Computational Methods and Tools

Final Submission

Modeling temperatures in Lake Geneva using a physical model and a statistical model

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1. Deviations from project proposal

Initially, we intended to base our project on a physical equation to predict the temperatures of Lake Geneva. We planned to start with a simple equation and gradually add parameters to make it more complex, with the goal of obtaining an equation that predicts temperatures the best way possible around the lake. However, we quickly realized that the research required to understand and apply these equations would be more time-consuming and complex than expected. This research work could overshadow the programming part, which was less interesting for our project and not the main goal.
At the same time, we found temperature data for the lake in a usable form. This gave us the idea to create a statistical model. Ultimately, we decided to redirect our project by comparing two approaches: a statistical model based on this data and a model based on simplified physical equations. This approach allowed us to focus more on predictions and less on theoretical research.

2. Introduction to the problem

As explained in our project proposal, climate change is an increasingly observable phenomenon, and we are concerned about its impacts on the environment, particularly on Lake Geneva. Water temperature is a crucial factor for the lake's ecological balance, influencing the distribution and survival of aquatic species. For example, fish, which are sensitive to temperature fluctuations, may migrate to deeper or cooler areas depending on temperature changes, or even face threats to their survival if these fluctuations become too extreme.
In this context, being able to predict the lake's temperature would be extremely useful. This would, among other things, allow us to identify the areas and depths where fish are located at different times of the year, while also anticipating risks for certain species in the event of excessive warming. In short, a better understanding of Lake Geneva's temperatures could play a crucial role in managing the ecosystem, enabling us to anticipate biodiversity behavior in the face of climate disruptions. It is worth noting that there are already 3D temperature models of the lake over time, provided by Alplakes[1], although these are highly complex.

[1] Alplakes website: https://www.alplakes.eawag.ch/geneva

3. Approach used

3.1 Approach

First of all, it is important to note that what we consider as measurements throughout our project comes from the Alplakes model. Lake Geneva has few measurement stations (two on the Swiss side, to our knowledge), and these datas would be insufficient for a complete modeling of the lake. Therefore, as mentioned earlier, we will use the results from the Alplakes model as a point of comparison with our own models, due to its complexity and the variety of parameters it incorporates.

After refocusing the project and finding usable data, we decided to focus on the evolution of temperatures over time at a specific depth (0.2 meters), using two approaches: a physical model and a statistical model. Additionally, since we are from Geneva and Morges, we initially based our models on these two locations. However, our code is adaptable to other areas, as long as the necessary parameters are included (details are provided below).

We then compared the performance of both models in 2024 and 2050 to assess the differences between the physical and statistical models, as well as the impact of climate change on temperatures over time.

Finally, to complete the project, we modeled a map of the lake at several points, displaying the average temperatures for a given day, once using the measured data and once using statistical predictions.

3.2 Physical Model

Modeling a lake physically can be quite challenging because it is influenced by many parameters. To simplify this process, we chose as the base of our model a sinusoidal equation developed by refining the one from the Swiss Hydrological Atlas[2]. This equation includes only five parameters: latitude, altitude, continentality (data obtained from lake.lindt[3] and mapgeoadmin[4]), time, and the climate warming factor (data from CIPEL[5]). This equation provides an overall summary of the temperature trend throughout the year.

To generate an annual curve, we calculate a temperature for each day and aggregate all these values to create a continuous curve. We then gradually complexified the model by adding new parameters.

First, we introduced daily and annual random noise, modeling the daily temperature fluctuations compared to a smooth curve. Next, we added "extreme events," i.e., random heat or cold waves of varying intensity. Finally, we incorporated the thermal inertia of the lake's waters as well as marine currents.

[2] Swiss Hydrological Atlas website: https://atlashydrologique.ch/
[3] Lake Lindt website: https://lake.lindt.one/
[4] Swisstopo website: https://map.geo.admin.ch/
[5] CIPEL website: https://www.cipel.org/

Only the basic libraries "stdio.h" and "stdlib.h" were used, and the necessary random functions were also coded manually.
The basic equation used to model the temperatures is as follows:

$$T(t, y) = \overline{T}_{in} + dT(t) * sin(2 * \pi * t / P + \phi) + y * R$$

With the following parameters:

- **t**: the day of the year
- **y**: the number to be added to 2024 to model the desired year
- **P**: the period (365 days)
- **ϕ**: the phase, adjusted to have the hottest day between July 15 and August 15
- **R**: the temperature warming factor at the surface of the lake

