- ORIGINAL ARTICLE -

Dengue Dynamics: Modeling Spread and Environmental Interactions.

Dinámica del dengue: Modelización de la propagación y las interacciones ambientales

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Abstract

The objective of this study is to analyze the behavior of dengue fever in the city of La Plata during one year, considering temperature as an environmental factor, its influence on the mosquito population and the transmission of the DENV virus (which causes dengue fever, also known as dengue fever). To become aware of the magnitude of the problem in the future, and using the temperature estimated by the global warming trend, we sought to project an increase in average annual temperatures for the coming years, and thus estimate the impact on the spread of dengue fever. The Netlogo simulation tool was used to model the behavior of a mosquito population and the spread of the dengue virus through contact with the human population. Using official data from the National Meteorological Service, a scenario of spread was simulated for the period November 2022-November 2023, and the increase in temperature due to climate change was projected to simulate how it affects the spread of the virus and the mosquito population, maintaining the same trend for 2024, 2025 and 2030. It was concluded that climate change may generate an expansion in both the size of mosquito populations and their annual activity, leading to the appearance of dengue outbreaks outside the identified warmer seasons.

Keywords: Simulation, Dengue, Mosquitoes, Climate change, ABMS

Resumen

Este trabajo tiene como objetivo analizar el comportamiento del dengue en la ciudad de La Plata durante un año teniendo en cuenta la temperatura como factor ambiental, su influencia sobre la población de mosquitos y la transmisión del virus DENV (causante de la enfermedad dengue, también conocida como fiebre de dengue). Para tomar conciencia de la magnitud del problema a futuro, y usando la temperatura estimada por la tendencia del calentamiento global, se buscó proyectar un aumento en las temperaturas medias anuales para los años venideros, y así estimar el impacto de dicha problemática sobre la propagación del dengue. Utilizando la herramienta de simulación Netlogo, se implementó un modelo del comportamiento de una población de mosquitos y la propagación del virus del dengue a partir del contacto con la población humana. haciendo uso de datos oficiales del Servicio Meteorológico Nacional, se simuló un escenario de propagación para el período noviembre 2022-noviembre 2023, y se proyectó el aumento de las temperaturas a causa del cambio climático, para simular cómo afecta la propagación del virus y la población de mosquitos manteniendo la misma tendencia para 2024, 2025 y 2030. Se concluyó que el cambio climático puede generar una expansión tanto en el tamaño de las poblaciones de mosquitos como en su actividad anual, propiciando la aparición de brotes de dengue fuera de las temporadas identificadas como más cálidas.

Palabras claves: Simulación, Dengue, Mosquitos, Cambio climático, ABMS

1 Context

In recent years, there has been a worldwide increase in the occurrence of natural disasters: floods, droughts, snowfall and record temperature levels (both highs and lows). These changes in meteorology can be explained by the phenomenon known as climate change, defined as "long-term changes in temperatures and weather patterns" [1]. This has a climatic, ecological and social impact, generating new problems and conflicts [2, 3]. On a global scale, from the end of the 20th century onwards, an alarming increase in temperature per year is recognized, ranging from 0.6 C° around 1980 to 1.2

C° in 2022, and if we continue on the same path, an average global temperature increase of 2.5 degrees is expected by 2040. These changes over time can lead to the extinction or drastic mutation of the behavior of the planet's flora and fauna, and in particular for this study, we focus on the repercussions of the current changes and the possible future impact throughout the life cycle of dengue fever [4]. Our region is constantly affected by dengue, caused by environmental conditions such as temperature. Since 2009, the first nationwide epidemic in Argentina, dengue outbreaks have become a seasonal phenomenon and are spreading to more regions of the country. Infections have increased significantly in 2023, compared to 2016 and 2020, with cases in more and more provinces, although they are still concentrated in the northwestern (NOA) and northeastern (NEA) regions of Argentina, where temperatures are higher during most of the year [5]. Studies show a drastic increase in the number of dengue cases from the year 2020 where the peak of cases was recorded around epidemiological weeks 13 and 16 with approximately 6000 cases, the year 2023 shows a peak of up to 18000 cases in those weeks [6]. For these reasons, it is of interest to analyze the behavior of propagation based on temperature data recorded in the year 2023. Although this case study is based on temperature data obtained for the city of La Plata, the simulation model is highly configurable for a variety of scenarios if the temperature values of the area to be simulated are available.

