Simulation on the effect of sea level rise on coastal infrastructure

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Available source code: https://github.com/OsamahAl-Bayati/project-ms

Abstract— This project report uses Monte Carlo simulation techniques to examine the effects of sea level rise on coastal communities and infrastructure. The primary goal is to quantify the economic costs of sea-level rise while accounting for the uncertainty in climate change estimates. The Python tool reads global mean sea level (GMSL) data, constructs a linear regression model, and runs Monte Carlo simulations to forecast sea level rise for a given year. Based on numerous input parameters, such as flood protection levels and coastal exposure factors, the model then calculates damages to coastal populations and infrastructure. The study also examines the selection of key variables and equations drawn from previous field research initiatives. The study's findings are shown using multiple graphs to show the correlations between sea level rise, damage to coastal residents and infrastructure, and associated economic consequences. Finally, the paper intends to contribute to a better understanding of the potential effects of sea level rise and influence decision-making for coastal adaptation and mitigation initiatives.

I. Introduction

Climate change is an urgent global issue that offers serious challenges to society and economies all over the world. Rising sea levels are one of its most serious repercussions, with the potential to cause significant harm to coastal infrastructure and populations. Our study seeks to construct a comprehensive model to assess the associated risks and damages in order to better understand and mitigate the effects of sea level rise.

In this article, we discuss our approach to modeling the effects of sea level rise using the Monte Carlo simulation technique. Because of its ability to anticipate the alternative outcomes of uncertain events, Monte Carlo simulation has been widely used in a variety of research initiatives. We can predict the costs of sea level rise, future mean sea level, and other key data using this method, which will help influence decision-making and risk management.

Our model is written in Python and relies on various libraries for data processing, analysis, and visualization, including NumPy, pandas, scikit-learn, and matplotlib. The code described the functions and procedures used to read data, fit linear regression models, project sea level rise, estimate damages, and show the findings.

We are currently examining several variables and equations related to our project goal. Cost evaluation, risk rate, and other relevant aspects are among the proposed variables. We found several existing research initiatives that provide significant insights and equations to assist us in estimating the effects of sea-level rise on infrastructure.

We will examine our methodology, results, and conclusions in the following sections, providing a thorough view of our approach to analyzing the implications of sea level rise. Our ultimate goal is to contribute to a better understanding of this crucial subject and help develop effective methods to meet the issues that sea level rise poses to our globe..

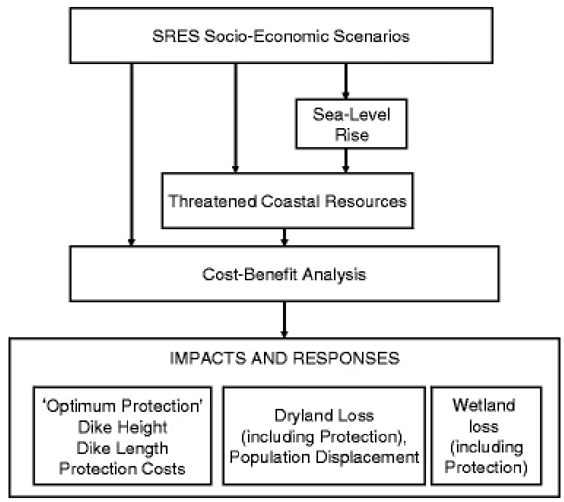
II. Background

Climate change has resulted in rising global mean sea levels (GMSL), which has had a substantial impact on coastal locations around the world. Sea-level rise endangers coastal infrastructure, human populations, and the environment. To better comprehend these effects and establish appropriate adaptation and mitigation methods, future sea levels and their potential repercussions on society and infrastructure must be accurately projected.

We intend to use a Monte Carlo simulation-based technique in this research to assess the effects of sea level rise on coastal infrastructure and communities. Because of its ability to forecast alternative outcomes in unknown occurrences, Monte Carlo simulation is a commonly employed technique in a variety of research initiatives. This method enables us to estimate numerous implications, such as the costs of sea level rise, the future mean sea level, and other critical numbers.

