## Moody's Mega Math Challenge 2017

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## The Tides They Are A'Changing

## Executive Summary

The United States National Park system is one of the primary methods for citizens to connect with nature. Unfortunately, increased sea levels put coastal national parks at risk of completely disappearing. In our first model, we predicted the local sea levels rise in each of the five given national parks over time by modeling the mean global temperature increase with respect to time. From here, we performed five separate linear regressions to fit a sea level growth equation for each park to a function of global temperature change. We proceeded to apply our sea level forecast to topographic maps of each of the parks in order to categorize the sea level change risk at each of 10, 20, and 50 years; Acadia, Kenai Fjords, and Olympic were at low risk due to their high elevation and rocky terrain, while Cape Hatteras and Padre Island were at higher risk due to lower elevation and a sandy terrain more prone to erosion.

In our second model, we coupled the information found in section 1 with natural disaster data for each of the five national parks. This compiled data prompted us to determine climate vulnerability by finding the cost of maintenance for each park over the next 50 years. We associated a cost with different natural disasters and determined the frequencies of these natural disasters for each of the parks. We further used our risk level from section 1 to estimate the acreage of the park that would be underwater. Taking into account the average revenue generated per acre of a national park, we determined the revenue lost due to climate change, which we consider as lost opportunity. Lastly, we incorporated a common measure of the extremity of the climate of a park, known as the Climate Extremity Index (CEI). Calculating the average cost per acre of national parks, we found the cost per acre for a specific park, as well as the average cost per acre of a generic acre. In totality this model led us to conclude that over the next 50 years, Padre Islands National Seashore will have the highest extra cost per acre ( $\$ 23.289$ per acre), while Olympic National Park will have the lowest extra cost per acre ( $-\$ 1.708$ per acre), relative to the other parks.

We then predicted the future number of visitors at each national park by using the chance of natural disasters in each park, as well as the current visitor statistics in a Monte Carlo simulation. We found that Acadia National Park and Kenai Fjords National Park both will experience a growth in the number of visitors, while the other parks will experience a decline in visitors. We recommend that funding should be increased at parks with more visitors in order to generate revenue for the NPC. However, funding at parks should not be allocated solely based on the number of visitors. The mission of NPS is to preserve the natural environment; as such, it is necessary to invest money in the high-risk parks. Accordingly, high levels of funding should also be maintained for the particularly vulnerable Cape Hatteras and Padre Island National Seashores.

## Introduction

## Background

The National Park Service (NPS) strives to protect more than 84 million acres of America's unique, extraordinary places, including cultural and historical sites, and connect over 275 million citizens to nature every year [1]. Comprising 417 official units, the NPS is a federal agency within the Department of the Interior dedicated toward maintaining, cleaning, conserving, and repairing national parks within its system [2]. Although the NPS has implemented several initiatives within its first 100 years, global change factors prompt a novel collection of programs designed to account for changing park resources and visitor experience [1]. As it enters its second century of service, the NPS has accordingly reinstated its mission, adjusting the goal of the agency towards preserving natural and cultural resources so that future generations can reap the benefits of unimpaired national parks.

Climate change is undoubtedly one of the primary issues facing our society today. Since the industrial revolution, humanity has dramatically increased its output of carbon dioxide into the atmosphere. This carbon dioxide has ascended into the stratosphere and currently acts as a greenhouse gas, trapping outward-bound radiation and as a result increasing the global mean temperature [4]. This increase in temperature leads to land ice melting in the Arctic and to the density of seawater decreasing, which causes the ocean volume to increase. Together, these two effects will cause global sea levels to rise over time. This sea level rise puts many of the United States' beautiful coastal national parks at risk of increased natural disasters and of being wiped off the map entirely as they sink beneath the ocean [3].

We were requested by the NPS to provide insight and help strategize with the NPS to adjust its policies based on climate change. Initially tasked to develop a mathematical model to determine a sea level change risk rating of high, medium, or low and predict the future ratings for five national parks, we embedded this model to investigate the effects of all climate-related events on coastal park units. This second model assigns a single climate vulnerability score to any NPS coastal unit, taking into account both the likelihood and severity of climate-related events. Lastly, we were asked to advise NPS regarding the allocation of future financial resources; we incorporated visitor statistics and vulnerability scores in order to reach our conclusion.

