Modeling the impact of temperature and anthropogenic activity on a coral ecosystem

Gili Matra Marine Recreational Park

Computational Methods and Tools Project

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1.1 Introduction

Coral reefs are among the marine ecosystems most vulnerable to climate change and other anthropogenic pressures. The first model presented aims to simulate the evolution of coral, anemone, wrasse and starfish populations in the Gili Islands (more precisely in the *Gili Matra Marine Recreational Park*) in response to water temperature and interspecies interactions.
This modeling could be useful in determining the future of these rich and magnificent ecosystems in the context of climate change, and in encouraging their protection. It could also be a response to requests from governments or associations wishing to raise awareness or implement measures to preserve these ecosystems.
For the sake of clarity and readability, we will deal first with the impact of temperature and the associated results, and then with the anthropogenic impact.

1.2 Methods

1.2.1 Model equations

The model is defined by a set of differential equations describing the dynamics of each species as a function of temperature and biological interactions [2].

$$\begin{aligned}
\frac{dW}{dt} &= W\left(\phi_1\left(1-\frac{W}{1+\theta_1 C}\right)+\delta_1 S\right)-\mu WA-\gamma_w T,\\
\frac{dA}{dt} &= A\left(\phi_2\left(1-\frac{A}{1+\theta_2 C}\right)\right)-\mu WA-\gamma_a T,\\
\frac{dC}{dt} &= C\left(\phi_3\left(1-C\right)-\frac{uS}{C+p}\right)-\gamma_c T,\\
\frac{dS}{dt} &= S\left(\phi_4\left(1-S\right)-\delta_2 W+\frac{C}{C+q}\right)-\gamma_s T,
\end{aligned}$$

where :

- W, A, C, and S represent the populations of *wrasses*, *anemones*, *corals* and *starfish* respectively,
- T is the water temperature (*cf. Section 1.2.3*),
- ϕ_i, θ_i, δ_i, μ, u, p, and q are parameters describing biological and environmental interactions (*cf. Section 1.2.2*),
- γ_w, γ_a, γ_c, and γ_s are heat stress factors for each species, updated at each temperature value (*cf. Section 1.2.4*).

In addition, it is important to note that in the *Gili Matra Marine Recreational Park*, there are two main types of coral: *acropora*, which are highly sensitive to temperature, and *porites*, which are slightly less so. These two species alone account for a major part of all corals. However, it is difficult to find an exact percentage of the park's however, remains difficult to find. We will therefore apply this model for acropora, then porites and finally the other, less temperature-sensitive corals, each time assuming that the coral reef is only composed of one of the species in question.
In short, C can represent acroporas, porites or all other park coral species.

1.2.2 Constants and initial conditions

To begin with, the constants used in the model and their units are summarized in the following table (*cf. Table 1*).

Parameter	ϕ_1	ϕ_2	ϕ_3	ϕ_4	θ_1	θ_2	μ	δ_1	δ_2	u	p	q
Value	0.1	0.05	0.03	0.02	0.5	0.4	0.02	0.01	0.005	0.001	0.1	0.15
Unit	%	%	$m^2\ kg^{-1}$	$m^2\ kg^{-1}$	-	-	$m^2\ kg^{-1}$	$m^2\ kg^{-1}$	$m^2\ kg^{-1}$	-	kg/m^2	kg/m^2

Table 1: Constants used in the model.

Subsequently, we found in the different initial percentages (*cf table 2* and bibliographie for sources) occupied throughout the park by each species (2020). Then, knowing that the surface area of the park is 3×10^6 [m^2] and taking into account the increase in seafloor depth, we find the surface area in [m^2] occupied by each species. Finally, using the respective biomass densities (*cf table 2*) and dividing by the surface area, we obtain the initial quantity of each population in [kg m^{-2}].

Metric	**Wrasses**	**Anemones**	**Corals**	**Starfish**
Initial Percentage (%)	0.17	0.03	0.35	0.01
Biomass Density (kg m^{-2})	0.01	0.02	7.0	0.15

Table 2: Initial percentages occupied by each population and their biomass density.

