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Dengue Infections According to Meteorological Conditions

Mosquitos are the world's deadliest animals because of the many diseases they carry including dengue fever, malaria, Zika virus and chikungunya. They are mostly active at higher temperatures during summertime, and with global warming, they have been expanding their “hunting territory”, with more and more species occupying colder countries. Being able to predict mosquito activity could allow us to take preventive countermeasures.

We have decided to create a model to predict dengue fever infections caused by Aedes Albopictus (tiger mosquito) depending on temperature and humidity. This model will be heavily influenced by the initial population of mosquitoes and their infection rate, both of which depend on temperature and humidity (according to literature [1,2,3]).

We therefore attempt to answer the following question : **What are the risks of contracting dengue through tiger mosquitoes, for different summer temperatures and humidities?**

I/ Mathematical model and equations

1) Compartimental and logistic population models

Firstly, we modelized our population dynamics thanks to 3 simple equations. Here, we do not take into account the influence of humidity or temperature. Here are the population variations through time :

Healthy humans	Infected humans	Mosquito
$\frac{dS}{dt} = -k * S * M$	$\frac{dD}{dt} = k * S * M$	$\frac{dM}{dt} = a * M * (1 - \frac{M}{C})$

We inspired ourselves of the SIR model for the human population and of the logistic model for the mosquito population with a carrying capacity, ***C***. There are no human “recovered” or “dead” populations because we are studying the unique apparition of the dengue, and are not doing an epidemiologic study of individuals through time. Therefore, the human population is constant because it is not the subject of interest. However, we study temperature *(and humidity)* and its influence on several factors.

In our model, temperature :

- regulates the infection rate ***k*** both positively and negatively (regulates the passage from healthy to infected humans). k is the chance of getting infected depending on the : percentage of infected mosquitoes*the biting rate (depending on T°)*the probability of transmission to the human (depending on T°). The equations we found for the coefficient k were found in a scientific article.
- regulates mosquito birth rate ***a*** positively for 20 < T < 30 and negatively elsewise. ***a = q*DailyEggs***, q depending on temperature (20 < T < 30), DailyEggs calculated for a certain T° and humidity % *(detailed in the code) & on Fig.X*.

The positive or negative influence of temperature is determined thanks to a bi-dimensional Gaussian curve we modelized from data in an article, setting T° = 25°C and 80% humidity as the maximum of this Gaussian curve.

2) Introduction of a anti-mosquito protection measure to negatively influence the mosquito population

To influence the population of mosquitoes, we introduced an anti-mosquito measure triggered at a certain threshold (whenever the infected human population surpassed the healthy population). We first simulated this measure thanks to a periodic function and a coefficient, ***u***, that we determined experimentally.

Our equation for the mosquito population looked like this : $\frac{dM}{dt} = a * M * (1 - \frac{M}{C}) - u * sin(\frac{t}{15})^{40}$

However, we were also interested in creating a repressive measure that would be triggered every ***x*** time when passing our threshold, so we replaced our periodic function by a subtraction called "harvest" that takes out ***y*** mosquitoes every ***x*** time. In this case, ***harvest = u*** *(same equation but without the sinus)*.

Here are the graphs we obtain for both methods at T° = 25°C & H = 0.8 :

