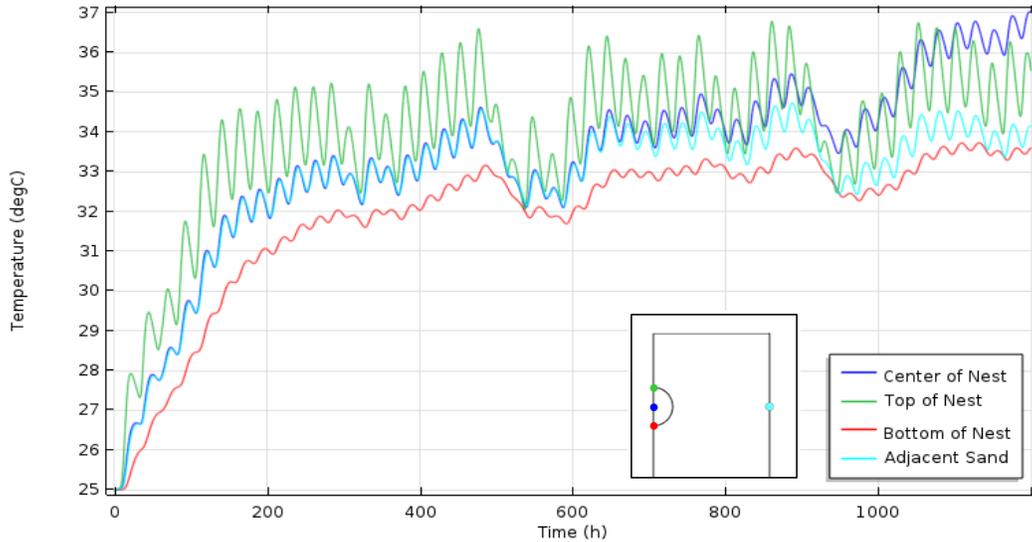


Fig. 3: Temperature profile for nest laid July 1 with 50% shading.

The implementation of empirical weather data at the top boundary resulted in variations reflective of conditions at the top surface. After equilibration from the input initial temperature, the temperature of the nest began to fluctuate around a fairly consistent average temperature. There was variation in different sections of the nest, with the top of the nest experiencing more fluctuation due to its proximity to the surface. The metabolic heating in the eggs resulted in an increase in the temperature of the nest compared to the adjacent sand, which can be particularly seen in the center of the nest.

As a result of changing boundary conditions, small variations in the temperature were expected. Decreases in nest temperature occurred directly after a decrease in radiative flux or air temperature, as shown in Figure 4.

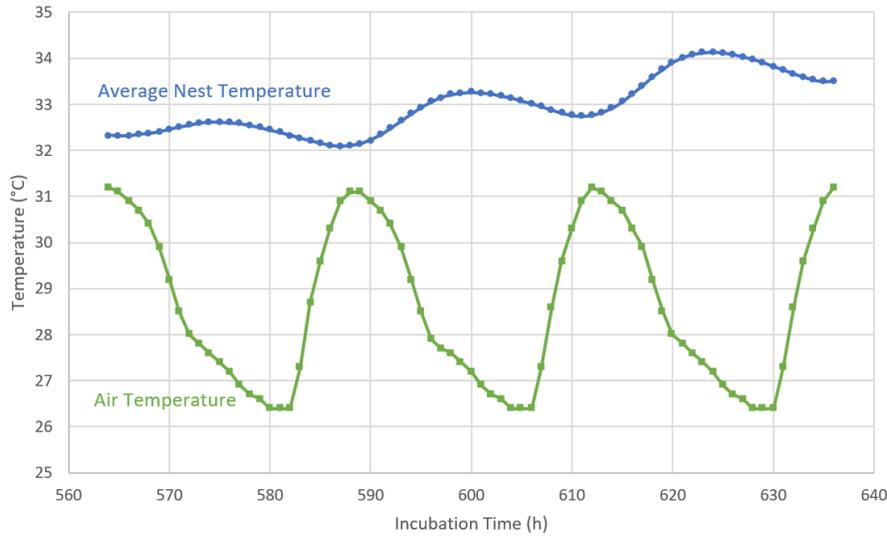


Fig. 4: Average nest temperature and air temperature over middle period of incubation. The temperature of the nest shows a damped response to changes in air temperature, with a delay time for heat conduction through the domain.

The nest temperature behaves as expected, with a dampened and delayed response to variations in the surrounding air temperature. The nest is also warmer than the surrounding air due to additional inward heat flux from solar radiation.

4.1 Sex Determination

The average temperature of the nest during the thermal sensitive period (TSP) was 33.63 °C, which corresponds to a 1.51% male clutch using the methodology developed by Laloe et al. (2014) (Equation 3).

4.2 Variation within Nest

To examine the effect of heat conduction from the surface and metabolic heating in different regions of the nest, cut points were taken at the top, bottom, and side edges of the nest in addition to the center. Results are summarized in Table 1.

Table 1: Calculated sex ratios for different regions of the nest using Equation 3.

| Nest Location | Average Temperature (°C) | % Male |
|---------------|--------------------------|--------|
| Top | 33.90 | 1.18 |
| Middle | 33.33 | 1.94 |
| Bottom | 31.91 | 6.72 |
| Side | 32.88 | 2.88 |

The top of the nest is the warmest, as heat from the sand surface reaches it more easily. The middle of the nest experiences the greatest effect due to metabolic heating, which, combined with effects of conduction from the surface, make it the next warmest region. Both regions have very low proportions of male hatchlings. However, the other regions of the nest, particularly the bottom, have slightly higher proportions of males, showing that variation within different regions of the nest affects the overall sex ratio.

4.3 Impact of Global Warming

To simulate global warming, the air temperature was increased by 1, 2, 3, and 4 °C over all time points. The resulting temperature distributions for the center of the nest are shown in Figure 5.