2 Theoretical framework

Modeling scenarios of mosquito-borne disease spread within a population is a topic of great interest, given its expansion both in terms of number of cases and global distribution [7]. This problem is usually tackled from two approaches: mathematical modeling and agent-based modeling. The use of each type of modeling corresponds to the aspect of the phenomenon it seeks to study:

- Mathematical modeling (known as EBM, "Equation Based Modeling"), used to describe the epidemiological dynamics of dengue fever since at least the 1970s [8], simplifies individual behaviors and adopts a homogeneous approach to the system. This facilitates its implementation and reduces its computational cost, but limits its capacity to simulate the complexities of the phenomenon. It is also less flexible in the event of seeking to expand the model with new variables.

- Agent-based modeling (ABM) makes it possible to represent and understand processes such as social interactions, coordination, cooperation and segmentation between individuals in a population [9]. Although it is more computationally intensive, it is capable of simulating the heterogeneity of events that can be observed during the spread of a disease in a delimited territory, and can adapt to new parameters or scenarios with less difficulty than EBM. The flexibility of this paradigm allows its application in fields as diverse as modeling and simulation of HPC software [10].

In the case of Pais, C. M. et al [11], two solutions were compared by applying EBM and ABM, and it was concluded that the variable density of mosquitoes and people observable in Oro Verde (the location under study) was more accurately captured in the results of the latter.

Agent-based models consist of two main entities: the mosquito and the human being. Generally, male mosquitoes are neglected or abstracted in the form of a "mating probability." [12], since only female mosquitoes transmit the disease. It is possible to find models that include the different stages of development of the transmitting mosquito (egg, larva, pupa and adult)[9], as well as those that focus on simulating its adult stage. [11, 13]. The representation of the human population is also usually homogeneous, adapting its number and geographical distribution to the data of the region from which the experimental data were obtained. Regarding the variables involved, there are models that integrate meteorological data (temperature, precipitation) in order to analyze the effect of environmental factors on mosquito behavior [14]. Regarding the origin of the meteorological data, the work [15] uses the daily temperatures recorded by the National Meteorological Service for the city of Buenos Aires.

Although the effect of climate change on the spread of dengue has been mentioned in the literature [11] in none of the works consulted was it considered as the main object of study. In the present work, an agent-based modeling approach will be taken, modeling three entities: the mosquito (in its adult stage), the human (which, given that a fixed urban population is represented, will remain at a certain point in the terrain) and the pool of water (which will simulate with one of its states the presence of mosquito eggs). The daily temperatures in La Plata (Argentina) will be included as a variable, and the rest of the environmental factors will be left aside, in order to study in greater detail the effect of fluctuations generated by climate change.

3 Procedure

The procedure followed during development can be summarized in the following steps:

- Domain research.

- Obtaining data on the temperature in La Plata.

- Generation of a mosquito object using netlogo which interacts with the input data and the environment.

- Generation of the environment using netlogo.
- Configuration of the simulator so that a different temperature is used for each step following the sequence.
- Configuration of the simulator to receive the output data.
- Execution of the simulator.
- Analysis of the results.

For an analysis of the situation it was necessary to collect data on dengue and its behavior in different climatic conditions. To make behavioral predictions, we simulated the propagating agents, in this case mosquitoes, and the creation of a standard environment for the proliferation of dengue, taking as input data the temperature of each day. No population growth of either mosquitoes or humans was taken into account, but both remain stable during the simulations.

4 Modeling

The mosquito is able to infect the person, which translates into a change of the "color" state in the simulation, and the person remains in this state of infection until he or she heals over time. In the same way, infected mosquitoes are differentiated from healthy ones by their color in the simulation, the healthy ones in yellow and those infected with the virus in orange, however, unlike people, mosquitoes, once infected, are carriers of the virus for life [16].