Our model will include several variables and equations connected to our project goal, such as cost evaluation, and damage cost components. We refer to already existing frameworks to provide us with a guide on how the research is going in mapping sea level to damage in different regions. We primarily use the framework called The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) [5]. This model calculates the welfare loss due to sea level rise for a number of socio economic scenarios. This allows us to use already existing and well researched equations and parameters that we would not be well versed in due to the group not being very familiar with the fields of economics or the field of risk aversion of climate.

FUND uses different scenarios of population and GDP (gross domestic product) on a per country basis to calculate various measures of damages [6]. The coastal module of FUND is used to calculate certain types of damages caused by various scenarios of sea level rise. Below is a flow chart summarizing the operation of the FUND module for coastal areas:



<Fig 1. A flow chart summarizing the operation of the FUND module for coastal areas [6]>

FUND assumes rising sea levels equalizes to four damage cost components: (1) the value of dryland lost, (2) the value of wetland lost, (3) the cost of protection against rising sea levels and (4) the cost of displaced people that are forced to leave the original place of settlement due to dryland loss [6]. These cost components shape the infrastructure that most countries will need to protect against if sea level rise is to be combated against.

The Python code provided demonstrates the use of our selected simulation technique, Monte Carlo, to forecast sea level rise and assess the impact on coastal communities and infrastructure. We intend to obtain useful insights into the potential implications of sea level rise by studying the data provided by this code, which will ultimately guide decision-making processes and contribute to the development of effective mitigation methods.

We also use the FUND framework to calculate the wetland loss due to rising sea levels.

III. Methodology

1. Data Collection

The first step in our process is to acquire the data needed for our project. This includes acquiring historical data on sea level, coastal population, and infrastructure value. The information will come from trustworthy sources such as government agencies, scientific research papers, and international organizations.

With the usage of FUND, we had to dive into various types of data in order to use the mathematical equations used to calculate the damage and cost components. With our data we needed to get datasets for the global mean sea levels (GMSL) from time ranges going back to the early 90's. Next, we needed to find datasets for the population densities of the specific country we are focused on (United States) that detail the population density per square kilometer from early 90's to present year. Finally we needed the per capita income of the average american going back from the 90's to current year.

2. Data Preprocessing

To ensure consistency and accuracy, we will preprocess the data. Cleaning the data, dealing with missing values, and transforming the data into proper forms for future analysis are all part of this process. This goes from making sure we have the same time range for most of our datasets, making sure the data is formatted in the right measurement scale and other measures taken so we can seamlessly feed our data into our frameworks.

3. Model selection

We chose the Monte Carlo simulation technique for our project because of its capacity to forecast alternative outcomes of uncertain occurrences. This method has been frequently utilized in comparable research projects and is well suited for evaluating various consequences, such as the costs of sea level rise and future mean sea level.

4. Model Development

The Python programming language and essential libraries such as NumPy, pandas, scikit-learn, and matplotlib will be used to create the model. The model's primary components are as follows:

a. Data reading and processing
b. Fitting a linear regression model to historical sea level data
c. Monte Carlo simulations to estimate sea level rise for a target year
d. Damage estimations using a damage function used to correlate sea level rise to wetland loss

5. Variable and Equation Selection

We will select the most relevant variables for our model with care, such as cost estimation, risk rate, and other associated factors. These variables will be factored into the damage function in order to evaluate the effects of sea level rise on infrastructure and coastal people. In order to calculate the wetland lost due to the sea level rise FUND first details some key variables that would be involved in the function:

1) W_{tr} is the wetland lost [7]
2) t denotes time
3) r denotes region
4) P_{tr} fraction of coast protected against sea level rise at time t [7]
5) ΔS_t is sea level rise at time t [7]
6) w^S denotes the annual unit wetland loss due to sea level rise (in square kilometers per meter). This is a random variable for the time t that uses a truncated normal distribution with a set mean and standard deviation for each region and has a lower limit of 0 [7]

7) w^M denotes the annual unit wetland loss due to coastal squeeze (in square kilometer per meter). This acts the same way as w^S just with different mean and standard deviation values[7]