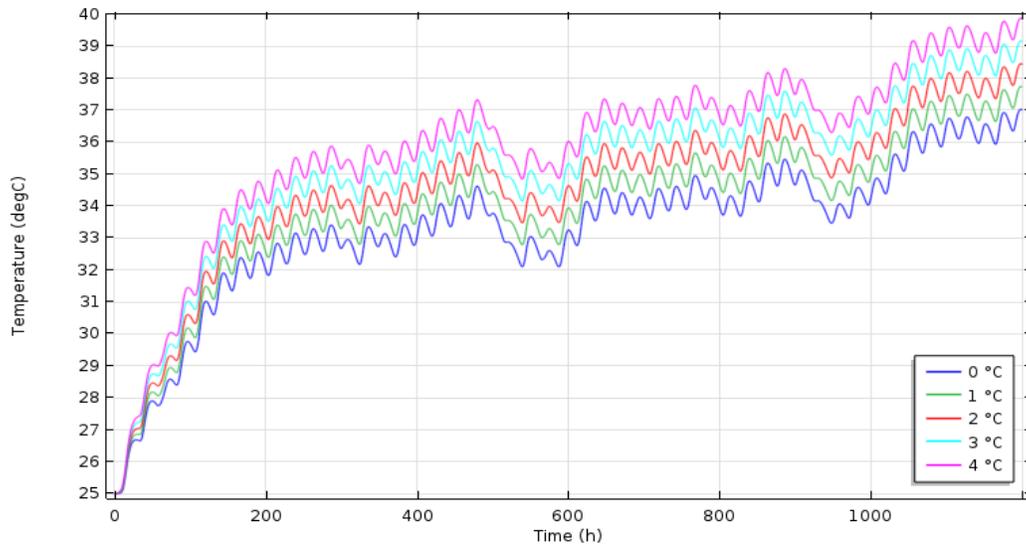


Fig. 5: Impact of varying amounts of global warming on the temperature profile of the center of the nest for eggs laid July 1st.

Beyond the initial equilibration, the nest quickly shows an increase in temperature over all time points directly correlated with the increase in air temperature. To examine the effects in more quantitative detail, the average temperature of the nest for each climate change scenario was calculated along with the resulting sex ratios. Results are summarized in Figure 6.

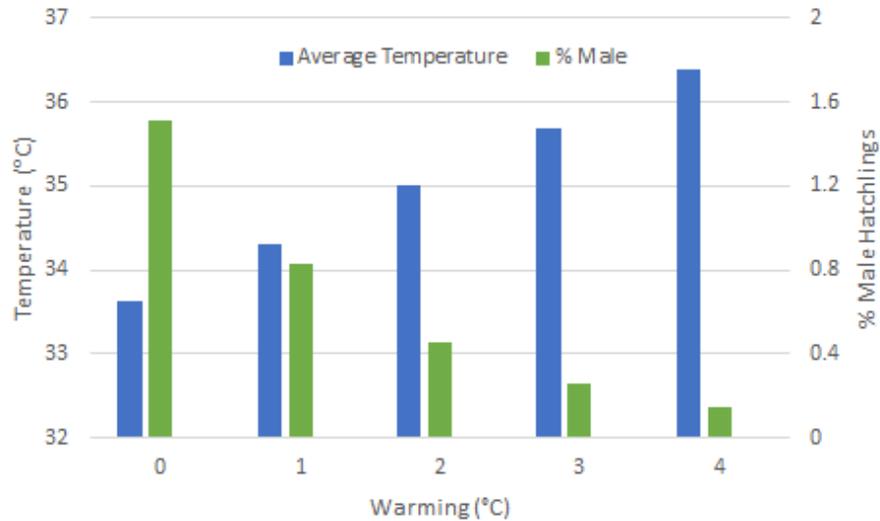


Fig. 6: Global warming and its effects on the average nest temperature during the thermal sensitive period and the percentage of male hatchlings. As the temperature due to global warming increases, the percentage of males in the nest falls to negligible levels.

For a nest laid in July, at the peak of hatching season, global warming has the potential to shift nests already laid near the upper limit of the sex-determining range of temperatures not only into temperature regions where virtually no male hatchlings will be produced, but that will significantly impact the health and survival of the hatchlings.

One potential adaptation for turtle populations faced with global warming is to nest during parts of the season where temperatures are cooler. To examine the effects of warming on a cooler nest, the model was run for a nest laid on April 1st, at the beginning of the nesting season (Sea Turtle Nesting). The resulting temperature distributions for the center of the nest are shown in Figure 7.

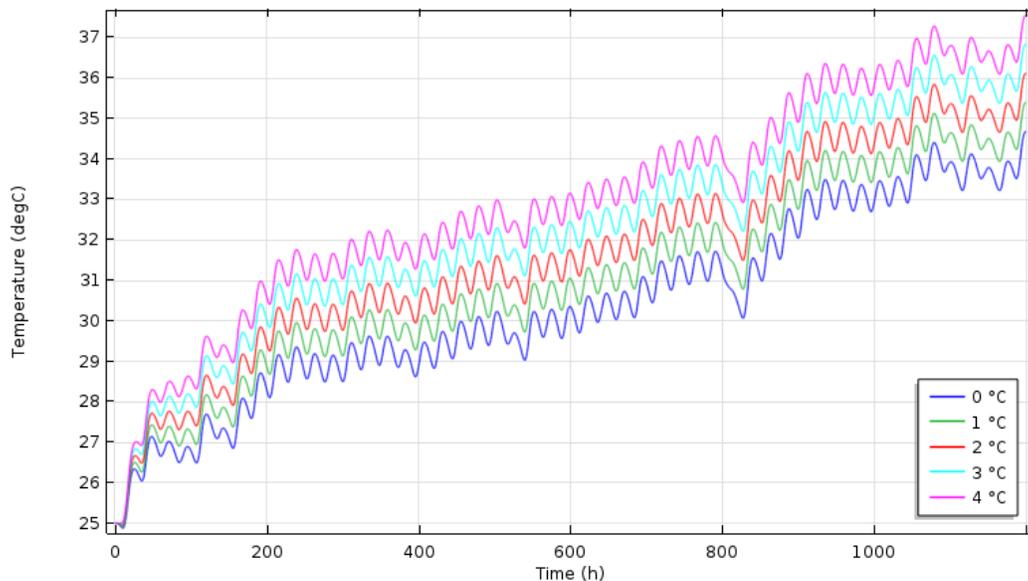


Fig. 7: Impact of varying amounts of global warming on the temperature profile of the center of the nest for a nest laid April 1st.

The nest laid earlier in the season has lower temperatures corresponding to the cooler weather, but shows a similar response to increasing temperatures as the July nest. The effects of the warming on the average nest temperature and the sex ratio are summarized in Figure 8.