4.1 Person model

For the purpose of the simulation the agent person has the sole objective of being bitten by mosquitoes, therefore, he can be infected with dengue fever and after a while he can be cured. Once recovered, the person can be infected again. In a real situation there are different "types" of dengue fever. A person who is infected and cured of a particular type may develop immunity to it, but for simplicity of the simulation this behavior is not contemplated in order to emphasize the spread of the virus.

- **duration-of-disease**: It is the only variable created for this agent. When a person is infected by a mosquito with dengue fever, this variable is updated to determine how long the person will be sick. On average, the virus remains in the person for about ten days. [16], Therefore, in the simulation the duration of the disease has a random factor making the time that remains infected a minimum of 7 days and a maximum of 14 days.

4.2 Mosquito model

The mosquito moves around constantly looking for someone to bite. When it succeeds, it automatically moves to the nearest puddle to deposit its eggs, and once they are deposited, it will leave again in search of another person to bite. The virus can infect both the mosquito and the person, if in the interaction of these agents one of them is previously infected.

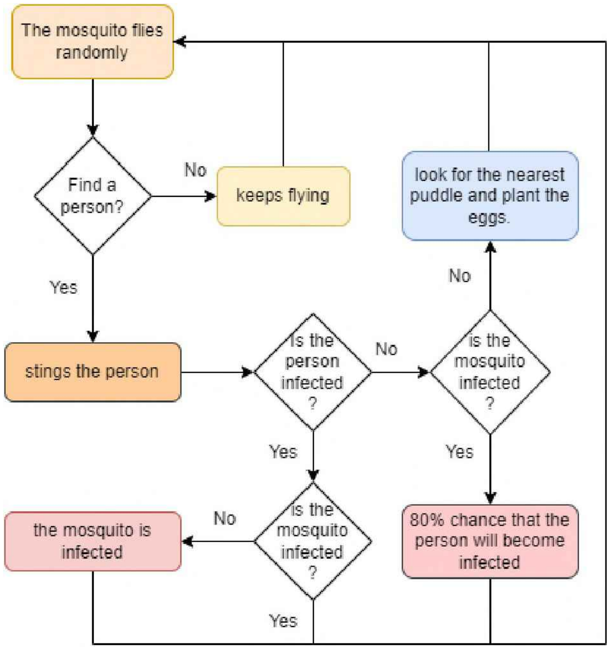

Figure 1: Mosquito behavior in the simulation space.

The mosquito agent has the following aggregated variables:

- **bitten-yet?**: Boolean variable used to switch between the two actions of the mosquito, if it has already bitten it has to go to a puddle to deposit its eggs, otherwise it keeps looking for someone to bite.
- **death-tick**: When a mosquito is born, a count is made of how long it will live as a mosquito and is stored in this variable. Throughout its life, very high or very low temperatures can cause this variable to change.
- **bites-count**: Stores the number of times a mosquito bites. In real life, a mosquito does not lay eggs every time it bites, but it does so a maximum of 4 or 5 times during its lifetime (it can bite and not lay eggs). Therefore, we limit the mosquito to bite 4 or 5 times.[21] This also means that there are a large number of bites that are not counted in relation to the total and that could become cases of dengue. The omission of these data is due to the fact that our study focuses on the effects of climatic variations on the spread of the virus. By focusing on a small group of the

population, such as only female mosquitoes, we simplified the sample to test the limits of spread on this scale.

In addition to the described basic behavior of the mosquito agent, a series of behaviors were added that vary depending on the temperature of the simulated scenario at the current time. The optimum temperature range for the propagation of both mosquitoes and dengue fever is between approximately 15°C and 28°C. However, extreme cases can be fatal for the insect. [19, 20]. To simulate this behavior, when the temperature drops below 10 C° each mosquito agent has a 35/100 probability of dying, and similarly, at high temperatures above 35 C° the life of the insect decreases in 1 day of simulation, for each cycle past this thermal threshold. As for virus transmission both at temperatures above 32 C° and below 15 C°, it is not possible at these extremes, so all transmission will occur between these temperature values. [19, 20].