1.2.3 Temperature Modelling

Water temperature $T(t)$ is modeled as a linear function of time with seasonal variations. We have also added a factor due to climate change. Under conventional climate change scenarios, temperatures in Indonesia could rise by 0.5 to 2°C above current levels by 2050, depending on the emissions scenarios adopted. This led to the following temperature formula:

$$T(t) = at + b + A \sin\left(\frac{2\pi t}{12}\right) + 0.15t,$$

where A represents the amplitude of seasonal variations and the factor 0.15 is linked to climate change. The latter seems to us to be a good compromise for quantifying the impact of climate change in the first instance. We will discuss its impact on the model later. a and b are the linear regression coefficients calculated from local data. Linear regression was performed to model the relationship between a dependent variable (y) and one or more independent variables (x). The model is defined by the following equation:

$$y = b + ax + \epsilon$$

To estimate b and a, the method of least squares was used, minimizing the sum of squared errors ϵ, given by :

$$\text{SSE} = \sum_{i=1}^{n} (y_i - (b + ax_i))^2$$

The steps followed are the calculation of averages and coefficients:

$$a = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sum(x_i - \bar{x})^2}, \quad b = \bar{y} - a\bar{x}$$

The results obtained make it possible to predict y as a function of x, and to evaluate the fit of the model using the residuals. Here, temperature $T[°\text{C}]$ as a function of time t. For the sake of accuracy, we applied linear regression to four different temperature data sets, each containing the average water temperature per month over the period January to December. We then took the average of the four a and four b found.

1.2.4 Thermal stress factors

Thermal stresses for each species are defined as follows:

$$\gamma_x = \begin{cases} 0 & \text{si } T \leq T_{\text{critique, x}}, \\ \min\left(0.1 \cdot (T - T_{\text{critique, x}}), 1.0\right) & \text{si } T > T_{\text{critique, x}}, \end{cases}$$

where T_{critical} is the critical temperature $[°C]$ specific to each species ($T_{\text{critical, s}}$ for starfish, for example). However, as corals are very sensitive to temperature, we have adapted the 0.1 factor according to coral species.

1.2.5 Numerical resolution

The model is solved numerically using the explicit *Euler* method with a time step $\Delta t = 0.01$. Simulations cover a period of 1,000 time units, corresponding to several decades in biological scale. The *Euler* method is a simple numerical technique for approximating the solution of an ordinary differential equation (ODE) of the form :

$$\frac{dy}{dt} = f(t, y), \quad y(t_0) = y_0. \tag{1}$$

It is based on approximating the solution over a time interval using increments proportional to the local slope given by $f(t, y)$. For a step of size h, this method updates the value of y at time t_{n+1} as follows:

$$y_{n+1} = y_n + h \cdot f(t_n, y_n). \tag{2}$$

First initialize the value y_0 to t_0, then choose a time step h and calculate y_{n+1} using the equation above for $n = 0, 1, 2, \ldots$. We've chosen this method for solving the problem because it's fairly simple to implement, compared with the *Runge-Kutta4* method, which is more accurate but more costly to implement and more complex in terms of time. The *Euler* method is well suited to a first approximation.

1.3 Simulated results

The best way to understand the impact of temperature and inter-species interactions is by means of a graph (see Figure 1), where the corals considered are acroporas.

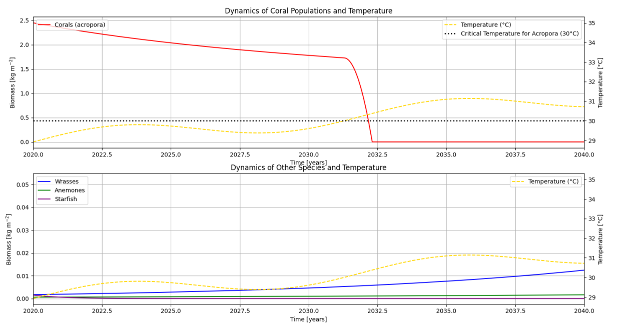


Figure 1: Evolution of biomass over 20 years as a function of temperature.

We immediately notice that when the water temperature reaches the critical temperature for acroporas, they die out in just over a year. Anemone and starfish populations decrease slightly, then stabilize. The wrasse population will increase slightly over time.

1.4 Discussion of results and limits

First of all, the results are consistent with the methods and assumptions made. Indeed, as temperatures do not reach critical temperatures for species other than corals, they do not disappear. However, it would be interesting to do this modelling with different global warming scenarios in order to quantify how much warmer the planet could get before corals die out, for example, something we haven't been able to do due to lack of time and knowledge.
In addition, it would be interesting to take measurements in the field to determine with greater precision the critical temperatures for each species. Finally, to bring some criticism to our model, it's important to mention that, in reality, species may adapt gradually to climate change. Furthermore, we haven't taken into account the possibility of human intervention to replant coral, as is currently the case in the Gilis Islands, or of an earthquake caused by a volcanic eruption, which could have a huge impact on the health of this ecosystem, although this is difficult to predict and model.