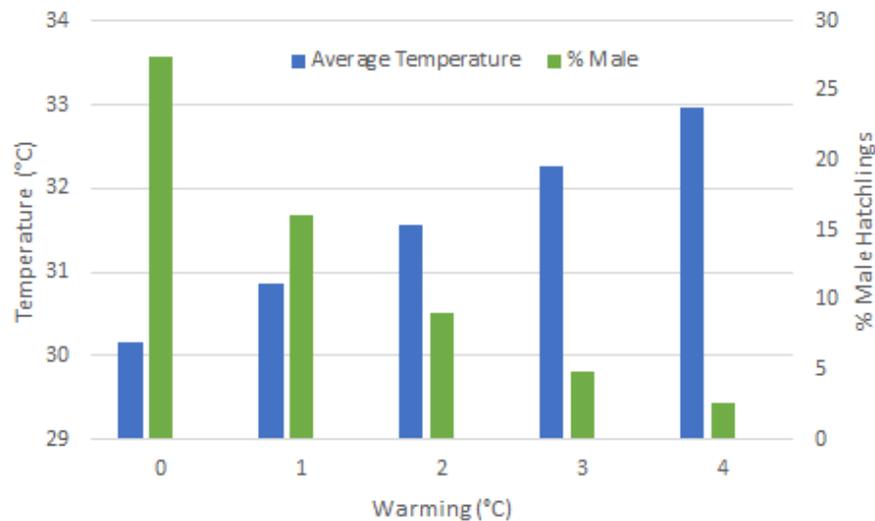


Fig. 8: Global warming and its effects on the average nest temperature during the thermal sensitive period and the percentage of male hatchlings for a nest laid April 1st. The increasing temperatures cause a drastic shift in the sex distribution.

For a nest laid at the beginning of the nesting season, the effects of global warming can be even more clearly seen. The baseline nest is reasonably balanced, with 27.42% male hatchlings, but a 1 °C increase in the air temperature causes the sex ratio to drop to only 16.1% male. The number of male hatchlings continues to decrease under more extreme climate scenarios; under the most extreme conditions, even nests laid in the coolest part of the nesting season may shift to almost entirely female. However, compared to the July nest, where global warming may threaten the survival of the hatchlings, nests laid in cooler weather may be able to retain a less skewed sex ratio and healthier hatchlings. This offers some opportunity for loggerhead populations to adapt to all but the most extreme global warming scenarios if the nesting season is shifted towards cooler parts of the year.

4.4 Effect of Shading

The most realistic and least invasive conservation strategy to counteract rising temperatures' effects on turtle populations is to introduce additional shading to nests. Since the radiation of the sun is the deciding factor in the core temperature of the nest, reducing the radiation in the model can be used to determine the effects of introducing shade to the nest. The results are shown in Figure 9.

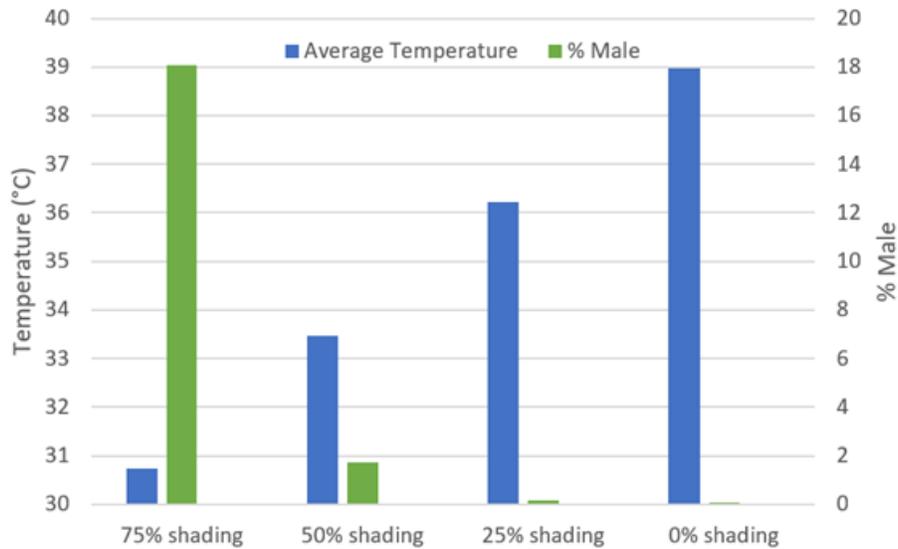
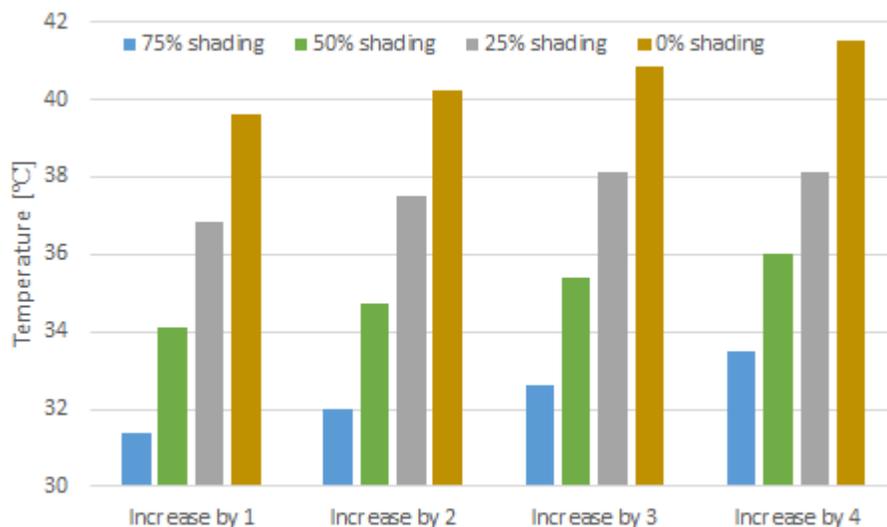
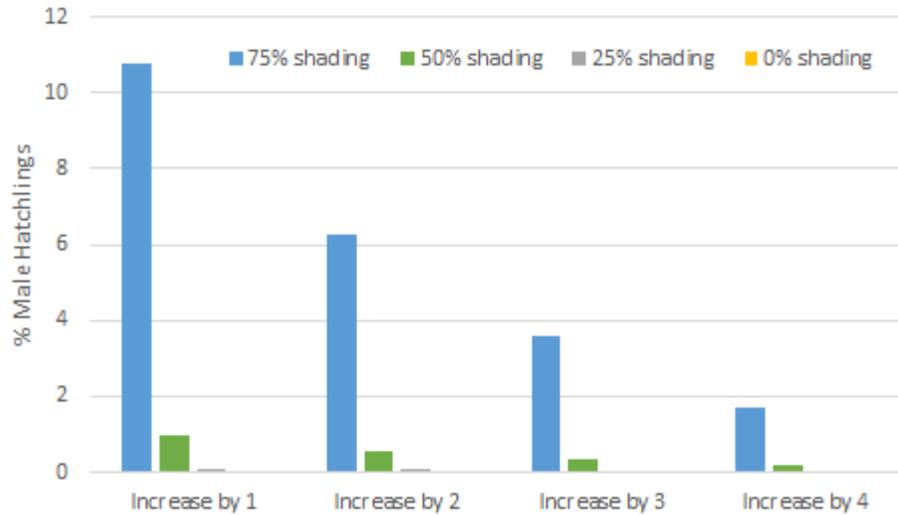