## Tides of Change

## Restatement of the Problem

The problem statement specifies that we should construct a model to determine the risk factor associated with sea level changes in each of the following five national parks:

- Acadia National Park, Maine
- Cape Hatteras National Seashore, North Carolina
- Kenai Fjords National Park, Alaska
- Olympic National Park, Washington


## - Padre Island National Seashore, Texas

We interpreted this problem to be twofold: we first forecasted how sea levels in each of the five parks will rise in forthcoming years, and then determined how those sea level changes will manifest in the national parks.

## Simplification

Simplification 1: Sea level is entirely contingent on temperature
Justification: Temperature directly causes a volume increase of the ocean and increased land ice melting. All other factors are negligible.

## Assumptions

Assumption 1: Changes in global temperature overshadow changes in local temperature in driving local changes in sea levels.

Justification: Since water is a fluid it will naturally effectively equilibrate such that local temperatures do not have a sufficiently large effect on sea level volume to cause large sea level changes.

## Determination of Sea Level

We begin by developing a model of how the sea level at each particular national park evolves over time. Given the NPS data on the mean sea level trends in each park [5], we began by simply forecasting the change in sea level with respect to time alone. We could compute aggregate change in sea level from 1997 according to

$$
\begin{equation*}
M S L(t)=\sum_{n=0}^{t} \frac{\Delta M S L}{\Delta t} \tag{1}
\end{equation*}
$$

where $\operatorname{MSL}(t)$ represents the mean sea level at a time $t$ after January 1, 1997, and each $\frac{\Delta M S L}{\Delta t}$ increment represents the change in mean sea level over a month. Then conducting various regression analyses on $M S L(t)$ vs. $t$, we could obtain reasonable forecasts of sea level over time.

The issue with this analysis, however, is that we merely lumped all sources of variation in sea level trends into equations that we could not interpret meaningfully; in other words, our model provided no insights into what specific time-dependent factors are catalyzing the rise in sea levels, and how those factors influence sea levels.

Per assumption 1, sea levels are predominantly contingent on global temperatures [6]. Oerlemans et al. propose that, on a global scale, the rate of ice lost is proportional to temperature increase over a threshold value; the ice lost in turn leads to rising sea levels. Quantitatively,

$$
\begin{equation*}
\frac{d H}{d t}=\alpha\left(T-T_{0}\right) \tag{2}
\end{equation*}
$$

Martin Vermeer and Stefan Rahmstorf [7], however, find that this relationship only holds for steady ice discharge rates over a steady long-term period; it did not suffice in explaining the significant impetus to ice discharge rates in recent decades. To account for the additional "momentum" driving the current sea level increases, Vermeer and Rahmstorf propose an additional term to the above equation to yield a first order approximation:

$$
\begin{equation*}
\frac{d H}{d t}=\alpha\left(T-T_{0}\right)+\beta \frac{d T}{d t} \tag{3}
\end{equation*}
$$

Global temperatures are the predominant factor driving changing sea levels on a local scale. Thus, we will use the right-hand side of the equation (3) to forecast local changes in sea level - $H$ will represent the sea level at each national park, and $T$ represents the global temperature. For each individual park, we will obtain the coefficients a and $\beta$ through multivariate linear regression, in addition to a constant term of $\gamma$ which accounts for some of the variations in higher orders of temperature as well as non-temperature variation.

$$
\begin{equation*}
\frac{d H_{p a r k}}{d t}=\alpha\left(T-T_{0}\right)+\beta \frac{d T}{d t}+\gamma \tag{4}
\end{equation*}
$$

Before we get to the matter of regression, we must determine a forecast of temperature to use in equation (4). Unfortunately, our motivation to introduce time-dependent explanatory variables into our sea level model cannot practically extend to a temperature forecast - there are simply too many factors which interact in too many ways that we simply could not account for in the allotted time. $85 \%$ of global temperature variation can be attributed to changes in the Earth's orbit around the sun and the angle of the Earth's rotation, according to sinusoidal Milankovitch Cycles [8]. $\mathrm{CO}_{2}$ growth over time exists in a positive-feedback loop with temperature, as increased temperature causes decreased $\mathrm{CO}_{2}$ in the ocean. Chlorofluorocarbon release also rapidly depletes the ozone layer, and its use poses significant variation. As a consequence, we simply consider temperature as a function of time - $T(t)$ — and conduct a series of Taylor approximations which increase in time order. In other words, we construct a polynomial which fits the data well but does not overfit, and per these specifications, we obtain a second order approximation of temperature:


Figure 1: A scatterplot of global annual temperature as a function of time. A quadratic regression line is plotted through the data.

$$
\begin{equation*}
T(t)=0.7920-.004120 * t+.00008168 e * t^{2} \tag{5}
\end{equation*}
$$

with an adjusted $\mathrm{R}^{2}$ (which is loosely a measure of how much variation our model explains penalized by how many variables we use) of $88.74 \%$, and $p$ values of less than .00001 for all coefficients.