2 Impact of human activity

2.1 Introduction

Nowadays, all the ecosystems are negatively impacted by anthropogenic activities, particularly of increasing the greenhouses gas as such CO_2. Our study proposes a simulation and a model that helps to quantify the quantity of CO_2 in the atmosphere, and how it impacts the acidity of oceans and coral health. This tool is designed for environmental associations, policymakers, or industries that implant ecological aspect in their projects. By simulate and modeling the process over 20 years, it can be a good base to build an ecological transition. We decided to make the simulation on C for the rapidity of calculation, and python for the numpy module that is really useful to build models with matrix.

2.2 Approach

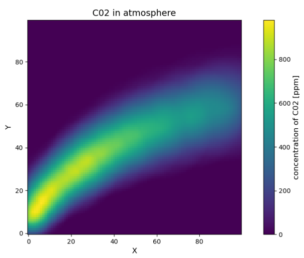
2.2.1 Simulation

The CO_2 is a greenhouse gas that affect the acidity of oceans. In fact, the oceans absorbs a part of CO_2 in the atmosphere, and release some protons. If we are increasing the concentration of CO_2 in the air, the water will absorbs more $C0_2$ and release more protons that cause an acidification, and affects marine ecosystems. This is why it's important to understand how the CO_2 affects corals to find solution to preserve it. We decided to make a simulation for different reasons as the flexibility to test different scenarios, the anticipation over a short-time distance (20 years) or for the cost-efficiency of this method. To simulate the propagation of CO_2, we assume a field of water that contains uniquely corals. All the parameters that we will use can be changed as you want. Here we take a 100 x 100 meters water field, representing by an 1D array). To start the simulation, we throw a package of $C0_2$ at position (x,y)=(0,0), an initial radius of 3 meters and a concentration of 275 ppm. The plume is spread by a wind in the direction of x-axis of 5 m/s, in the direction of y-axis of 0.3(x-2) m/s and also with a random motion in direction of x and y-axis. We iterate the movement of plume 100 times, and for each steps, the radius is increasing of 20/radius meters. To get closer to reality, we need also to simulate the effect of the diffusion of CO_2 over space. To make this, we include a loop that calculates the distance between the point and the radius of the package of CO_2. Further we are, further the gas is diffused. Finally, we add a source that absorbs a part of CO_2 that will not go to the water. It can be population that absorbs CO_2 to make photosynthesis for example. Now that we have the concentration of CO_2 in the atmosphere, we can see how much is going in the water, and how the pH is affected. We initialize the population of corals as 7.0 kg/m^2 (*cf.Section 1.2.2*). We need to estimate how the pH is affected by the CO_2 concentration. According to data, for a pH of water of 8.00, the mean concentration of CO_2 in the atmosphere is 800 ppm.We make here a big approximation with no mathematical relation, because a lack of data. For each range of CO_2 concentration, we decreased the associated value of pH as below:

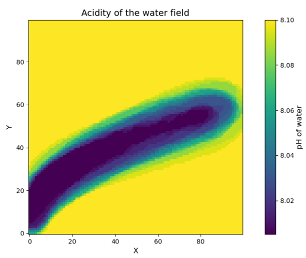
CO_2 [ppm]	[350,400]	[400,450]	[450,500]	[500,550]	[550,600]	[600,650]	[650,700]	[700,750]	>750
pH	0.005	0.01	0.02	0.04	0.06	0.08	0.1	0.2	0.4

Table 3: Decreasing pH in function of CO_2 concentration

We have now the concentration in atmosphere and pH of water over 20 years:



(a) Concentration of CO_2 in atmosphere over 20 years



(b) pH of water over 20 years

Note that the random movement is important over 20 years, and can change and unbalance the concentration of CO_2 in the air and the acidity of water. The figure 1 and 2 can be different over different simulations.