T_{in}, which corresponds to the annual average, also known as the **Mean Annual Epilimnetic Temperature (MAET)** for a specific location, is calculated as follows:

$$MAET = 44 - \left(\frac{750}{90 - Lat^{0.85}}\right)^{1.29} - 0.1 * Alt^{0.5} - 0.25 * (Cont^{0.9} + 500)^{0.52}$$

[Ottosson and Abrahamsson (1998)[6]]

With the following parameters:

- **Lat**: the latitude
- **Alt**: the altitude
- **Cont**: the continentality

3.3 Statistical Model

For the statistical model, we first collected temperature data from several measurement stations around the lake. These records, taken every 3 hours since 2018, served as the basis for our analysis.

Initially, we focused on the data from a single station, Morges in this case, creating a graph to visualize the trends. We then applied polynomial regressions year by year, adjusting the degree of the polynomial to achieve the best possible representation of the data.
The main objective of this part was to predict future temperatures based on historical records. To do this, we created a model capable of using all the temperatures for a given day from previous years to estimate the corresponding future temperature. This model uses linear regression, which "optimally links" the historical data points. We then trained this

[6] Ottosson and Abrahamsson study website:
https://www.sciencedirect.com/science/article/pii/S0304380098000672

model using the temperatures and their corresponding years. Finally, using the **predict()** function from a Python library, we were able to estimate the temperatures for the following years.
We then extended this approach to include all the measurement stations.
However, since these stations do not cover the entire lake, the initial predictions were incomplete. Therefore, we integrated a linear interpolation method, allowing us to estimate temperatures between the existing measurement stations. This was made possible by creating a map of Lake Geneva in parallel.
Thus, our statistical model combines polynomial regression and linear interpolation to provide temperature predictions across the entire Lake Geneva.

4. Results

For the sake of brevity, we will present only the graphs for Morges here; however, those for Geneva Eaux-Vives are similar.
The results of our project are mainly interpreted through graphs. Indeed, directly analyzing the CSV files of temperature data does not seem relevant here and is likely not the most intuitive way to observe and understand the evolution of temperatures.
We will begin with the measured data and their linear regression over the past six years, followed by the graphs for 2024, comparing the different models with the observed data. We will then present the predictions for each model in 2050, as well as a comparison between 2024 and 2050 based on the physical model. Finally, we will conclude with two maps representing the lake's temperatures for 2024: one based on the statistical model using predicted values, and the other with observed values, to evaluate the reliability of the prediction.
Here is the linear regression based on the observed data:

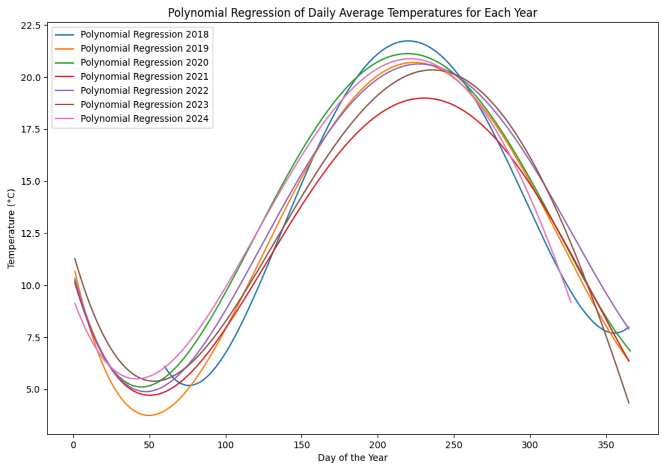

Figure 1: Polynomial Regression of the temperature in the last 6 years

We can first observe the sinusoidal pattern of temperatures throughout the year, with variations between 2.5°C and 21°C. Overall, there are few significant differences between the

years, except for natural fluctuations. However, we note a particularly cold winter in 2019 and a cooler summer in 2021. Over this short six-year period, no clear upward or downward trend is observable.
Let's now move on to the comparative graphs of the methods applied for 2024 and 2050.