Fig. 9: The average value of the nest temperature over the July incubation period with different amounts of radiation. As the shading of the nest increases, the temperature in the nest decreases and causes a greater percentage of males. This shows that shading the nest can have a significant effect on the male to female ratio in the nest and could be used for conservation purposes.

Introducing shade to the nest can be advantageous for situations where the radiation levels could prove lethal for the nest. A difference of several degrees in the nest could be easily achieved by only letting a quarter of the sun's radiation hit the sand. The future for loggerhead turtles may be dire if the global temperature continues to rise as predicted, and drastic conservation efforts will have to be made in order to ensure the survival of the species. To examine the effects of shading on nests under climate change scenarios, the model was run through multiple tests to simulate an increase in air temperature with varying amounts of shading. Results are shown in Figure 10.



a)



b)

Fig. 10(a-b): Change in core nest temperature for different levels of nest shading (a) and change in percentage of male hatchlings for different levels of shading with increasing global temperatures (b). The model was run over a typical July nesting period.

The model indicates that shading is an effective measure to significantly drop the temperature in the nest and ensure that some of the population develops into males. This may be achieved by using tents and tarps to cover identified nests. Wood et al. (2014) have been experimenting with this concept with loggerhead nests in Queensland, Australia by providing their turtle rookeries artificial and natural shading. The nests placed in the shade not only were incubated at lower temperatures but also produced up to 40% more males than the control.

By predicting nest temperatures from climate change data with the COMSOL model, conservationists would be able to determine the proper core temperature for the nest and control the male to female ratio. The model could be used to non-invasively monitor nests of interest and determine the best amount of shade to protect the hatchlings from the effects of climate change.

4.5 Validation

Hanson et al. (1998) examined several Loggerhead turtle nests laid in June and July on Hutchinson Island, Florida. Three nests, laid in mid-June, were equipped with multiple data loggers that measured temperature every 1.2 hours in the top, middle, and bottom of the nest, as well as the sand 1m from the nest at mid-nest depth, 45 cm from the surface.



Fig. 11: Experimental data for mean daily temperatures in three nests on Hutchinson Island, Florida compared with mean daily temperatures from the model, starting June 11th with 30% shading.

For data comparison, the model was run starting mid-June. Daily average temperatures were then calculated and plotted with the experimental data (Fig 11). The data from the model follows the same overall trends as the experimentally obtained data. Temperature differences between the data sets are typically no more than 5 °C, with this maximum difference reached at the top of the nest. The most variation is expected here, as weather data used in the model and the experimental data were taken in different years. The center of the nest tracks well with the experimental data, indicating that the metabolic heating term is accurately represented.

At most time points, the model resembles the values found in the experimental data, but modeled temperatures are consistently warmer. The probable cause of this is that the model does not include the effects of rainfall, which may act to decrease temperature.

4.6 Mesh Convergence

A fine sized mesh was created, and is shown in Figure 12.

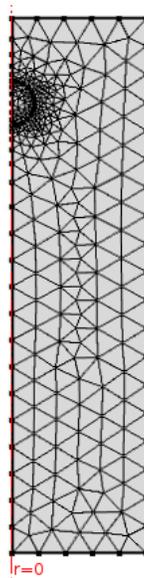


Fig. 12: Final mesh build over sand and nest domains.

A triangular mesh with fine sized elements was chosen for the temperature profile. The mesh is most important in regions above and around the nest, where the temperature is most vital to the developmental function.

To ensure that the model had minimal spatial discretization error, a mesh convergence was performed, as shown in Figure 13.

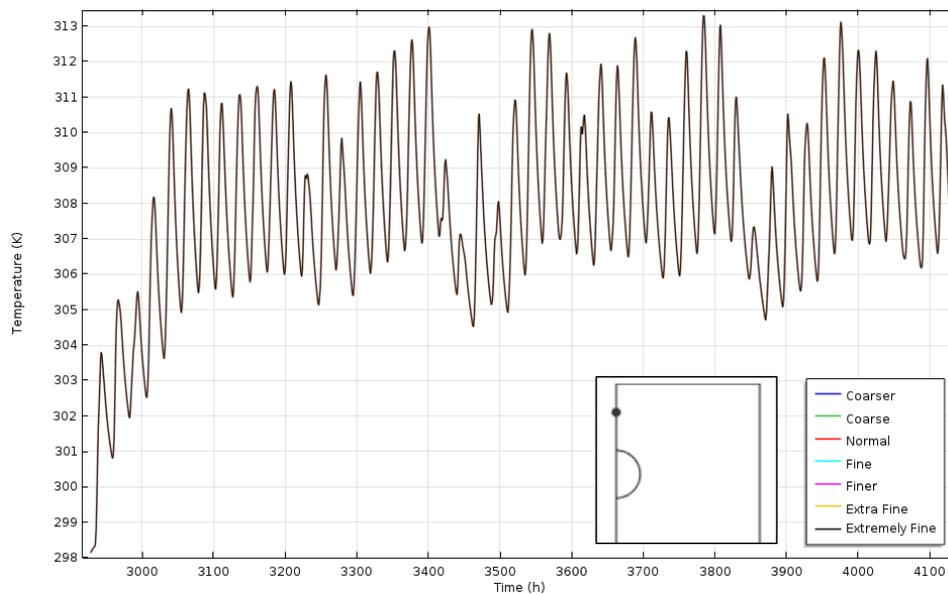


Fig 13: A mesh convergence was performed at a point above the nest in order to determine the minimum element size necessary to exclude discretization error from our model. All of the solutions for the differing mesh values seem to converge over all times.