Now equipped with a global temperature model, we transition back to equation (4). As mentioned previously, we seek to perform regression to predict coefficients $\mathrm{a}, \beta$, and $\gamma$ on a local park scale. To do so, we first must decide on a time interval for our training set, since we do not have a continuous $\frac{d H}{d t}$ function; we must instead perform regression on $\frac{\Delta H}{\Delta t}$ with respect to $T(t)-$ $T_{0}$ and $\left.\frac{d T}{d t}\right|_{t}$, where $t$ is the time associated with the interval (e.g., 2008). $\frac{\Delta H}{\Delta t}$ is far too variable on a monthly basis and not conducive to remotely useful regression ( $R^{2}$ values were in the range of $1 \%$ to $33 \%$ ). As a result, we choose our time interval to be one complete year. In doing so, we obtain the following coefficients:

|  | Acadia NP | Cape Hatteras <br> NS | Kenai Fjords <br> NP | Olympic NP | Padre Island <br> NS |
| :--- | :--- | :--- | :--- | :--- | :--- |
| $\alpha\left(T-T_{0}\right)$ | -0.137 | 1.394 | 3.077 | 3.083 | 0.203 |
| $\beta(\mathrm{~d} T / \mathrm{d} t)$ | 342.4 | 340.2 | -697.6 | -297.7 | -117.8 |
| $\gamma$ (constant) | -5.059 | -4.096 | 8.52 | 3.083 | 2.107 |
| $R^{2}$ adjusted | $31.96 \%$ | $49.52 \%$ | $54.94 \%$ | $19.10 \%$ | $2.83 \%$ |

Figure 2: Constants and parameters determined by our model.
A positive $\alpha$ coefficient indicates that the rate of sea level change varies positively with temperature, while a negative $\alpha$ coefficient indicates that the rate of sea level change varies negatively with temperature. If $\beta$ is positive, the rate at which the sea level increases varies positively with the rate at which temperature increases. We derive our function so that $\gamma$ is a higher-order temperature variation. The $R^{2}$ values of the majority of the national parks are fairly high, indicating that a significant portion of sea level rise can be modeled by temperature. However, Padre Island National Seashore has an extremely low $R^{2}$ because there is no better regression model aside from the mean.

Equipped with the requisite coefficients, we now transition into once again treating $\frac{d H}{d t}$ in its continuous form, and numerically integrating equation (4) in each of the national parks.

$$
\begin{equation*}
H_{p a r k}(t)=\int_{0}^{t} \alpha\left(T-T_{0}\right)+\beta \frac{d T}{d t}+\gamma d t \tag{6}
\end{equation*}
$$

After iteratively computing this integral for every year from 1997 (our baseline year) to 2067 (fifty years into the future from today) in MATLAB, we obtain the following graph:


Figure 3: Graphs of sea level height over time for all five parks
From this graph a general universal positive trend of sea level heights over time can be seen. Olympic, Acadia, and Cape Hatteras all lie along oceans and thus logically have similar upward trends. Meanwhile, Padre Island and Kenai Fjords both lie in gulfs (the Gulfs of Mexico and Alaska, respectively), and thus the relationship between their sea level rise and mean global temperature is much more complex and harder to predict since it also relies on knowledge of local current patterns.

## Part 2 - Interpretation of high, medium, and low

## Acadia National Park, Maine:

By 2026, the sea level is predicted to rise by 19.057 mm . Continuing the regression curve, the sea level will reach 36.036 mm in 2036 and 118.688 mm in 2067. Comparing these values to the topographic map of Acadia National Park (Figure 6), we categorize the national park as low risk for all three points in time, since the elevation of the vast majority of the region is well above 118.688 mm .

## Cape Hatteras National Seashore, North Carolina:

The sea level is predicted to rise 21.849 mm and 29.333 mm 10 and 20 years after 2016, respectively. Since various regions of the topographic map of Cape Hatteras National Seashore lie at or above 5 feet (Figure 7), we can reasonably categorize the national park as low risk 10 and 20 years after 2016. However, the sea level is expected to rise 53.899 mm by 2067, thereby falling into the medium risk category 50 years after 2016.

Kenai Fjords National Park:
According to the USGS, "Most areas on Kenai Peninsula (including Kenai Fjords NP) are emerging at a rate faster than the rise of eustatic (global) sea-level ( $1.8 \mathrm{~mm} / \mathrm{yr}$ )." The table (Figure 5) and topographic map (Figure 8) correlate this statement for all three points in time, leading us to conclude that Kenai Fjords National Park is of low sea level change risk 10, 20, and 50 years after 2016.