Figure 1. Periodic function

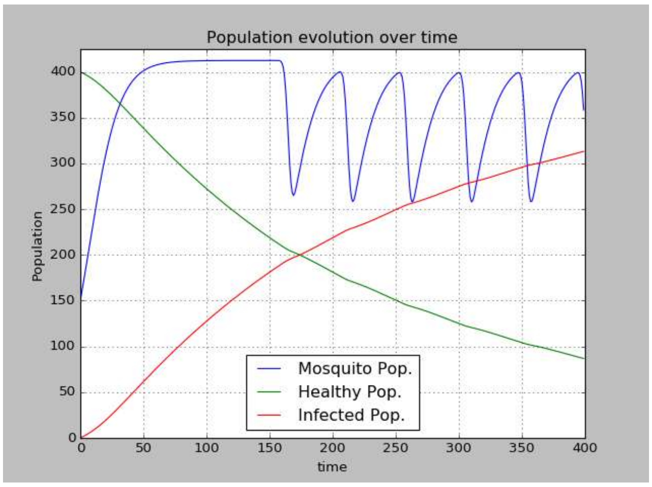
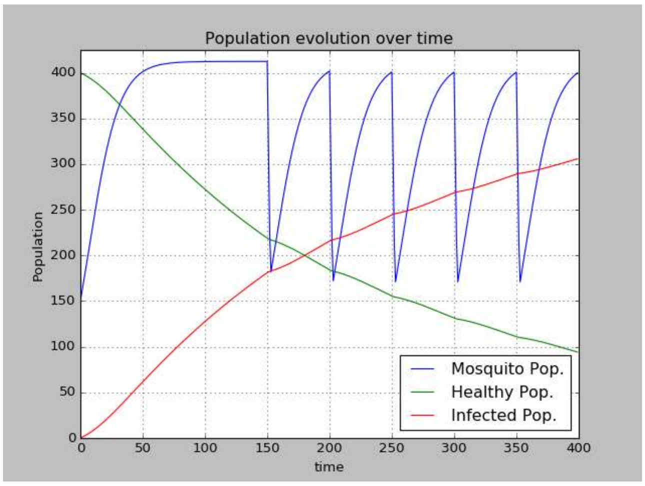


Figure 2. Harvest subtraction



On *Fig.2 bis*, the protection measures (harvest subtraction) has a clear impact on the infected population. Indeed, the curve's slope is altered (and diminishes during the repressive measures. The infection is slowed down because the mosquito population drastically diminishes during these measures.

II/ Simulations and phase diagrams

1) Population dynamics

In this section of the report, we plot different diagrams and discuss the influence and relation between different parameters. Firstly, we observe that the infected and healthy population evolve coherently *(Fig.4)* : the infected are deducted from the healthy compartment and added to the infected compartment, consistently with the populational equations we adapted from the SIR model. Also, conservation of the whole human population in the course of time is respected.

Secondly, the evolution of mosquito population is also consistent with either favorable or detrimental temperature (T) and humidity conditions (H) applied. At T = 10°C & H=80%, the birth rate is not sufficient to balance the death rate, and all mosquitoes end up dying *(Fig.3)*. In opposition, under optimal conditions (T=25°C & H=0.8), the reproduction rate is maximal and exceeds the death rate : the mosquito population increases. Nevertheless, once a certain threshold is reached, anti-mosquito measures are pulsed, and result in a regular decrease and increase in the mosquito population (*Fig.4*).

Finally, the influence of temperature on infection is also clear : as we can see on *Fig.1*, there is no dengue transmission at 10°C. As a matter of fact, a virus possibly transmitted by the mosquitoes is not viable under a certain temperature.

Figure 3. Evolution of mosquito, healthy and infected populations over time, at T=10°C & H=0.8 (harmful conditions)