The mesh appears to converge at all element sizes. However, because computation time was not significantly extensive for most mesh choices, a fine mesh was chosen to ensure that discretization error would not be a concern.

4.7 Sensitivity Analysis

The convective heat transfer coefficient is calculated using the average nesting season air temperature of 25 °C as well as empirical data for hourly wind speeds. To check whether more detailed, temperature-dependent properties of air would need to be implemented, the coefficient value was calculated at the minimum and maximum temperatures recorded during the nesting season. Using air properties at the minimum temperature (19°), the average temperature at the center of the nest decreased by 0.004°. Using the maximum temperature (31°), the average temperature at the center of the nest increased by 0.003°. This indicates that modifying the properties of air to account for ambient temperature changes has negligible effects on the implementation of the convective heat transfer boundary condition, and using the average ambient air temperature for the coefficient calculations is sufficient.

The significance of the thermal properties for each domain was determined by running a sensitivity analysis over the density, specific heat, and thermal conductivity of both the sand and the eggs. The parameters were varied using values for a 20% increase and decrease, and measured by comparing the temperature change at the center of the nest, which can be seen in Figure 14.

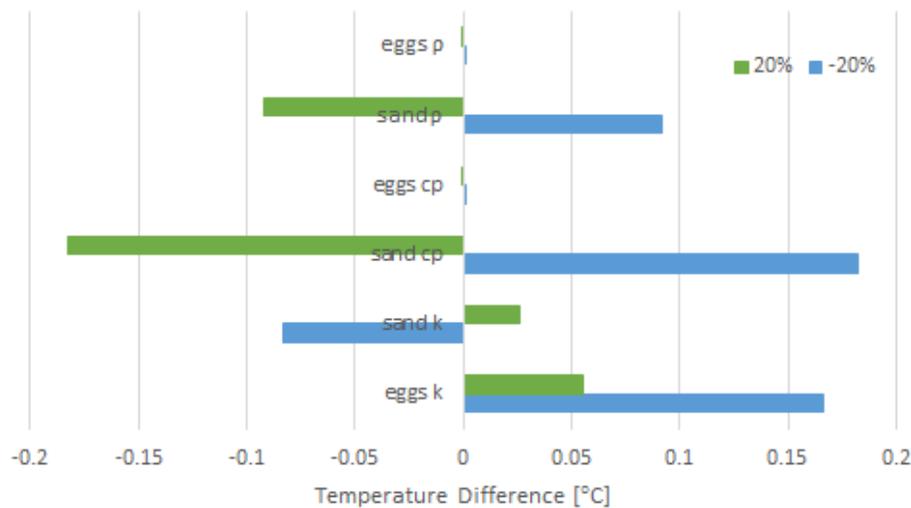


Fig. 14: A sensitivity analysis performed on the specific heat, density, and thermal conductivity of the eggs and sand shown in the model. Varying the parameters by +/- 20% showed very little effect on the average temperature at the center of the nest. The difference in the modified temperatures and the original is represented by the bars. The greatest temperature deviation was at most 0.18°.

The sensitivity analysis ultimately reveals that the above parameters have little impact on the average temperature at the center of the nest. In order for the parameters to have a major effect, they would have to be drastically increased or decreased. Literature searches have shown that the thermal properties of beach sand and turtles eggs do not deviate to this extent. The one atypical part of the sensitivity analysis was the increase in temperature that resulted from both a decrease and increase in the thermal conductivity. When the thermal conductivity of the eggs rises, it becomes easier for the eggs to be

affected by the radiation. Conversely, the eggs are better able to retain the heat from their metabolism when the thermal conductivity is lowered.

5.0 CONCLUSIONS AND FUTURE DIRECTIONS

5.1 Future Improvements

One potential improvement to the model would be to incorporate a mass transfer physics to account for varying water content in the sand due to precipitation and evaporation. To begin exploring the impact of evaporative heat loss on the nest, an approximate boundary condition was incorporated for evaporative heat loss. The boundary condition assumes a constant relative humidity of 75%, consistent with average values for Miami (Florida Climate Center), and the convective mass transfer coefficient is calculated using an approximate air temperature of 298 K and the empirical wind speed data. In reality, the water content of the sand would vary drastically with precipitation events, so to explore the effect of different levels of saturation, a parametric sweep was run to compare the current surface conditions (dry sand; no evaporative heat loss) with varying levels of saturation (Figure 15). Note that for the implementation of the sand parameters (thermal conductivity, specific heat, and density), water content is not altered; the surface is still treated as dry with increasing saturation with depth for the calculations of these properties, and only the boundary condition treats the surface as having different saturations.

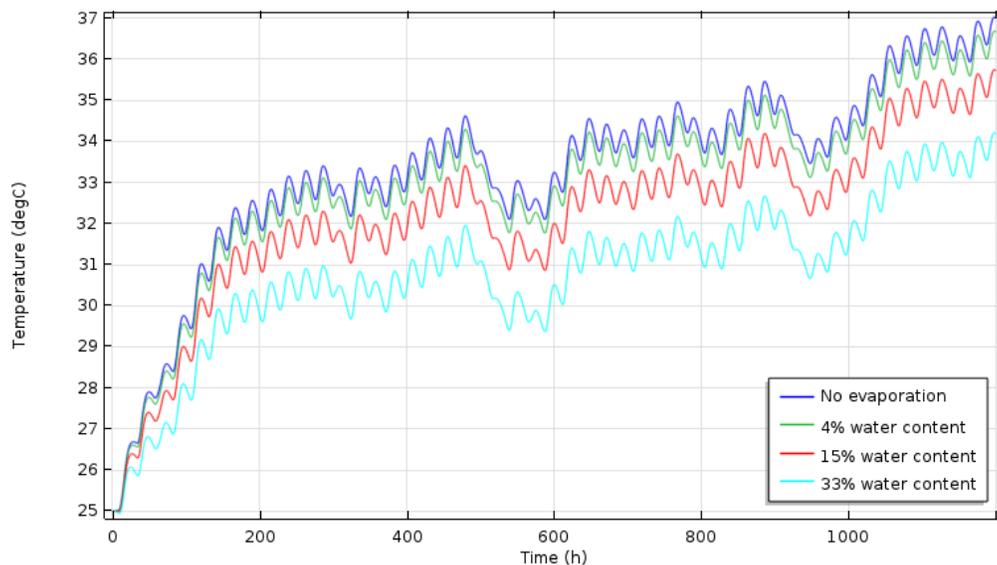


Fig. 15: Impact of approximated evaporative heat loss on the temperature profile of the center of the nest. "No evaporation" represents the current conditions of the nest (laid July 1st, with 50% shading).