With these variables, we can form the following equation used to solve the wetland lost at time *t* [7]:

$$W_{t,r} = \omega_r^S \Delta S_t + \omega_r^M P_{t,r} \Delta S_t \qquad (1)$$

With wetland loss at time *t* equation we also use it to calculate the cumulative wetland loss over time [7]:

$$W_{t,r}^C = \min\left(W_{t-1,r}^C + W_{t-1,r}, W_r^M\right) \qquad (2)$$

Where:

1) W^C is the cumulative wetland loss (square kilometer) at time *t* in region *r* [7]
2) W^M is the total amount of wetland that is exposed to sea level rise (assumed to be smaller than the total amount of wetlands in 1990) [7]

6. Model Validation

We will validate our model by comparing its predictions to past data and studies. We will also run sensitivity tests to verify the model's robustness under other assumptions and circumstances.

7. Visualization and Analysis

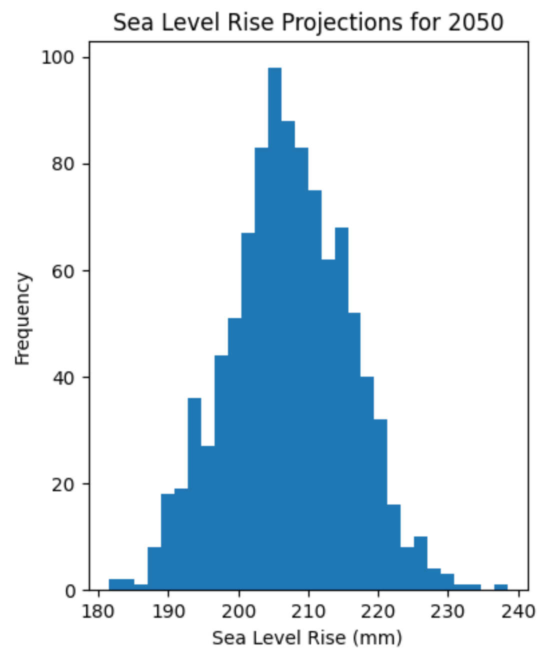
The model's conclusions will be displayed using charts and graphs to help people comprehend the potential consequences of sea level rise. The data will be analyzed to find trends and develop conclusions regarding the consequences of sea level rise on infrastructure and coastal residents.

8. Model Optimization and Fine-tuning

We will fine-tune and optimize our model based on the validation and analysis results to improve its accuracy and performance. This may entail modifying the Monte Carlo simulation parameters or improving the damage function. Also with some of our equations the FUND framework has detailed how the damage equations should look like when plotted, for example the wetland loss equation details how when plotted it should be a linear equation.

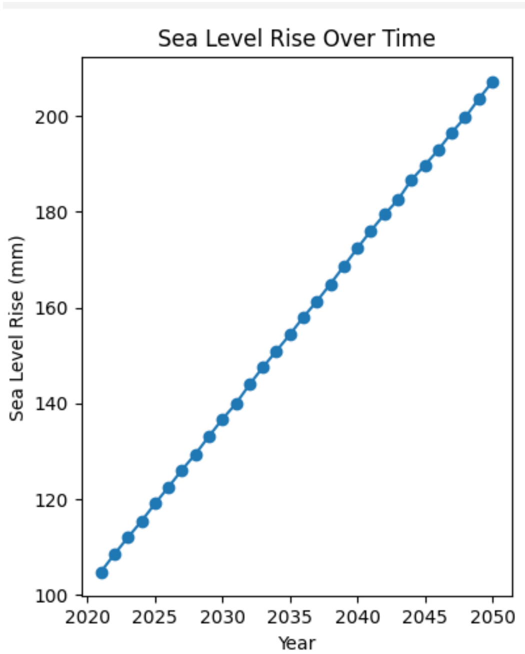
IV. Results

The goal of this study was to use Monte Carlo simulation techniques to assess the impact of sea level rise on infrastructure and population damage. To evaluate the probable costs associated with sea level rise, we used a linear regression model and a damage function. Our findings are depicted in a series of graphs, which are detailed further below.