Finally, the movement of the mosquitoes itself is prone to changes along with temperature variations such as those shown in Table 1. In modeling our agent, we reproduced this specific behavior by modifying the speed at which the mosquito moves through space.

Table 1: Speed of mosquito movement in space as a function of temperature.

T < 10 C°	speed * 0.5
10 C°< T < 25 C°	speed * 1
26 C°< T < 28 C°	speed * 1.5
T > 28 C°	speed * 1

4.3 Puddle model

The puddling agent is a static agent that mosquitoes approach when laying eggs. In doing so, the eggs hatch in the puddle after a certain time. In the simulation, the puddle changes from blue to turquoise when a mosquito lays its eggs, and the incubation stage begins. It turns blue again when the eggs hatch to generate new adult mosquitoes. Infected mosquitoes can pass the virus to their offspring, so it was decided to contemplate within this model that the eggs, once hatched, can do so already infected.

Finally, temperature plays a fundamental role in the mosquito growth stage, since at high temperatures the time it takes for the eggs to hatch is reduced by half, potentially making the dengue virus spread faster. [20]. On the other hand, very low temperatures are not suitable for mosquitoes to thrive, so the planted eggs go into a kind of hibernation waiting for the temperature to rise. [21]. In the simulation framework, this is implemented by updating the time at which eggs hatch, adding more time if temperatures are low and subtracting when they rise. A mosquito egg at a temperature below 12 C° will extend its own incubation duration by one day for each simulation cycle below this threshold, and likewise accelerate its incubation if above 28 C° making it take 1 day less to hatch for each tick in the system that meets the requirement. Below is a diagram showing the behavioral flow of the puddle agent (Figure 2).

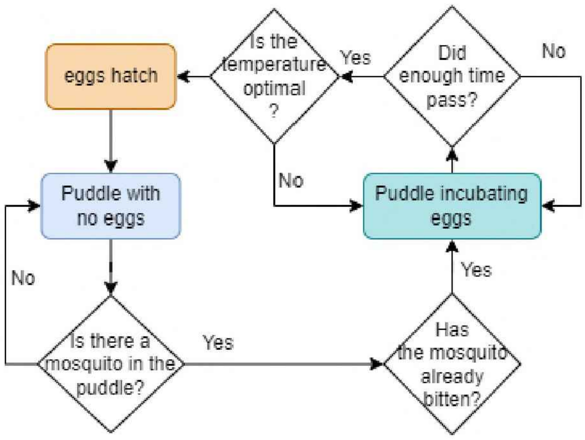

Figure 2: Diagram of the behavior of the puddle agent.

4.4 Temperature and time

To add the temperature variable to our environment we looked for actual temperature data for each day over the course of a year to feed into the simulation. For each day we found the maximum and minimum temperature, to which we added the average temperature using those two. It should be noted that the time in our implementation is measured in simulation ticks, each tick is considered a simulation cycle. When trying to emulate something as complex as the real world, at some point concessions must be made, so we chose to consider that one tick of simulation is equivalent to 8 hours of real time, i.e., one day is equivalent to 3 ticks of the system. The first tick of the day, from 0 hs. to 8 hs., is the first tick of the day, to which we associate the minimum temperature. The next band goes from 8 a.m. to 4 p.m. and therefore has the maximum temperature of the day assigned to it. And finally, the remaining portion of the day, from 4 p.m. to 0 a.m., receives the average temperature. As the simulation progresses, the temperature will be updated accordingly. This resolution serves both to lighten the computational load on the hardware and also on the software used, by assigning an approximate temperature in a simple and practical way, not without some concessions. By running the simulation with these 3 daily slots, we sacrifice accuracy in terms of the number of interactions between mosquitoes and people, since in this configuration a mosquito can bite once per slot, and we easily obtain future forecasts of the mosquito behavior pattern.