## Olympic National Park, Washington:

The predicted sea level rise of Olympic National Park is expected to remain under 230.381 mm within the next 50 years. Since the topographic map indicates that the elevation of the vast majority of Olympic National Park is above 20 feet and the coastlines are cliffs (Figure 9 ), in essence, the sea level change risk is low 10, 20, and 50 years after 2016.

## Padre Island National Seashore, Texas:

Padre Island National Seashore is at high sea level change risk; the minority of its elevation is above 5 feet (Figure 10), while its sea level is predicted to rise 11.613 and 12.605 mm 10 and 20 years after 2016, respectively. Predicted sea level rise decreases to 6.770 mm 50 years after 2016, but Padre Island National Seashore is categorized as high due to its extremely low elevation.

| Predicted Sea Level Rise (mm) |  |  |  |  |  |  |
| :---: | :--- | :--- | :--- | :--- | :--- | :---: |
| Years after <br> 2016 | Acadia NP | Cape Hatteras <br> NS | Kenai Fjords <br> NP | Olympic NP | Padre Island <br> NS |  |
| 10 | 19.057 | 21.849 | 53.780 | 88.681 | 11.613 |  |
| 20 | 36.036 | 29.333 | 61.894 | 121.018 | 12.605 |  |
| 50 | 118.688 | 53.899 | 61.077 | 230.381 | 6.770 |  |

Figure 5: The table compares the amount of predicted sea level rise in the five national parks given, projected 10,20 , and 50 years into the future.


Figure 6: The map describes the topology of Acadia National Park, with contour intervals of 20 feet. Photo from [9].

Fig


Figure 8: The regional map of Kenai Fjords National Park uses contour intervals of 200 feet to graph its topology. Photo from [9].

aphical map demonstrates variable elevation on Cape Hatteras National Seashore, with contour intervals of 5 feet. Photo from [9].


Figure 9: Olympic National Park's topology is modeled by the map above, with contour intervals of 20 feet. Photo from [9].


Figure 10: The topology of Padre Island is graphed above, with contour intervals of 5 feet. Photo from [9].

## Sensitivity Analysis of Sea Level Model

We performed sensitivity analysis for each national park in the following manner:

1) Keeping $\alpha$ constant, we chose eleven equally spaced $\beta_{i}$ values which are within one standard error of the predicted $\beta$ value (i.e., ten $\beta_{\mathrm{i}}$ values from the interval $\left[\beta-\mathrm{SE}_{\beta}, \beta+\right.$ $\left.\mathrm{SE}_{\beta}\right]$ ). For each new $\beta_{\mathrm{i}}$ value, we computed the predicted sea level in 2036 and determined the variance of the ensuing prediction set divided by the mean (to normalize the variance).
2) Likewise, keeping $\beta$ constant, we chose eleven equally spaced $\alpha$ values which are within two standard errors of the predicted $\alpha$ value and determined the normalized variance of the 2036 sea level prediction set.

The normalized variances are as follows:

|  | Acadia NP | Cape Hatteras <br> NS | Kenai Fjords <br> NP | Olympic NP | Padre Island <br> NS |
| :--- | :--- | :--- | :--- | :--- | :--- |
| $\alpha(T)$ | 118.32 | 233.65 | 37.38 | 87.19 | 267.56 |
| $\beta(\mathrm{~d} T / \mathrm{d} t)$ | 0.56 | 1.10 | 0.24 | 0.43 | 4.70 |

Figure 11: Normalized variances.

As evident in the above table, our model is not especially sensitive to the $\beta$ coefficient; however, our model is incredibly sensitive to the temperature coefficient. This makes complete sense the $T$ dependence represented a long-term trend in temperature growth, and thus small variations in the $T$ coefficient should be very significant in predicting future ocean levels. Our $\frac{d T}{d t}$ dependence represents a more short-term adjustment factor, whose effect should pale relative to millennia-long trends.

## Strengths and Weaknesses

Our model does very well in making a meaningful forecast of sea levels in each of the five national parks over the next five decades; it demonstrates that global temperature clearly has an effect on sea levels (as determined by our regression analysis on equation (4)), and it carefully utilizes that temperature dependence to predict sea levels. Our sea level analysis plays directly into determining the risk factor for each park based on its topology.