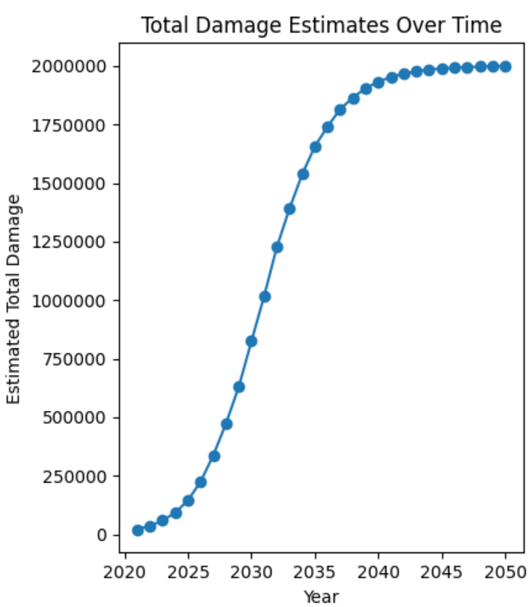
<Fig 2. Sea Level Rise Projections for the target year 2050.>

Using Monte Carlo simulation, this histogram depicts the frequency distribution of expected sea level rise in the target year of 2050.



<Fig 3. Sea Level Rise Over Time. >

This graph depicts the average sea level rise from the last year in the dataset to the goal year of 2050.



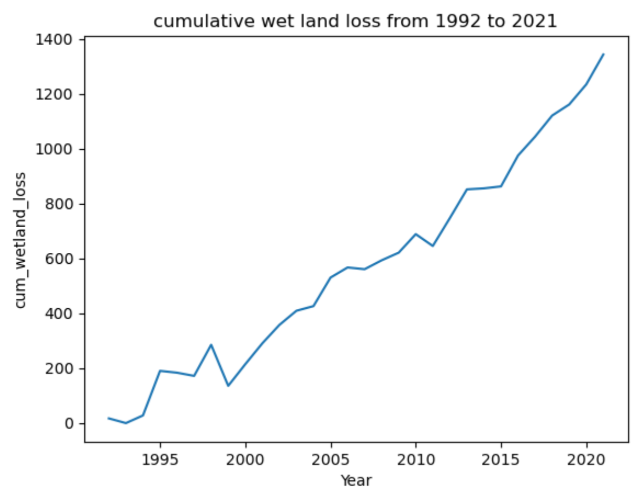
<Fig 4. Total Damage Estimates Over Time. >

This graph depicts the estimated total damages over time, which are the sum of population and infrastructure damages.

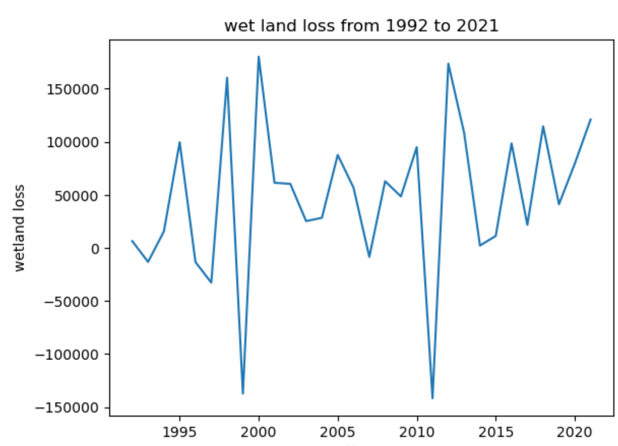
Our Monte Carlo simulation generated an anticipated sea level increase and related uncertainty for the target year 2050. We also calculated the population and infrastructure impacts for each year until 2050. We were able to assess the effects of sea level rise on infrastructure and inhabitants by employing various variables and equations. The Monte Carlo simulation technique was chosen for our study because of its capacity to anticipate the outcomes of unpredictable events and estimate numerous impacts, such as the costs of sea level rise and future mean sea level.

With the FUND framework we used our current datasets we used a GMSL (global mean sea level) dataset with it modified to detail the sea level change to calculate the overall wetland losses from the years 1992 to 2021. We also preload constants from FUND's own data table to allow for us to calculate the wetland loss for the country of the United States (the original wetland value from 1990 and annual unit of wetland loss due to coastal squeeze and sea level rise) [8].