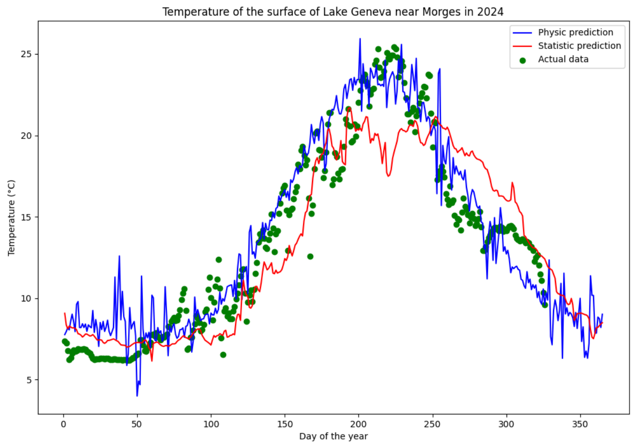

Figure 2: Physic and statistic prediction, and measured values for 2024

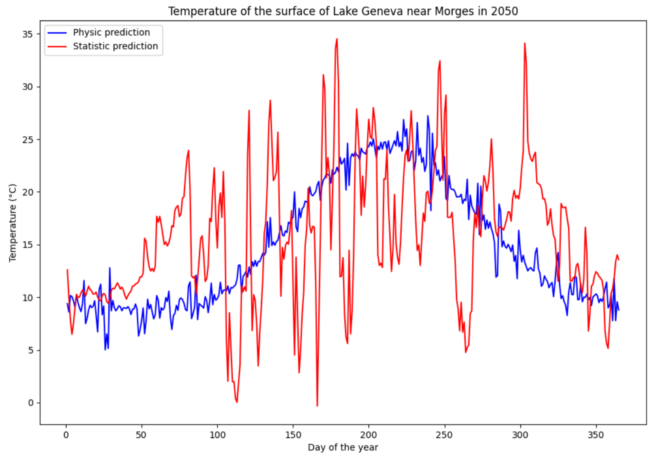

Figure 3: Physic and statistic prediction for 2050

In **Figure 2**, we observe that both models provide generally correct values, but the physical model shows a better correlation with the measurements. The statistical model, in fact, is based on data collected over the six years preceding 2024. It only takes into account six values per day, which means that each value has significant weight. Outliers, which could be caused by experimental errors or other factors, considerably disrupt the model, explaining this difference. The physical model, although it presents some extreme values, generally follows the measurements with great accuracy, demonstrating its effectiveness.
Figure 3 shows a complete breakdown of the statistical model, indicating that, given the small number of data points used, its long-term predictions are not reliable. Moreover, this model could benefit from using monthly averages, which would provide more values per day and reduce the impact of outliers. However, even with such an adjustment, this model remains ineffective for long-term forecasts.
Let's now move on to the graph for Morges, comparing the predicted data with the physical model for 2024 and 2050.

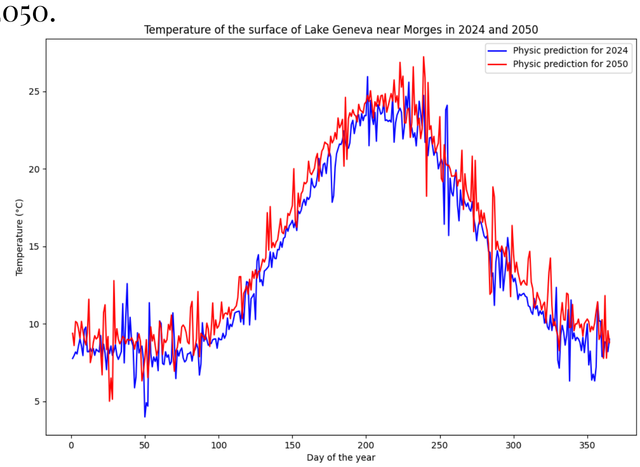

Figure 4: Comparison with the physic model between 2024 and 2050

Our function takes into account a climate warming index (0.05°C per year), which is evident in this graph, as the red curve (2050) is consistently warmer than the blue curve (2024). According to this model, the temperature is projected to increase uniformly by about +1.25°C by 2050. By calculating this, we obtain an increase of 3 to 4°C by the end of the century, which aligns with the forecasts from the National Centre for Climate Services[7] (NCCS), even without accounting for the potential increase in the climate warming factor.
At these temperatures, exceeding 25°C in summer, certain fish species, such as trout, can no longer tolerate the heat, putting the species in great danger. This phenomenon also affects other animals accustomed to colder, oxygen-rich waters, a condition that is disrupted by rising temperatures. Additionally, invasive species and diseases are likely to spread more widely.