5 Simulation

Using a 2D agent-based simulator, the following variables were made available to modify the initial values of the simulation in order to perform several tests with different starting points.

- **setup:** creates the simulation scenario with the current configuration and prepares it to run.
- **go:** executes a simulation tick if the setup was previously done.
- **go(loop):** runs the simulation if the setup was previously done until it is finished or paused.
- **population:** Number of people with whom the simulation starts.
- **mosquitos-pop:** Number of mosquitoes with which the simulation starts.
- **infected-people-pop:** Number of infected people in the population.
- **infected-mosquitos-pop:** Number of mosquitoes with dengue with which the simulation starts.
- **puddle:** Number of puddles with which the simulation starts.
- **infection-rate:** A healthy person's probability of catching the virus when bitten.
- **eggs-per-puddle:** Number of mosquitoes that will hatch from the puddle after a while.
- **fumigate:** Pressing this button simulates large-scale spraying that directly kills a large percentage of the mosquito population by randomly selecting them. [22].
- **clean containers:** By pressing this button, all puddles of water containing eggs become clean, thus killing any mosquito eggs that may be growing.

The following table shows the initial configuration used to run the simulation.

Table 2: Initial configuration used for the simulations.

population	78
mosquitos-pop	40
infected-people-pop	15
infected-mosquitos-pop	20
puddles	10
eggs-per-puddle	6
infection-rate [16]	79

Human population values, represented by the parameter "population", the maximum number of eggs per mosquito ("eggs-per-puddle"), and those of

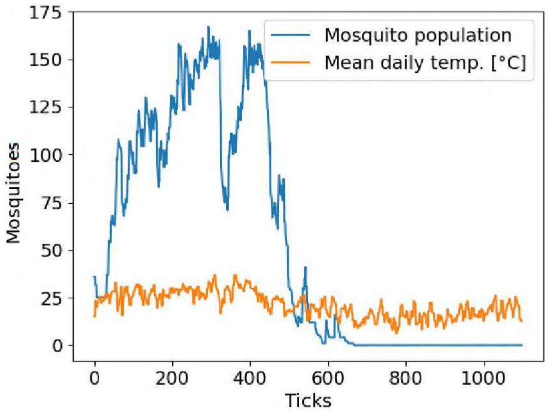

Figure 3: Mosquito population and average daily temperature in degrees Celsius during 2023.

mosquito population ("mosquito-pop"), were selected in such a way that the latter remains stable during the simulations and is able to cover the replacement rate throughout the year, even if the entire adult population dies due to temperatures. Similarly, the parameters "infected-people-pop" and "infected-mosquito-pop" were chosen to ensure that the virus responsible for DENV remains active and can continue to spread.
With this in mind, the simulator was run. Starting with temperatures corresponding to November 2022 the mosquito population is in the ideal climate to thrive and procreate more mosquitoes. As will be seen in the next section, the insect population rises almost constantly (except for two abrupt drops due to very low minimum temperatures in the middle of the summer) until it reaches a population ceiling, and at around 500 ticks the population begins to decline. These first 500 ticks of simulation correspond to part of the spring of 2022, summer 2022-23 and the beginning of the fall of 2023 where the mosquito population finally starts to decrease. When winter arrives, the mosquito population declines drastically. However, most of the puddles are still harboring eggs, as they are not yet at optimal temperatures, the eggs do not hatch, entering a state of hibernation. On the other hand, the temperature graph tends to decrease and the cases of dengue fever are decreasing until they disappear as people are healing. Once winter is over and temperatures begin to rise, the cycle begins again. The hibernating eggs hatch when spring begins and quickly spread causing the population, and thus the virus, to increase again.