One weakness of our model is that it will not work in a 100-year time span. This is because it does not take into the account the inevitable tipping point at which the Greenland and Antarctic Ice Sheets will begin to melt [12]. At this point sea level rise will increase dramatically, and we are not taking this critical point into account. Our assumption that global temperature changes overshadow local temperature changes leads us to not consider local factors, such as local current patterns.

## Summary

Our model relies on a quadratic temperature forecast into the future, and an ordinary differential equation relating the rate of sea level rise to temperature and the rate of temperature change. Upon performing regression to fit coefficients of the differential equation, we forecast how sea levels in each of the five national parks will evolve in the forthcoming decades. Using our forecast of sea levels, we consider the topology of the national park to assess the risk factor associated with sea level rise. We find Olympic and Cape Hatteras to experience the largest increases in sea level rise, while Padre Island and Kenai Fjord expect smaller but still noticeable increases.

## The Coast Is Clear?

## Restatement of the Problem

The NPS has asked us to develop a model to assign a climate vulnerability score to any coastal unit. There are several significant factors that influence the vulnerability to climate change in a specific region; these are mainly composed of sea level changes, temperature changes, and natural disasters. Natural disaster vulnerability specifically is composed of the frequency of a natural disasters and the damage caused by that natural disaster.

## Assumptions

Assumption 1: Frequency of earthquakes, hurricanes, and wildfires will not vary significantly over the next 50 years.

Justification: Earthquakes are caused by the movement of tectonic plates, which move significant distances over timescales of millions of years, and therefore would not change significantly over 50 years. Wildfires are primarily caused by droughts, which over long periods
of time increase due to climate change; however, over a short period of time such as 50 years, the drought frequency will not vary appreciably. Hurricanes similarly are complex meteorological processes that occur in small discrete amounts. To be confident about a decrease of a rate of 3 major hurricanes every 10 years to 2 major hurricanes every 10 years would be naive.

Assumption 2: The cost of general upkeep of the park is the product of the base general upkeep for a general national park and the Climate Extremity Index (CEI).

Justification: All parks have common infrastructure which would contribute to the total cost, but specific parks need more or less of this cost depending on their specific extremity of climate, as measured by the CEI.

Assumption 3: The average wildfire at Padre Island National Seashore only costs $1 / 10$ of a generic wildfire at other parks.

Justification: Almost all of the land at Padres Island National Seashore is brush; by common logic, brush fires cost significantly less than generic wildfires since brush is much smaller than trees.

Assumption 4: Only earthquakes above 5.0 on the Richter Scale cause monetary damage. Justification: Earthquakes below 5.0 are very weak and cause little to minor damage [10].

## Approach

We assign a climate vulnerability index by predicting the total cost per acre of climate related events at national parks over the next 50 years. The cost is predicted by summing the predicted cost associated with earthquakes, hurricanes, wildfires, rising sea level, global temperature rise, and the cost of general upkeep of the park.

## Model

## Part I - Determining Cost due to Climate

We determine the cost by first determining the average cost associated with an earthquake, hurricane, and wildfire, along with the respective frequency of each. We then found costs associated with sea level increase and global temperature increase, both of which were determined in Model 1. We incorporated the general cost of park maintenance into the total cost by multiplying a constant base cost for running any national park per acre by the climate extremity index (CEI) number of the region. After doing this we determined the cost to be as follows:

# Total Cost $(t)=\frac{\left(1.2 \times 10^{7} \times F_{\text {EQ }}+\frac{1.8 \times 10^{9} \times F_{\mathrm{H}} \times \text { AcrePark }}{246293600}+225 \times F_{\mathrm{W}} \times \text { Acre }_{\mathrm{W}} \times \text { Weight }_{\mathrm{W}}\right) \times t}{\text { AcrePark }}$ <br> $+203.6 \times$ Percent Under <br> $+\frac{\left(\text { Weight }_{\mathrm{CEI}}-1\right) \times \text { Budget }_{\mathrm{NPS}}}{\text { Acre }_{\mathrm{NPS}}}$ 

| $F_{\text {EQ }}=$ Frequency of Earthquakes at the Park | (8) |  |  |
| :---: | :---: | :---: | :---: |
|  |  | Acrenps $^{\text {a }}$ - Total Acreage of all the national parks | (16) |
| $F_{\mathrm{H}}=$ Frequency of Hurricanes at the Park | ${ }^{(9)}$ |  |  |
| Acrepark $=$ Acreage of the Park | (10) | $1.2 \times 10^{7}=$ Average cost of an Earthquake | (17) |
| $F_{\text {W }}=$ Frequency of Wildfires at the Park | (11) | $1.8 \times 10^{9}=$ Average cost of a Hurricane | (18) |
| Acrew $=$ Average Acreage a Wildfire at the Park | (12) | $246492600=$ Average Acreage of the Area Effected by Hurricanes | (19) |
| Weight $_{\text {w }}=$ Weight of the cost of Wildfires | (13) |  |  |
| Weight $_{\text {CEI }}=$ CEI of the Park | (14) | 225 = Average Cost of a Wildfire per Acre | (20) |
| Budget $_{\text {NPS }}=$ Total Budget of the NPS | (15) | 203.6 = Average Revenue per Acre of a National Park | (21) |