Now, here is a map of Lake Geneva with the interpolated temperatures, both measured and statistically predicted.

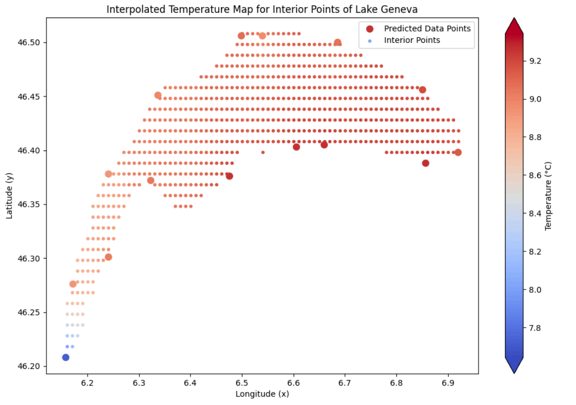

Figure 5: Lake Geneva with measures for 2024

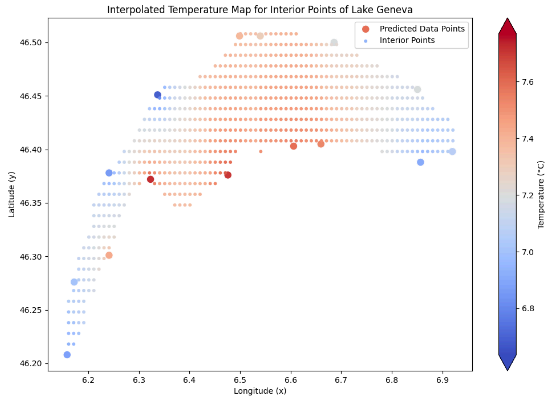

Figure 6: Lake Geneva with the statistic prediction for 2024

By comparing the two maps, we quickly notice a significant temperature discrepancy, about 1.5°C for the maximum values and 1°C for the minimum values, between the actual measurements and the statistically predicted data. This difference can be explained by looking again at **Figure 1**, which presents the measurements as a linear regression. The statistical model indeed relies on measurements from previous years to predict subsequent values. We observe that the temperature hovers around 10°C on January 1st, which explains why the predicted values for 2024 are close to this temperature, while the reality, shown in **Figure 5**, indicates a slightly lower water temperature.

Regarding the distribution of temperatures on the map, the prediction generally follows the trend observed in the measurements. In winter, the center of the lake is warmer, while the edges, like those near Geneva, are cooler. However, an issue arises in the prediction for the eastern part of the lake, where the temperatures are too high compared to expectations. This could be explained by the influence of the rivers that flow into the lake. During flood periods, these rivers can significantly alter the water temperature in this area.

[7] NCCS website: https://www.nccs.admin.ch/nccs/en/home.html

5. Conclusion and outlook

Through this project, we aimed to model and predict the temperature of Lake Geneva using two distinct approaches: a physical model based on simplified equations and a statistical model using temperature data measured over recent years. Despite the challenges encountered, the results provide important insights into the evolution of the lake's temperatures, especially in the context of climate change.

The physical model proved to be more reliable and consistent than the statistical model, particularly for long-term forecasts. It successfully reproduced the observed trends and offered plausible predictions for future years, such as 2050. However, the reality is much more complex, and adding dynamic interactions, such as the influence of winds or precipitation, would further enhance the model's realism. In contrast, the statistical model only works effectively over short periods due to the limited time sample (6 years) and could be improved by integrating monthly averages, as mentioned in the results section.

An interesting approach could have been to combine the two models by training the statistical model with data provided by the physical model.

The integration of climate warming factors allowed us to align the predictions with established trends, including an average increase of 3 to 4°C by the end of the century. By 2050, surface temperatures of the lake are expected to rise significantly, with summer peaks exceeding 25°C. Such conditions pose a severe threat to species adapted to colder waters while disrupting the lake's overall ecological balance. This highlights the importance of continuing and intensifying efforts to preserve the balance of lakes and, more broadly, all bodies of water, both in Switzerland and abroad.

In conclusion, while the physical model showed promising results, this project highlights the importance of ongoing research and interdisciplinary collaboration to better understand the effects of climate change on aquatic ecosystems such as Lake Geneva. By refining our models and expanding their scope, we will be better prepared to anticipate and mitigate the challenges ahead.

6. Bibliography

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