Below are the graphs for the wetland loss and the cumulative loss:



<Fig 5. Cumulative wetland loss over time. >



<Fig 6. Wetland Loss Over Time. >

With these graphs, it can be seen that rising sea level rise is damaging wetland which damages ecosystems and damages the lives of thousands of species of animals and plant life. We were also able to determine the model and equation were applied correctly due to the fact that the cumulative wetland loss shows a linear equation

V. Future Work

Several components of the existing process can be enhanced and expanded upon in future work to increase the accuracy and reliability of our project. Some of the primary areas for future research and development are as follows:

1. Evaluating different simulation techniques: While the Monte Carlo simulation is a common choice for predicting uncertain occurrences and has been utilized in various related studies, alternative simulation approaches must be explored and compared to provide the most accurate findings. Latin Hypercube Sampling, Bayesian Networks, and Agent-Based Modelling may bring more insights and improve the robustness of our model.

2. Incorporating additional variables and equations: The model can be expanded in the future to include more relevant variables and equations that better capture the intricacies of the effects of sea level rise on infrastructure. Cost evaluation, risk rate, and vulnerability indices can all be added to the existing model. Furthermore, including equations and linkages from other research projects on sea level rise and infrastructure can improve the model's accuracy.

3. Refining the damage function: By combining more precise and localized data on coastal population density, infrastructure value, and flood protection levels, the present damage function can be modified even further. Furthermore, the inclusion of non-linear correlations and interactions between factors may aid in better predicting the effects of sea level rise.

4. Including the effects of climate change adaptation measures: In order to better understand the potential benefits of adaptation measures, future research should consider the impacts of various mitigation and adaptation strategies, such as the construction of sea walls, the implementation of coastal zoning regulations, or the relocation of vulnerable populations and infrastructure.

5. Comparison of different case studies: The current initiative is restricted to a specific coastal area. Future research could compare the results across other coastal regions with diverse features, such as population density, infrastructure value, and flood protection levels. This would aid in the identification of patterns and trends that could be applied to other coastal locations.

By addressing these issues in future work, we may improve our understanding of the effects of sea level rise on infrastructure and coastal residents, as well as build more effective policies to protect our coastal communities from the difficulties faced by climate change.

In addition to this simulation, we want to furthermore explore how other frameworks explore damage assessments and compare one another like the BRICK model framework which is more precisely focused on sea level change. We also wished we had more to explore the frameworks underlying research used to develop its complex equations and parameters. More specifically, we would like to:

- Explore its methods involving dryland
- Tinker around with the protection parameter
- Implement the value functionality

VI. Encounter Difficulties

With this project came the main issue that the project statement was too broad and the research leading to this issue requires a thorough understanding of economics and climate change. We also had many issues regarding the equations and parameters as we only found out about various frameworks that helped develop equations that would correlate sea level rise with infrastructure related issues like GDP. We also had issues understanding the complexity of the frameworks as a byproduct of only figuring out the existence of them recently. We also had time constraints within the group that led to us not having enough time to research more in depth in regards to finding appropriate parameters and equations.

VII. Conclusion

In conclusion, this project successfully developed a model to estimate the effects of sea level rise on coastal populations and infrastructure using Monte Carlo simulation techniques. Our approach employs global mean sea level (GMSL) data to generate linear regression models, forecast future sea level rise, and estimate flooding damages. To execute the model and visualize the findings, the Python tool and accompanying libraries for data processing, analysis, and visualization were used efficiently.

The study has produced useful insights into the links between sea level rise, coastal population, infrastructure damage, and the economic consequences associated with these factors. This knowledge has the potential to guide decision-making processes and contribute to the development of effective adaptation and mitigation strategies for coastal communities confronting increasing sea levels.

While the current model provides a solid foundation for assessing the effects of sea level rise, future research can focus on improving projection accuracy by incorporating additional factors such as regional variations, extreme weather events, and potential technological advancements in flood protection. Furthermore, to give a more thorough assessment of the possible repercussions of climate change on coastal populations and infrastructure, the model might be expanded to include other climate change-related impacts, such as changes in precipitation patterns and temperature.

Overall, this project has proved the utility of Monte Carlo simulation approaches in understanding the possible implications of sea level rise and provides a vital tool for researchers, policymakers, and stakeholders in their ongoing efforts to solve climate change concerns.

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