If the surface of the sand is treated as damp, at a 4% water content equivalent to the water content at nest depth, there is a slight decrease in the overall nest temperature. The temperature decreases further with increasing water content, and at fully saturated values (33% water content), the temperature at the center of the nest drops by nearly 3°. In reality, the sand would only be fully saturated during heavy precipitation, and would then equilibrate to a drier surface due to evaporation and downward water flow, but these results give a good indication that the inclusion of precipitation events would have a cooling effect on the nest, increasing the accuracy of the model. Future studies should consider a mass transfer

physics to account for water accumulation and flow in the sand domain, which would give more accuracy to the model and allow for better predictions of nest conditions.

5.2 Conclusions

The goal of this project was to develop a predictive model for the development of Loggerhead sea turtle nests and to use this model to examine the potential effects of climate change on the population. The model developed uses a novel incorporation of 2D axisymmetric heat transfer with empirical weather conditions, metabolic heat generation, and depth-dependent thermal properties to achieve these goals. With future work to implement the effects of mass transfer and evaporative heat loss due to precipitation events, this model has the potential to become a highly accurate way to non-invasively monitor and research Loggerhead turtle nests. It can also be easily adapted to other species for which incubation temperature is an interest. As climate change becomes an increasing concern for conservationists, computational modeling should be considered as a powerful tool to examine the impact of a changing environment on vulnerable species around the globe.

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7.0 APPENDIX A: INPUT PARAMETERS

Constant Parameters

Table A1: Constant parameters found from literature. Thermal properties of the egg domain were calculated as a weighted average by volume of eggs and air.

| Input Parameter | Value/Expression | Source |
|---|---|---|
| $Q_{\text{metabolic}}$ (<i>egg metabolic heat generation</i>) | Based on empirical data (W/m^3) | Sandoval, S., et al (2011) |
| k_{eggs} (<i>thermal conductivity of eggs</i>) | 0.203 $\text{W}/\text{m K}$ | Poppendieck et al (1966) |
| c_{peggs} (<i>specific heat of eggs</i>) | 1542.7 $\text{J}/\text{kg}^*\text{K}$ | Sandoval, S., et al (2011) |
| ρ_{eggs} (<i>density of eggs</i>) | 58.161 kg/m^3 | Limpus (1985) |
| k_{sand} (<i>thermal conductivity of sand</i>) | Based on empirical data ($\text{W}/\text{m}^*\text{K}$) | Smits (2010) |
| c_{psand} (<i>specific heat of sand</i>) | Based on empirical data ($\text{J}/\text{kg}^*\text{K}$) | Alnefaie and Abu-Hambae (2013) |
| ρ_{sand} (<i>density of sand</i>) | Based on weighted average (kg/m^3) | Handham, I.N., Clarke, B.G. (2010) |
| Θ (<i>water content</i>) | Based on empirical data | Lutz, Peter L., Musick, John A. (1996) |
| h (<i>convective heat transfer coefficient</i>) | $4.5286(u_{\text{air}})^{0.5} \text{W}/\text{m}^2*\text{K}$ | (u_{air} based on empirical data, see Fig. 9) |
| ϵ_{sand} (<i>emissivity</i>) | 0.75 | Bolz and Tuve (1973) |
| $T_{i, \text{sand}}$ (<i>initial sand temperature</i>) | 298.15 K | |
| $T_{i, \text{eggs}}$ (<i>initial egg temperature</i>) | 298.15 K | |

Surface Conditions

Empirical data for hourly average air temperature and wind speed for several sites in Florida was obtained from the National Centers for Environmental Information and was imported from Excel into COMSOL. The heat transfer coefficient for the convective boundary condition was calculated from Miami wind speed data and average air temperature during the nesting season. Hourly data from 2016 values of solar radiation (W/m^2) for the Everglades was obtained from the USDA Natural Resources Conservation Service National Water and Climate Center and was imported from Excel into COMSOL.