6 Results

Once the model was developed and adapted to an agent-based simulation environment, simulations were performed on data collected by the National Meteorological Service (SMN) between November

1, 2022 and November 1, 2023 [23]. For each elapsed day, the maximum and minimum temperatures measured at the La Plata city weather station in Barrio Aeropuerto in the city of La Plata were recorded. In order for the simulation to use them, they were adapted to a CSV file ("comma separated values"), containing 3 columns: minimum temperature ("TMIN"), maximum temperature ("TMAX") and the average temperature of the day ("TPROM"). This last value was calculated from the average between the maximum and minimum temperature of that day. Therefore, the first tick of the day was assigned the minimum temperature, the second tick the maximum temperature, and the third tick the average temperature. Data is available until tick 1098 (3 ticks for each of the 366 days). Once tick 1099 is reached, we return to the first value (minimum temperature on 01/11/2022) and run through the data again. In the following tests, we will simulate up to tick 2190, to obtain the results of a simulation over 730 days.

In order to estimate the impact of rising temperatures due to climate change, the TMIN and TMAX data were randomly scaled up between 0 and 1°C each day using a script in the Octave numerical analysis environment. In the same script, the number of days that equaled or exceeded 32°C, those that equaled or were below 0°C, and the average temperature were reported in order to represent a 0.5°C increase in mean annual temperature. Data were also generated for a hypothetical temperature increase with respect to 2023 of between 0 to 2°C per day by 2025, and from 0°C to 7°C by 2030, obtaining the following results.

The first two rows ("Max.>=32 C°" y "Min.<=0 C°") represent the number of days with temperatures greater than or equal to 32C° and less than 0C° respectively for the years 2023, 2024, 2025 and 2030, and the last row (Annual average) compares the average annual temperature in each of these years.

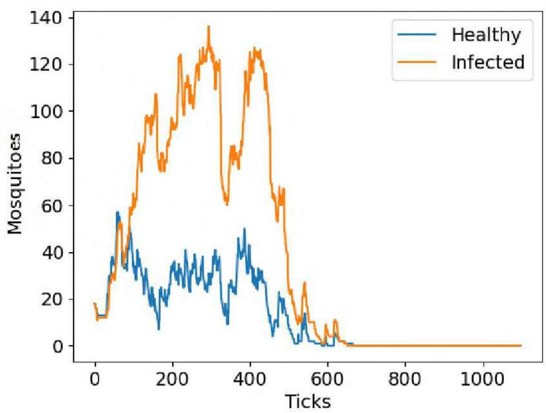

Figure 4: Population of healthy and infected mosquitoes in 2023.

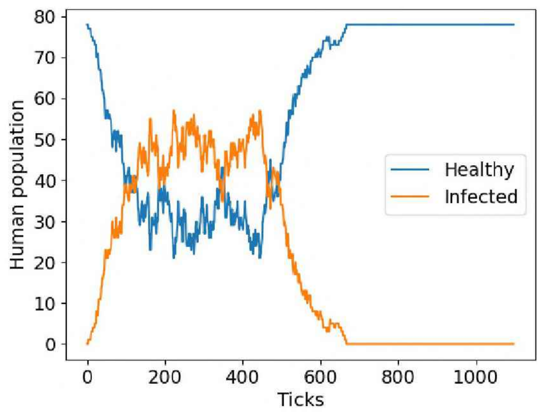

Figure 5: Population of healthy and infected persons in 2023.

Table 3: Data obtained for the annual temperature in 2023, and data generated for the temperature in the 2024, 2025 and 2030 scenarios.

Year	2023	2024	2025	2030
Max.>=32 C°	21	23	26	58
Min.<=0 C°	8	4	3	1
Annual average (C°)	17.66	18.16	18.66	21.23

The following results are obtained from these data:

The graphs in the first row show how the total mosquito population reaches increasingly higher peaks: from 186 in 2023 to 191 in 2024, 194 in 2025 and 200 in 2030. Changes in mosquito metabolism, due to the increase in temperature, may explain this growth in the maximum as well as in adult survival: between 2024 and 2030 the population curve is widening, meaning that the number of days in which there are live adult mosquitoes is increasing. With an average of 220 days with adult mosquitoes in the 2024 sample, in 2030 the number of days with live mosquitoes increases to 320, i.e. an increase of 45% in 6 years. In the second row, it can be seen that the number of infected in 2025 reaches two peaks that exceed those of 2024. In addition, these samples show an increase in the total number of days in which the infected population of mosquitoes is greater than the healthy population, with an average of 192.8 days in 2024, 198 days in 2025 and 286 days in 2030. In 2030, cases are recorded almost year-round, in contrast to the case-free periods in previous years, and the curve of infected at the time of peak infection is steeply widened. In the third row, it is noticeable how both maximum and minimum temperatures progressively increase, from a maximum of 40.9°C in 2024 to 43.6°C in 2025 and 47.8°C in 2030; and from a minimum of -4.4°C in 2024 to -5.1°C in 2025 and -7.2°C in 2030.

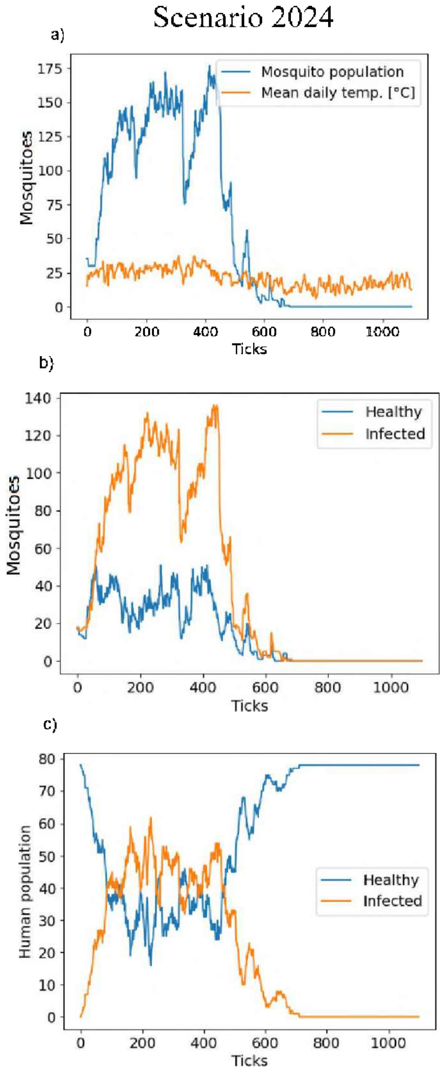

Figure 6: Results of the scenarios simulated from the data generated for 2024. a) Total mosquito population and average daily temperature in degrees Celsius; b) population of healthy and infected mosquitoes; c) population of healthy and infected people.

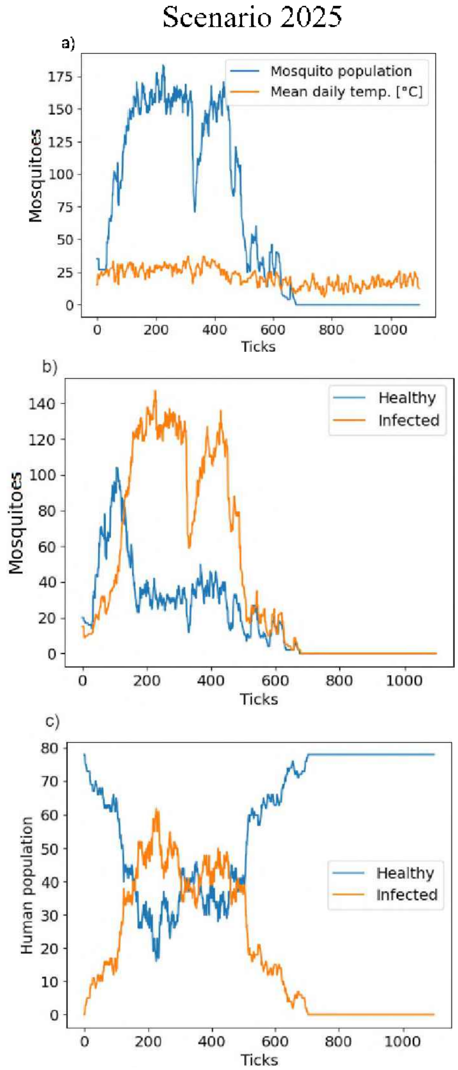

Figure 7: Results of the scenarios simulated from the data generated for 2025. a) Total mosquito population and average daily temperature in degrees Celsius; b) population of healthy and infected mosquitoes; c) population of healthy and infected people.