2.2.2 Model

To see how the health of corals are impacted by the acidity of water, we need to choose a relation between the mass of coral by squared meter and the value of pH. First, we will collect a dataset with different observations. To be sure that our dataset is compliant, we need to include functions that will accord for a single value of pH, a single value of coral health. It avoids to have more observations than results. We plot our observations on python, and we obtain the following figure:

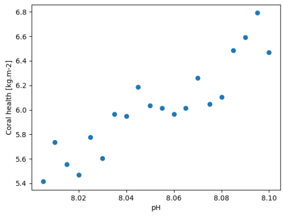


Figure 2: Observations

At first sight, we see that observations seems correlate by a linear curve. We decide to make a linear regression, we want to obtain the following relation:
$y = ax + b$,where a,b are constants that we want to estimate. We create 2 matrix, X and theta:

$$X = \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_m & 1 \end{bmatrix} \qquad \Theta \ = \begin{bmatrix} a \\ b \end{bmatrix}$$

where x is the pH of water, m is the number of observations, y is the mass of coral in kg/m^2.

When we multiply X and Θ, we obtain the following system of equation:

$$Y = \begin{bmatrix} ax_1 + b \\ ax_2 + b \\ \vdots \\ ax_m + b \end{bmatrix}$$

Now that we have the model, we need to estimate a and b. We introduce what we call the "cost function" in sense of mean squared error:

$$J(\Theta) = \frac{1}{2m} \sum_{i=1}^{m} \left(Y^{(i)} - y^{(i)}\right)^2$$

The estimation of a and b can be make by what we call the "downward gradient". We will take the derivative of the cost function with respect to a and b.

$$\frac{\partial J(\Theta)}{\partial \Theta_j} = \frac{1}{m} \sum_{i=1}^{m} \left(Y^{(i)} - y^{(i)}\right) x_j^{(i)}$$

This methods consist to apply the gradient on a little step, and see if it is equal to 0, i.e the minimum of the function is reached. Note that we used this methods because the derivative of this function is easy to calculate. As long as the derivative is different of 0, we update a and b as:

$$a := a - \alpha \frac{\partial J(\Theta)}{\partial a}$$

$$b := b - \alpha \frac{\partial J(\Theta)}{\partial b}$$

We introduce the learning rate α, it is the value of the "little step". We iterate the process n times, until it reaches the minimum. Note that α and the number of iterations n need to be determined by testing different values, there is no theoretical values. Once the derivative reaches the value of 0, we have our final Θ, with a and b that are estimated accurately as possible. We obtain the final curve:

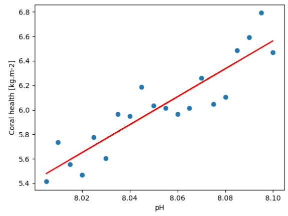


Figure 3: Corals health in function of pH

Here, we took $\alpha = 0.01$ and n = 10000. It can be adjusted as we want. Finally, we obtain our relation of coral health in kg/m^2 in function of pH:

$$y = 0.329x + 6.021$$

For each unit of pH, the health of coral is increasing of approximately 0.3, means that for a small diminution of pH, a big amount of coral disappears. We see that our b doesn't make sense, for a water that is really acid, the health of corals are higher than for a pH of 8. Its probably due to a lack of data, especially for pH<8.

2.3 Discussion of results and limits

We see that in general, the observations are not so far from the red curve, our estimation of the coral health in function of pH. However, there are some observations that are far from it, and not satisfying for our simulation. This extreme values can be caused by different factors, as the estimation of impact of CO_2 on water pH, or as the random movement due to hazards over 20 years, that changes the simulation. In view of the approximations made, our modeling is far from the reality and doesn't take in account a lot of factors as pics of pollution or sensitivity of corals on pH. The evolution of coral in function of pH is probably more complex than just a linear relation. The model can be improve including new observations for values of pH< 8. However, this can be a first model to understand the influence of CO_2 on corals, and as you go along, add more elements.

3 Conclusion

The simulation-model of temperature impact depend ultimately on the critical temperatures of each species and the temperature scenarios. One thing's for sure: no matter what the warming factor, coral will always disappear from the Gilis Islands.
The simulation-model of anthropogenic impacts, although its far from reality, can be useful to show that for a small diminution of pH, an important part of coral disappears. It can be a tool for association to educate, put a pressure on companies and industries but also for fishing or tourism companies to plan the impact on their future business. Finally, we see that our modeling present a big range of incertitude after 20 years (pH<8 or surviving of other species), and can be improve in future for a bigger range of time.
Finally, it might be interesting to apply our modeling to the Red Sea, where corals are more resilient to climate change than in the rest of the world. This might enable us to identify the parameters that enable them to withstand these changes less effectively [1].

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N.B : You can find this documents in PDF on *github* in the Sources folder.
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