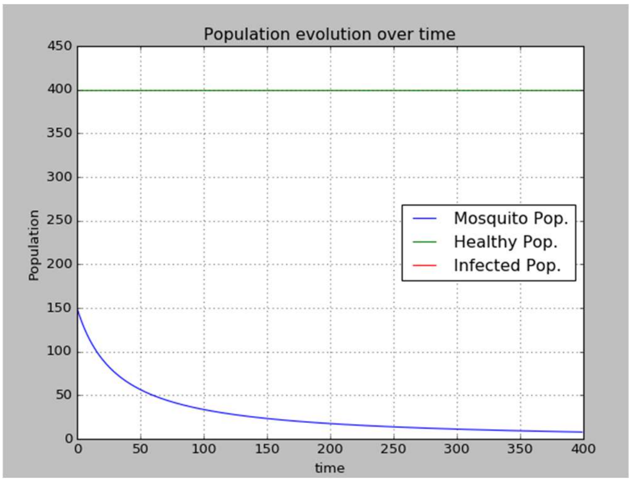
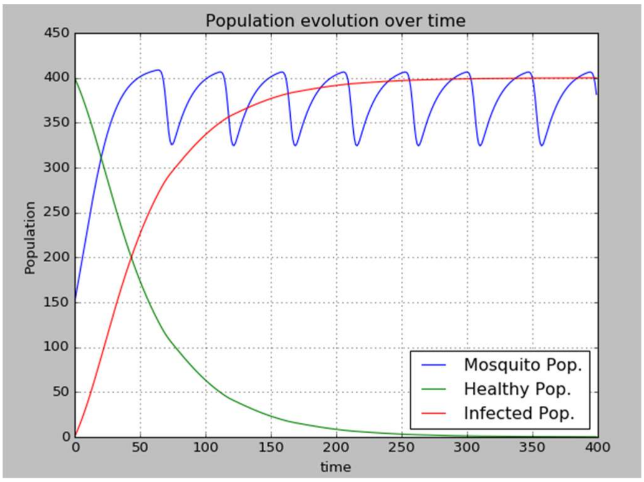


Figure 4. Evolution of mosquito, healthy and infected populations over time, at T=25°C & H=0.8 (optimal conditions)



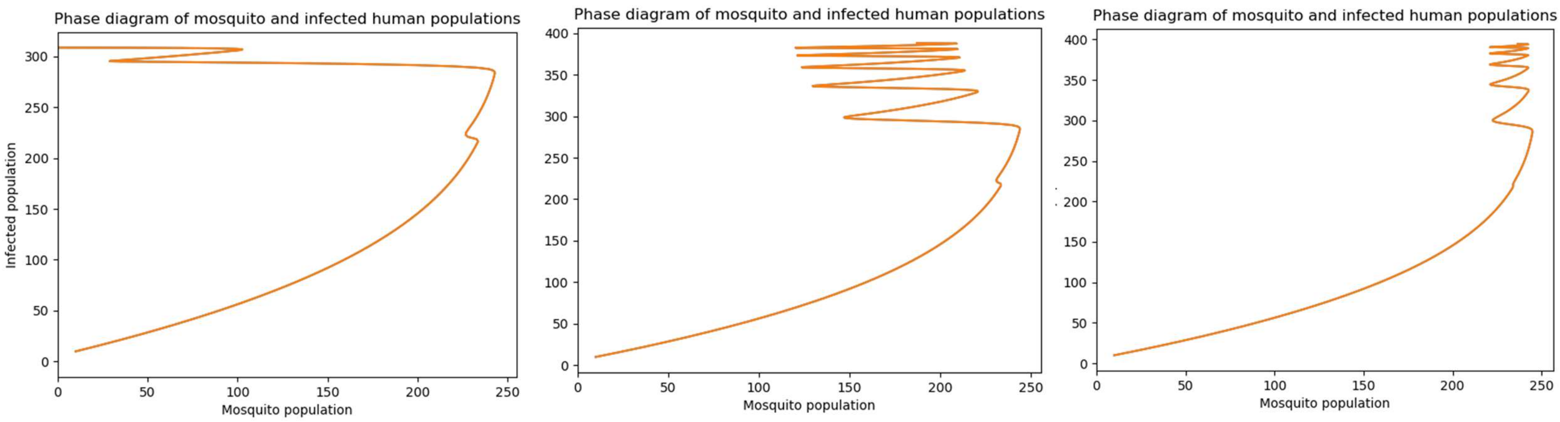
2) Interrelationship between mosquito and human populations & impact of repression

The interaction between the mosquito and human population is also interesting to observe. Firstly, when no mosquito regulation is applied, and if temperature conditions enable dengue transmission, the number of infected people increases, logically. Then, once repressive measures are taken, the growth of the infected population slows to finally reach an equilibrium, while the number of mosquitoes oscillates in an interval.