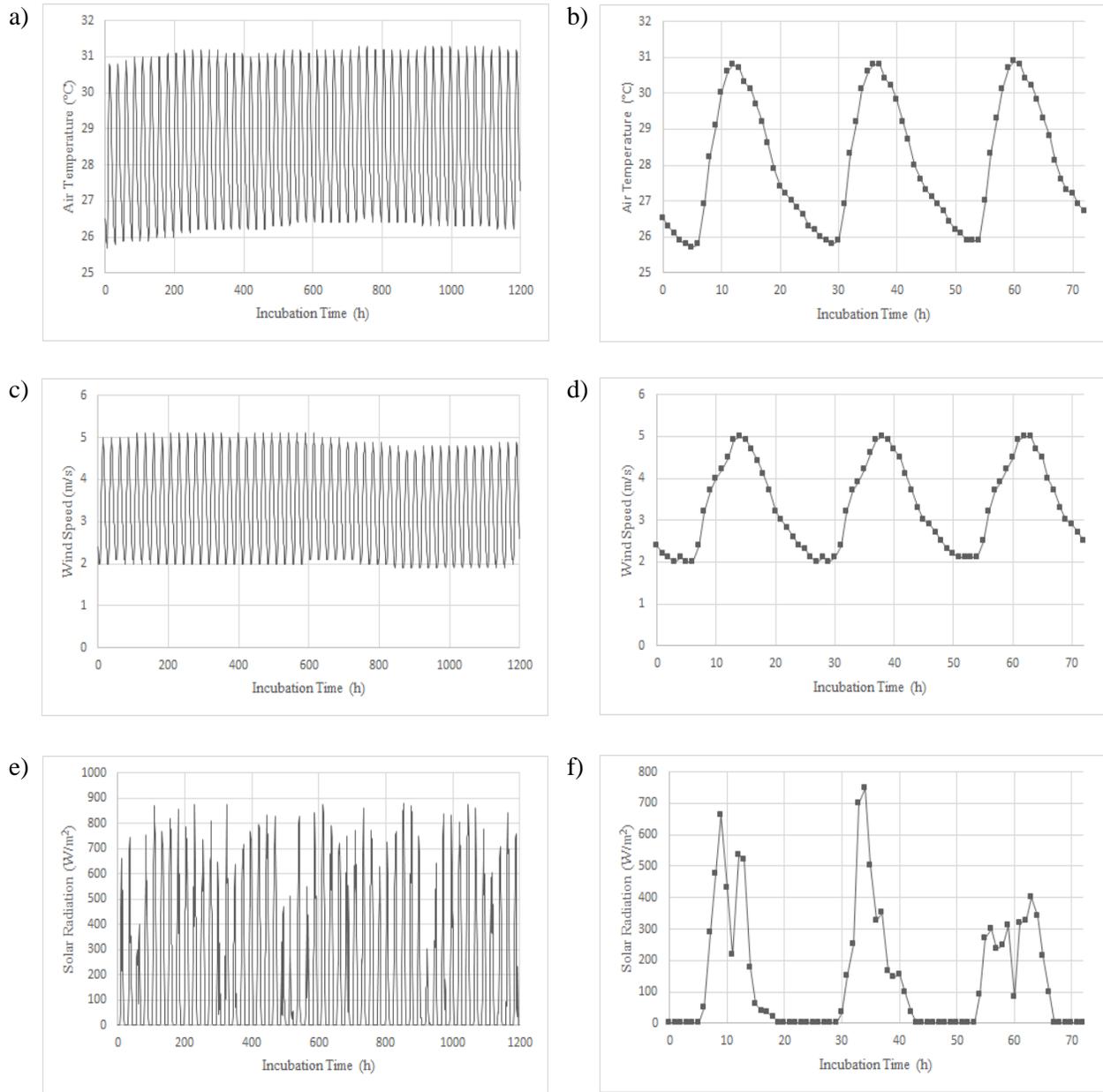


Fig. A1(a-f): Weather data for external air temperature (a-b), wind speed (c-d), and solar radiation (e-f) used in the model. The duration of incubation beginning July 1 is shown in (a), (c), and (e), and the first 72 hours of incubation are shown in detail for easier visualization in (b), (d), and (f).

Metabolic Heat Generation

In order to determine metabolic heat generation, we applied the metabolism trends identified by Sandoval et al. (2011) on metabolic heat estimation of the sea turtle *Lepidochelys olivacea* over forty days. Based on the data, we approximated metabolic heat generation as 0 W for the first half, increasing by .03 W per day for the third quarter, and increasing by .9 W per day for the fourth quarter of incubation. These values were divided by the volume in order to determine the heat flux generated by each egg in the nest.

Sand Properties

Thermal properties of sand are highly sensitive to moisture content. For this reason, the thermal conductivity and specific heat of the sand were implemented based on a water content function (Fig. 16). The sand is treated as very dry at the surface, then rapidly increases to a moisture content of about 4% (Lutz 96). The 4% moisture content is approximated as constant until the depth approaches the estimated water table depth of 2 m (Alves and Pezzuto 2009), where it reaches saturated levels of 33% water content.

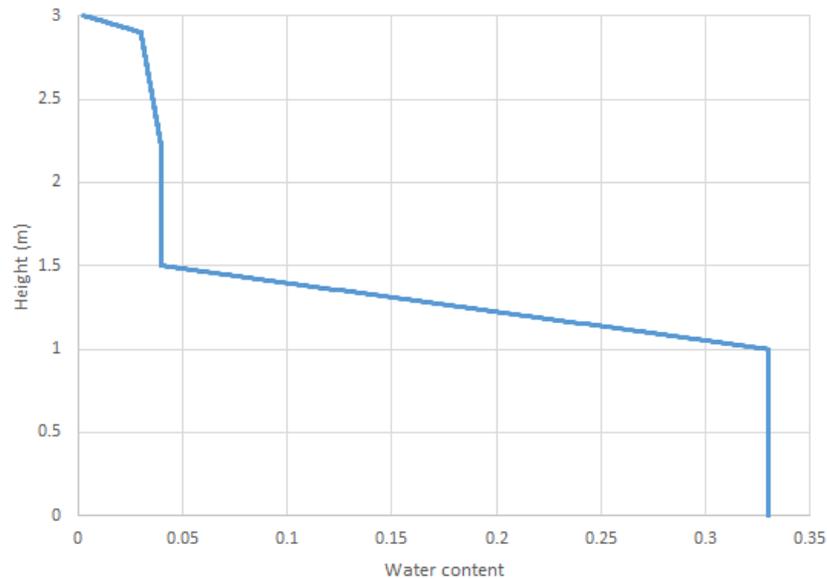


Fig. A2: Water content of the sand domain. Water content increases as distance from the surface (at 3 m) increases.

A function for specific heat as a function of water content was interpolated from a value for specific heat of dry sand and a value for specific heat of sand saturated with water. The specific heat was assumed to change linearly with water content between those two values (Alnefaie and Abu-Hambae 2013).

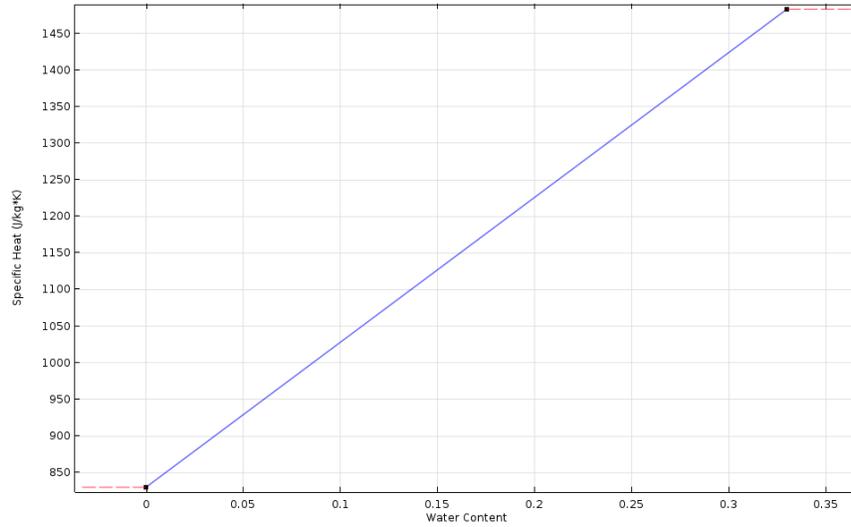


Figure A3: Specific heat as a function of water content. The specific heat assumed to change linearly between the values for fully dry sand and fully saturated sand.