The values of the variables for each of the parks is shown in Figure 12 below.

|  | Acadia NP | Cape Hatteras NS | Kenai Fjords NP | Olympic NP | Padre Island NS |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Acre $_{\text {Park }}$ | 59052 | 30351 | 669984 | 922650 | 130434 |
| FW$^{*}$ Acre $_{W}$ | 60.6250 | 215.1250 | 0.0000 | 10031.5000 | 2798.5125 |
| Weight $_{W}$ | 1.0 | 1.0 | 1.0 | 1.0 | 0.1 |
| $\mathrm{~F}_{\text {EQ }}$ | 0.000 | 0.000 | 0.125 | 0.100 | 0.000 |
| $\mathrm{~F}_{\mathrm{H}}$ | 0.0238 | 0.1810 | 0.0000 | 0.0000 | 0.5380 |
| Weight $_{\text {CEI }}$ | 1.2270 | 0.9970 | 1.0000 | 0.8540 | 0.9140 |
| Percent | Under | 0.00 | 0.05 | 0.00 | 0.00 |

Figure 12: Coefficient for the model for each national park.

| Park | Lost Revenue per Acre per Year after 50 Years <br> (in Dollars) (Vulnerability Index) |
| :--- | :--- |
| Acadia | 8.902 |
| Cape Hatteras | 10.063 |
| Kenai Fjord | 2.239 |
| Olympic | -1.708 |
| Padre Island | 23.289 |

Figure 13: Vulnerability index for each national park. The higher the value, the more fragile the climate of a park. The vulnerability index is the lost revenue for each acre of land per year in 2067.

## Summary

The model results in a prediction that in 50 years, Acadia National Park will cost $\$ 8.902$ per acre, Cape Hatteras National Seashore will cost $\$ 10.063$ per acre, Kenai Fjords National Park will cost about $\$ 2.239$ per acre, Olympic National Park will cost $-\$ 1.708$ per acre, and Padre Islands National Seashore will cost about $\$ 23.289$ per acre all relative to the base cost of a park today. The fact that Cape Hatteras National Seashore and Padre Islands National Seashore both have large costs per acre per year is reflective of their location on coasts, and therefore vulnerable to high cost hurricanes. Due to their low elevations, we expect them to lose ground due to sea level rise within 50 years. Acadia has the next lowest cost per acre per year, which we attribute to the high CEI of Acadia National Park, causing the base cost discounting natural disasters to be much higher than the average cost. Kenai Fjords National Park and Olympic National Park both are stable, and not extremely prone to natural disasters, leading to them have a low cost per acre per year. This is especially evident for Olympic National Park, where the relative cost is negative, indicating that the cost for Olympic National Park will be lower than the average cost for national parks in 2067.

## Let Nature Take Its Course?

Restatement of the Problem
Since the NPS operates upon limited financial resources dependent on factors such as climaterelated events, costs often exceed revenues and funding. The NPS therefore must prioritize where to spend monies, asking us to develop a model to predict long-term changes in visitors for each park. The output from this model provides insight into the allocation of NPS's future financial resources.

## Simplification

Simplification 1: We are only concerned with the yearly visitor statistics as opposed to monthly or weekly visitor statistics.

Justification: Yearly visitor statistics provide a fairly accurate estimation of the visitation pattern. Further, the problem would be reduced to 5 regressions, as opposed to 60 regressions.

Simplification 2: All types of natural disasters are considered equal in every park.
Justification: Although not all natural disasters would affect each park the same way, the overall effect of having a variety of these disasters over the long run will cause the average percentage decline in visitors to be the found selected constant. This means that instead of running 5 Monte Carlo methods that differ greatly by considering the propensity for each separate natural disaster, we can instead run 1 Monte Carlo simulation that only differs each time by one probability.

## Assumption

Assumption 1: The variation in the climate vulnerability model within a year is fairly insignificant.