The intensity of repression impacts the rapidity for which this equilibrium is reached, and its position. For a strong repression, an extinction in the mosquito population stabilizes the infected population to a value inferior to the total human population, meaning that not all the humans were infected. For small to medium repressions however, our model predicts that all humans should end up being infected, while the number of mosquitoes oscillates very slightly *(Fig 5.)*. However, it takes time to reach total infection (approx 250 days), and summer is only 93 days long; which suggests that the mosquito population should have decreased with the fall of temperature before the entire human population would have been infected.

It is noticeable that the rapidity of infection is also controllable by the threshold from which repression starts (depending on the number of infected and healthy people).

Figure 5. Evolution of the infected people and mosquitoes population given different repression intensities



Strong repression (u=40) Medium repression (u=20) Small repression (u=5)

The intensity of repression was then fixed (to u=20) so that the infected humans and mosquitoes population interrelationship was observable, as commented in *Fig 6., 7.* and *8 below*.

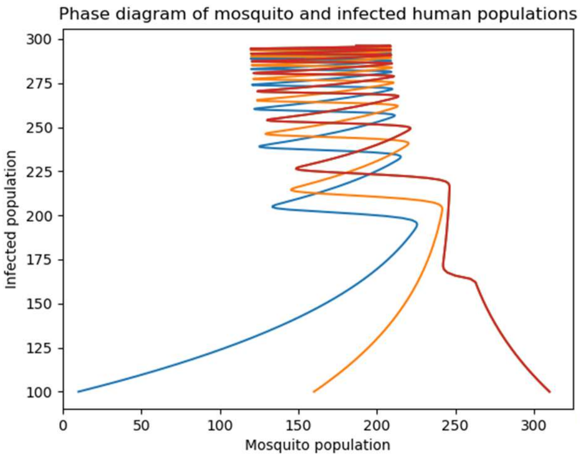


Fig.6 : The infected population increases and stabilizes to a value of equilibrium once anti-mosquito measures are taken, independently of the initial mosquito population.

7. Influence of the initial infected people
ulation on the number of mosquitoes

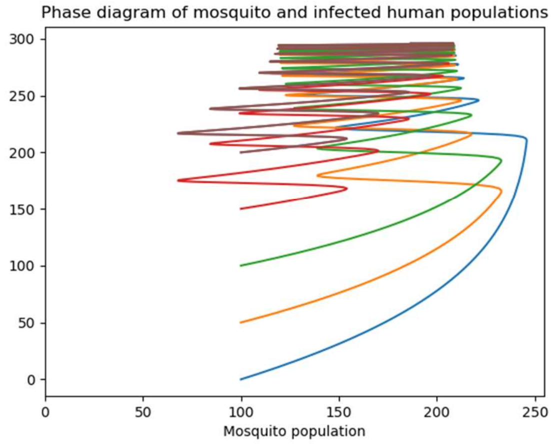


Fig.7 : Depending on the initial infected population, the equilibrium is more or less rapidly reached.