A function for thermal conductivity as a function of moisture content was based on a graph from a paper by Smits et al showing thermal conductivity as a function of moisture content of sand.

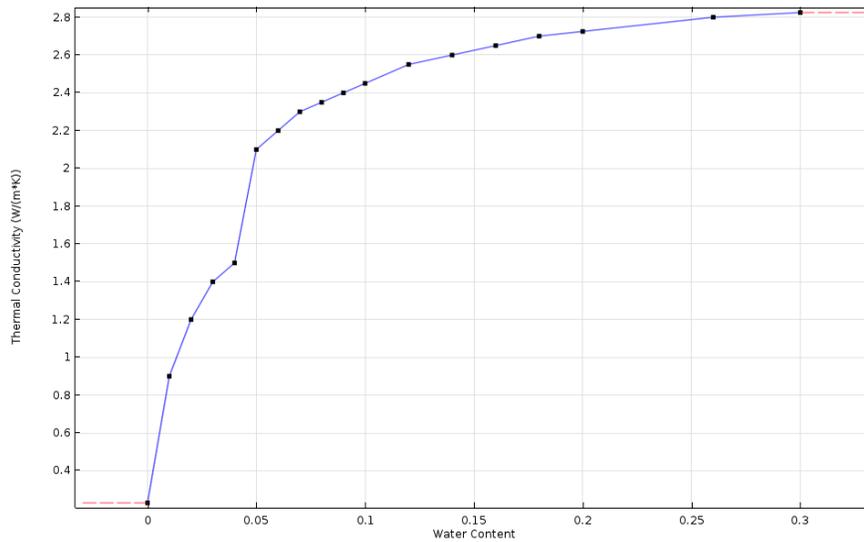


Figure A4: Thermal conductivity as a function of water content of sand.

To accommodate c_{psand} and k_{sand} changing with moisture content, a function was interpolated for each. The sand was assumed to follow the water content graph given above, starting at zero at the surface and quickly reaching 4% saturation through the middle. Using the functions of c_{psand} and k_{sand} , their values at the depths in the model given the water content were determined. When moisture content was constant, below a depth of 2m, thermal conductivity was also assumed to be constant. The data points for thermal conductivity as a function of moisture were taken from an article (Smits et al, 2010) with the assumption that the sand was tightly packed. This data was implemented in COMSOL with the function thermal conductivity as it varied with moisture content.

8.0 APPENDIX B: COMPUTATIONAL METHODS

8.1 Computation Time

Computation of a typical solution, such as 1200 h for a nest laid July 1 with 50% shading, took 116 s (1 minute, 56 seconds), using a physical memory of 1 GB and virtual memory of 1.14 GB.

8.2 Computational Methods

When initially running the model with the default free time stepping used by COMSOL, the model sometimes encountered an error where the boundary conditions were not incorporated for the full duration of the simulation. To resolve this, the solver was switched to a strict time step. The model was run at varying maximum time steps to determine the necessary step size where temporal discretization error was minimized.

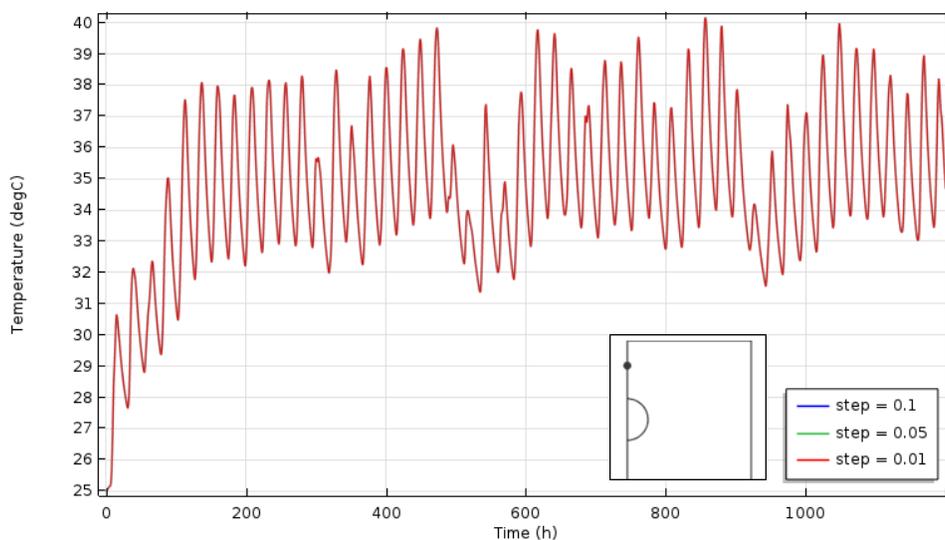


Fig. A5: A time step convergence was performed at a point above the nest in order to determine the necessary maximum step size. The default size of 0.1 h does not diverge from smaller step sizes.

Because all examined maximum step sizes converged, COMSOL's default value of 0.1 h for maximum time step was used. Default settings for absolute and relative tolerance were left unchanged.

9.0 TEAM RESPONSIBILITIES FORM

| Team member name | Lauren | Samantha | Katie | Allison | NOT DONE |
|---|--------|----------|-------|---------|----------|
| Wrote abstract | | x | | | |
| Edited abstract | x | x | x | x | |
| Wrote introduction | | x | | | |
| Edited introduction | x | x | | x | |
| Wrote method section | x | | x | | |
| Edited method section | x | x | x | x | |
| Wrote results section | x | | x | x | |
| Edited results section | x | x | x | x | |
| Wrote discussion section | x | | x | x | |
| Edited discussion section | x | x | x | x | |
| Wrote summary and conclusion section | | | | x | |
| Edited summary and conclusion section | x | x | | x | |
| Wrote bibliography section | x | x | | x | |
| Edited bibliography section | x | x | x | x | |
| Prepared processed data table for appendix | x | x | x | x | |
| Checked data in processed data table in appendix | x | x | x | x | |
| Prepared figures or tables for main text | x | x | x | x | |
| Checked figures or tables in main text | x | x | x | x | |
| Assigned tasks to group members | | | | x | |
| Put the report together from the parts provided by others | x | x | x | x | |
| Read and edited entire document to check for consistency | x | x | x | x | |