Justification: The climate vulnerability model predicts the cost required to maintain the park, with regards to climate-related factors, summing the predicted cost associated with earthquakes, hurricanes, wildfires, rising sea level, global temperature rise, and the cost of general upkeep of the park. We assume that the impact of these sea level changes, temperature changes, and natural disasters are essentially evenly spread out within the year.

Assumption 2: The proportion of visitors in a specific month to visitors in a year will not vary significantly within the time frame considered.

Justification: As the climate varies yearly, the monthly climate is accordingly impacted as well. Since the climate has a fairly consistent relative impact throughout the year, we can assume the proportion of visitors in a specific month to visitors in a year does not vary significantly.

## Approach

In order to accurately model the effect of large natural disasters on the visitation of each of the National Parks, it is necessary to reflect the random and discrete nature of such natural disasters. In order to do this, we used a Monte Carlo modeling methodology which simulates the visitation patterns of national parks: each week, a natural disaster is assumed to hit with a probability created by looking at past research of natural disasters.

## Model

In problem 2, we looked at the amount of money each national park lost per acre from natural disasters of wildfires, earthquakes, and hurricanes. We can assume that this loss of revenue directly correlates with the loss of visitation that will concurrently occur as a result of the natural disasters. And, in order to simplify our Monte Carlo model, we then disregarded the inherent variability in the costs and likelihoods of the three natural disasters (for instance, earthquakes are infrequent but extremely expensive, while wildfires are common but inexpensive). Instead, we considered one generic natural disaster to find the average expensiveness of the three natural disasters weighted for their likelihoods and created a weekly probability function that such a disaster would occur in each of the parks. This function was derived by dividing the lost revenue per acre per year in each of the natural parks as found in question 2 by the hypothetical lost revenue that would occur if one of our generic natural disasters hits the national park every single week. This process is seen in equation (22) below. Thus, for a park like Kenai Fjords National Park, which has very spare but very expensive natural disasters, a smaller generic natural disaster will be simulated more often. The weekly probability of having a generic natural disaster in each of the parks is seen in the table below (Figure 14).

## $\frac{\text { Maximum Cost }}{\text { Acre }}=222.92$

$$
\begin{equation*}
=\frac{48 \times\left(1.2 \times 10^{7} \times \frac{9}{208}+\frac{1.8 \times 10^{9}}{246293600} \times \frac{12}{208}+5000 \times 225 \times \frac{187}{208}\right)}{\overline{\text { Acte Park }}} \tag{22}
\end{equation*}
$$

$5000=$ Average Acreage of Wildfire
$\overline{\text { AcrePark }}=$ Average Acreage over all 5 parks

|  | Acadia NP | Cape <br> Hatteras NS | Kenai Fjords <br> NP | Olympic NP | Padre Island <br> NS |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Probability of <br> disaster | 0.00182 | 0.0248 | 0.01004 | 0.01681 | 0.02759 |

Figure 14: Probability of a generic disaster at each of the national parks.
To run the Monte Carlo simulation, we first ran a linear regression on the yearly visitation statistics given to us for each of the parks over time. For Olympic National Park, Padre Islands National Seashore, and Kenai Fjords National Park, we created our linear regression from the past twenty years of visitor data. However, for Acadia National Park and Cape Hatteras National Seashore, the late 1990's and the early 2000's saw very little growth in the numbers of visitors before growing at a linear rate in the rest of the century. This meant that the linear coefficient was too small if the regression was run for the full 20 years. For these two parks, we ran the linear regression on the last 10 years. Additionally, we found the monthly distribution of visitation per month. Then, to create a baseline visitation number for each week of our Monte Carlo simulation, we multiplied the expected visitation of the year times the visitation share of the given month divided by 4 (since our Monte Carlo was week-long steps not month-long steps). If no natural disasters were occurring, we kept this base visitation number as the amount of visitors coming. However, if a natural disaster happened to randomly occur, we decreased this base visitation number by $40 \%$ and then increased the visitation $5 \%$ each week until it was back to the base visitation number. These numbers of $40 \%$ and $5 \%$ were found by looking at the effects of both large natural disasters (such as the category 4 Hurricane Bret that hit the Padre Islands in 1999 and affected visitation statistics for almost a year) and small natural disasters such as grade A wildfires which had very little effect. Given that we did not have the time to accurately match each natural disaster to a respective decrease in visitation, we decided on these numbers as a rough estimate given our few examples.