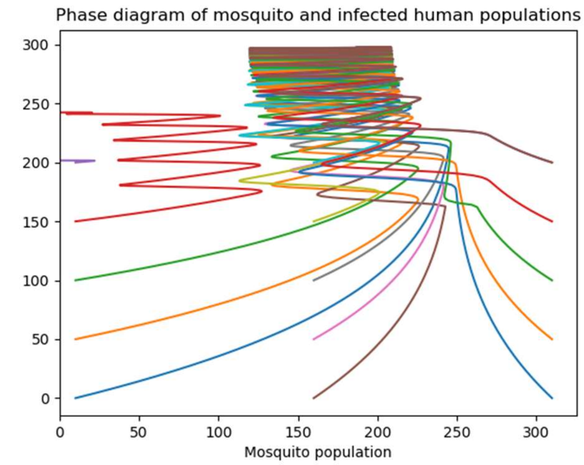
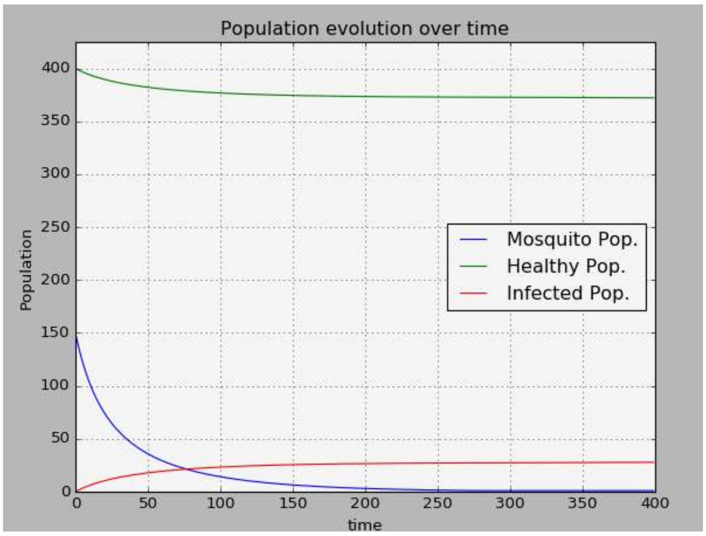


Fig.8 : The combination of different initial mosquito and infected populations give rise to the same observations. One interesting case is to be noticed : when there are too many infected people at the beginning, repressive measures are taken immediately and enable to lead to mosquitoes extinction (cf. red curve of *Fig.8*).