7 Conclusions and future work

Starting from a model of the life cycle of the Aedes Aegypti mosquito and its dengue virus transmission habits, it is possible to develop an agent-based simulation that receives real data from the National Meteorological Service for La Plata and obtain an approximation of the impact of environmental factors on the epidemiological dynamics of dengue.

It was concluded that a sustained increase in mean annual temperature may have the following effects:

- An increase in the total mosquito population in the peak season of 61.5 percent between 2023 and 2030.
- A more extensive distribution of mosquito activity during the year, equivalent to a 45.4% increase in the number of days.
- An increase in the total number of dengue cases of 40.1% by 2030 compared to 2023, with increasing peaks of concurrent cases.
- A wider distribution in the number of dengue cases throughout the year, with infections becoming possible outside the typical season.

These record temperatures, both annual and seasonal, imply that outbreaks will become more frequent and will occur in geographical regions where they were previously infrequent, such as the La Plata district.

Regarding future work, by continuing this research we will seek to scale the number of agents to a number that better represents the problem in the real world. Taking this into account, it is likely that it will be necessary to resort to parallelization of the simulation.

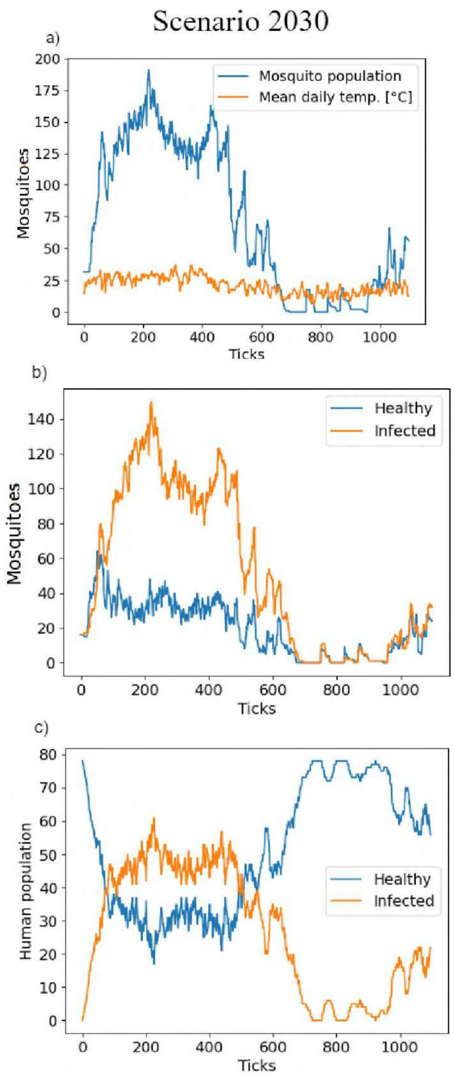

Figure 8: Results of the scenarios simulated from the data generated for 2030. a) Total mosquito population and average daily temperature in degrees Celsius; b) population of healthy and infected mosquitoes; c) population of healthy and infected people.

Another alternative would be to demonstrate the impact of different measures to combat both mosquito population growth and virus transmission, such as spraying of public areas, recommendations to the population to keep water containers clean and/or covered to prevent mosquitoes from using them to lay their eggs, and vaccination of people against the virus.

Competing interests

The authors have declared that no competing interests exist.

Authors' contribution

- Conceptualization (DE,FR,JM,JS,LM)
- Software (JM,JS)
- Supervision (DE,FR)
- Redaction - original manuscript (DE,FR,JM,JS,LM)
- Redaction - review and editing (DE,FR,JM,JS,LM)

All the authors have read and approved the final version.

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