All the graphs in Figure 15 are generally linear because they are averages of 1000 trials. Thus, all the individual variations of each trial (as seen in Figure 16) average out. In general, the virtually linear graphs we found in Figure 15 are similar to those expected by using only visitation statistics, However, their slopes are lower due to effects caused by natural disasters. And those sites with higher probabilities of a natural disaster occurring have lower relative slopes. Given more time we would quantitatively extend this idea further.


Figure 16: The predicted number of annual visitors from one run of the Monte Carlo simulation for the Kenai Fjords National Park. The graph is less linear than the graphs in Figure 15, since here each point is not the average of many different trials. This shows the effects of natural disasters on visitation.

|  | Current Number of <br> Visitors | Projected Number of <br> Visitors in 2037 | Projected Number of <br> Visitors in 2067 |
| :--- | :--- | :--- | :--- |
| Acadia NP | $3,303,393$ | $3,968,908$ | $6,878,267$ |
| Cape Hatteras NS | $2,411,711$ | $1,360,516$ | 611,190 |
| Kenai Fjord NP | 346,534 | 414,626 | 580,349 |
| Padre Island NS | 634,012 | 433,597 | 273,266 |
| Olympic NP | $3,390,221$ | $2,108,745$ | $1,451,733$ |

Figure 17: Table showing number of projected visitors at each national park last year, 20 years from now, and 50 years from now.

Given the trends in visitation found above and the expected vulnerability to the changing climate as found in section 2, we propose that the NPS spends a majority of their money on Acadia, and to lesser extents Cape Hatteras and the Padre Islands. Because of their high vulnerabilities it is important that the NPS spend the necessary funds to preserve the land of Cape Hatteras and Padre Island. However, along with preserving the land of those two national parks, it is also important that the NPS gain considerable revenue so that it has the monetary resources to protect the United States environment as a whole. In order to gain this revenue, we think the NPS should heavily invest in Acadia. Based on current visitation trends and a complete lack of natural disasters, we predict that Acadia will considerably increase its amount of visitors in the future. Creating appropriate infrastructure and government business within Acadia would cause an increase in revenue for the NPS that takes advantage of the visitation boom which we are predicting. Additionally, Acadia's vulnerability is quite high due to its large ECI. Thus, added revenue would be helpful to maintain a high standard of trails and other outdoor amenities, as
this would otherwise be difficult with a constantly changing climate. Keeping Acadia highly functioning is absolute necessity in order to maintain the expected visitation increase without disappointing those who eagerly come.

## Strengths/Weaknesses

## Strengths

A major strength of this model stems from its Monte Carlo nature. Natural disasters are inherently quasi-random events, and our model takes this into account. While doing this, our model is still able to depend on general trends in visitation statistics that have already been observed in each of the five parks in the past thirty years. Additionally, we were able to do 1000 trials for each park, which limits any possibility of random variations influencing our final results.

## Weaknesses

The largest weakness in our model is simply how few factors we considered. Given the time constraint we were only able to fully consider natural disasters and general visitation trends. Given more time we would extend our model to include local temperature, as we expect this to possibly also correlate with visitation.

## Summary

Using our Monte Carlo model we were able to predict the future number of visitors at each national park. We found that Acadia National Park and Kenai Fjords National Park both will experience a growth in the number of visitors, while the other parks will all experience a decline in visitors. However, funding should not be allocated solely on the number of visitors. The mission of NPS is to preserve the natural environment, and as such it is necessary to invest money in the most vulnerable parks [11]. We therefore recommend that high levels of funding be maintained for Cape Hatteras and Padre Island National Seashores in order to protect the most vulnerable parks. Funding should also be kept at a high level for Acadia National Park so that paying visitors can finance the more vulnerable and less visited parks.

## Conclusion

The NPS has a large task ahead of them as it attempts to preserve its 83 million acres of wildlife against the harsh reality of impending climate change. As sea level rises, parks such as Padre Island and Cape Hatteras will invariably start to descend underwater. It will take incredible effort to do the necessary outreach and preemptive planning to limit these harrowing effects. However, the added foresight will invariably help the cause. Additionally, over the next 50 years numerous natural disasters will negatively affect visitation statistics. In particular the high propensity for hurricanes in both the Padre Islands and Cape Hatteras will keep visitors at home instead of enjoying the beauty of the National Parks. These natural disasters along with a general historical trend cause us to unfortunately predict a large decrease in attendance for these two
parks. On the other hand, we expect Acadia National Park to become a revenue center for the NPS. A lack of natural disasters, no immediate sea level issues, and a general trend of increased visitation cause us to predict large upticks in the amount of people who go to Acadia. We recommend that the NPS take advantage of this foresight and invest in keeping the park as up-todate as possible.

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