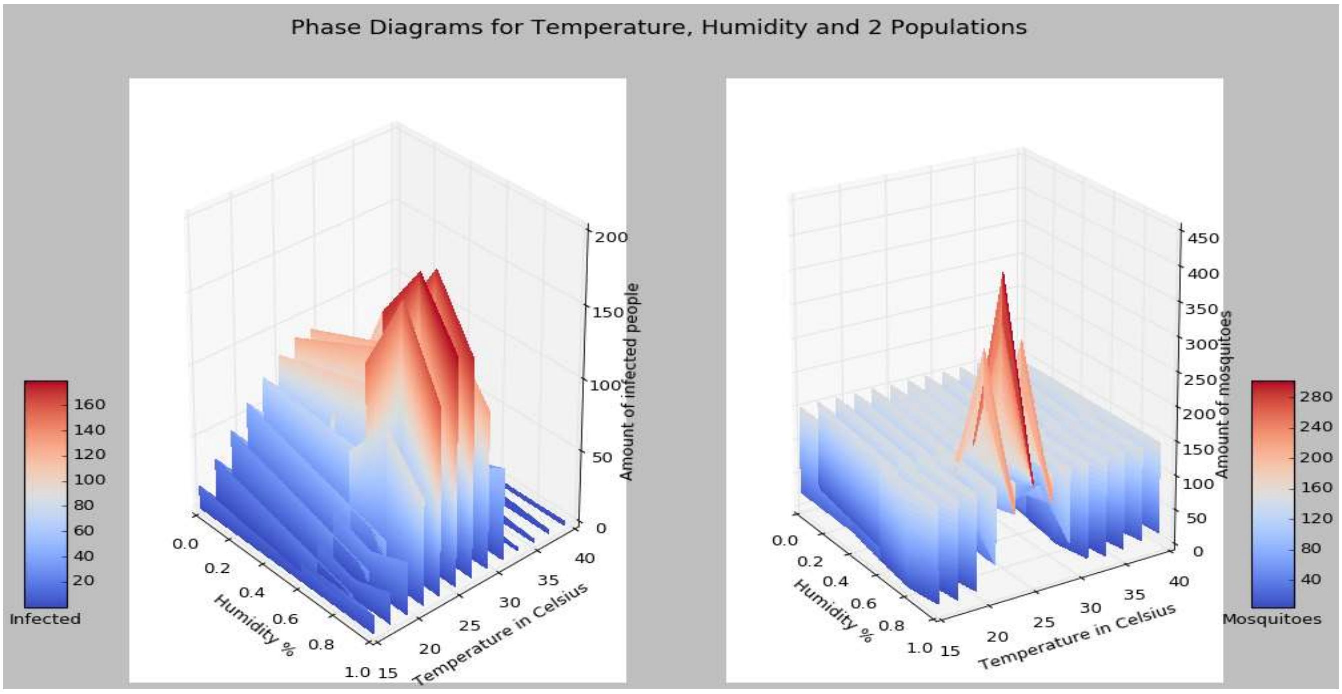
3) Temperature and mosquito birth rate

Moreover, as introduced in the first section of this report; we introduced a parameter, ***q***, dependent on the temperature to furthermore impact the evolution of the mosquito population.

For T in [20°C;30°C], q > 0. If not, q < 0. When the mosquito population is equal to zero, the human healthy and infected populations are fixed and tend towards an asymptote. *(Fig.9)*

Figure 9. Population evolution over time for T = 10°C

A final representation of the influence of temperature and humidity on the amount of infected people, as well as the mosquitoes population, is given by the two phase diagrams below (*Fig.10)*.



As expected, the number of infected people is maximal at T=25 °C and H=0.8, consistently with the number of mosquitoes. The distribution of the infected population in function of temperature and humidity follows a double Gaussian curve centered on this peak.

The amount of mosquitoes is highly restricted by a concave function on temperature, killing mosquitoes under 20°C and over 30°C. Furthermore, the gaussian on humidity has a small standard deviation (0.136) which explains why humidity rapidly decreases as it distances itself from its mean (0.8).
For both of these diagrams, we note an unstable state for 25°C and at 0.8 humidity, at the peak of the Gaussian curves.

III/ Limits and continuation of our model

Our model appears to be satisfying to modelize humidity and temperature effects on both mosquito growth and infection rates. It gives, first, a study of the mosquito population, and furthermore, a simulation of the number of people infected by dengue depending on the mosquito population. Results are rather consistent with those described in literature.

Studying two variables, i.e. temperature and humidity, is a first advantage of our model, despite humidity not being taken into account for the dengue transmission rate. Also, other meteorological conditions such as wind or storms could have also been included in the model. Some variables like pollution rate might also influence mosquito growth and activity.

Many parameters were also tested, and several of them were based on literature, such as the biting rate of mosquitoes or the proportion of dengue-transmitting mosquitoes. One limit is that the equations and parameters used to describe temperature influence on dengue transmission were reported for another type of mosquito than *Aedes albopictus,* named *Aedes aegypti.* Also, we modelized our double Gaussian based on only six couples of data (temperature, humidity) from an article, which is a low amount of data.

The development of mosquito populations also highly depend on geographical characteristics such as altitude or the presence of swamps and stagnant water. We haven't taken into account these parameters in our model.

Our model seems to predict infection tendencies in summer, with the goal of improving preventive measures and fighting against mosquito propagation. Possible acquired biological resistance to mosquito repellents was not taken into account. Also, our model neglects the individual variability of humans, even though we thoroughly studied the individuality of humans by reading up on the influence of factors such as color, odor, clothes, genetic factors and outdoor activities.[5,6,7]

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$$99 \times e^{-\frac{1}{2}\left(\frac{T-Tmax}{\sigma \quad T}\right)^{2}} \times e^{-\frac{1}{2}\left(\frac{H-Hma}{\sigma \text{[redacted]}}\right)^{2}}$$