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A Study on Global Reef Deterioration: Exploring Coral Bleaching

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by

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Abstract

This thesis is a study on coral bleaching and coral mortality, studying the relationship between variables such as depth, exposure, distance to shore, and temperature for percent bleaching. All of the analyses were made using two different data sets, that contain information about bleaching events in specific regions, and dates, and provide information factors such as depth, temperature, and exposure. Models were created for different relationships of variables for eco-regions, recent data, and countries. I attempted to find relationships between variables such as depth, temperature, exposure, and distance to shore, and how they affect coral bleaching. Unfortunately, I did not find any meaningful relationships. There is a also case study on reefs found in Broward County, Florida derived from data from 2005 to 2006. I found a seemingly positive relationship between temperature and coral bleaching in this region. Coral bleaching events are worth studying because by finding the relationships between these variables and the levels of coral bleaching, this research can be used to slow the effects of coral bleaching and coral mortality.

Acknowledgment

I want to thank my parents, Danay and Guido, for sacrificing everything by leaving Cuba to provide a better life for their family. Thank you for always pushing me to be the best I can be and supporting me all the way. I also want to thank my wonderful friends who have shown me unconditional love and support throughout my college career. Lastly, I would like to acknowledge Dr. Sarah Cannon, my thesis advisor, and professor, who introduced me to data science and has greatly influenced my academic and career choices.

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1 Background on Global Warming

Global warming is the phenomenon of rapid increases in the rate of the planet's average surface temperature. An environmental concern with political and economic consequences, global warming has become a major threat to all countries around the world. This section will provide some background information on the impact of global warming and human practices on the environment, and more specifically, the world's coral reefs.

1.1 The Impact of Global Warming

Human activities continue to raise carbon emissions and cause issues, such as deterioration of the ozone layer, exhaustion of resources, increases in temperature, extreme weather conditions, and an increase in the sea level of the world's oceans. These human activities include the following: burning fossil fuels, such as coal, oil, and natural gases; manufacturing goods; ocean dumping; and cutting forests. Cities like New York and Los Angeles, which have higher densities of people, greatly contribute to climate change because of the harmful characteristics of urban life, specifically, the abundance of greenhouse gas emissions. According to United Nations Environment Programme, cities produce 75 percent of the global CO2 emissions largely because of transportation and buildings [1].

Although the effect of global warming is felt all around the world, developing countries face harsher consequences. With fewer resources and technologies to reduce the effects of global warming, developing countries have the worst effects. Many factors contribute to global warming, but greenhouse gases are the primary contributors. These greenhouse gases include methane, nitrous oxide, ozone, carbon dioxide, water vapor, and chlorofluorocarbons [6]. It is important to note that the greenhouse effect is a naturally occurring phenomenon that is necessary for weather and climate cycles. However, the negative effects occur when greenhouse gas emissions reach high levels. Notably, the emissions have increased greatly since the industrial revolution, which took place at the turn of the 19th century. The effects of increased manufacturing effects are being felt the most in the last decade, as people experience warmer climates, unpredictable weather conditions, less prominent seasons, and more hurricanes, droughts, floods, and other extreme weather.

Global warming also directly impacts the ocean. Since 1901, the average sea surface temperature increased by 1.5 F, an average rate of 0.13 F per decade [8]. Oceans cover about 2/3rd of the planet and significantly influence weather and climate patterns. Because oceans absorb heat trapped in the atmosphere by greenhouse gases, the ocean's temperature continues to increase. Every year, the ocean absorbs about one-quarter of all the carbon dioxide emitted into the atmosphere. With the ocean being a key component of the water cycle, the rising temperatures negatively impact the Earth's climate and weather. Increased temperatures cause more water vapor in the atmosphere, which could lead to heavy rainstorms and snowstorms.

An increase in global temperatures has also caused the ice near the Arctic and Antarctica to melt. Greater ice melting has raised sea levels at alarming rates [7]. In fact, the global average sea level increased by eight to nine inches since 1880, revealing this concerning trend. This issue has worsened in the past two decades. In fact, the sea level's growth rate doubled between 2006 and 2015 [13]. About 30% of the population of the United States lives in highly dense coastal areas. The rising sea level threatens the infrastructure of these cities by potentially destroying roads, bridges, power plants, and train lines. The rising sea levels also heighten the risk and impact of storm surges and flooding [13].

More harmful gases in the atmosphere lead to acidification, which is the reduction of the pH value of the ocean and reduces the number of carbonate ions. Acidification is extremely harmful to marine ecosystems, and especially coral communities [16]. The acidification leads to a disruption in the symbiotic relationships of many species of marine life and negatively impacts the chemical balances of the ocean. Carbonate ions play a large role in the structural building of seashells and coral skeletons. This decrease in carbonate ions also makes it harder for various shellfish, such as oysters, clams, coral, and calcareous plankton, to calcify [16]. Not only does the chemical imbalance harm calcifying organisms, but it also hurts non-calcifying organisms. For instance, fish's ability to detect predators is significantly worse in more acidic water. This difficulty among fish could cause huge disruptions in the ocean food chain, highlighting how global warming could have wide-ranging impacts.

1.2 Coral Bleaching

Corals are invertebrates that belong to the group of animals called Cnidaria. They are colonial organisms, which means that corals live and grow together in communities. Corals are made up of polyp which is a tube-shaped and transparent structure that is fixed to a reef at one end and has an opening at the other. The opening has a mouth that consists of tentacles [3]. Corals utilize the calcium found in the ocean to make their skeletons, which leads to the formation of coral reefs. Consequently, the sustainability of coral reefs requires the existence of other species, making the relationship between corals and other oceanic organisms extremely sensitive and important.

The phenomenon of massive coral bleaching has led to the deterioration of coral ecosystems and large amounts of loss of marine wildlife. Coral bleaching is the process of corals expelling the algae zooxanthellae that live in their tissues, which causes all pigment on the coral to disappear until the coral is white [16]. Algae and coral have a symbiotic relationship, with the algae being coral's primary food source and form of waste disposal. External factors, such as an increase in temperature and pollution, hurt this relationship and cause stress to the coral. The algae are then expelled, leading to the bleaching of the coral. Coral bleaching is a natural process and a normal stress response for coral, however, increasing temperatures have extended the duration and intensity of these bleaching events. Ultimately, this increases the risk of coral mortality, reduces the expansion of the coral ecosystems, and limits the biodiversity of species.

As these events become more frequent and severe, the reefs cannot continue to recover at normal rates. The severity of the bleaching depends on the amount of time endured by thermal stress. With the rising sea temperatures, the risk of bleaching has considerably increased. There is a global increase in coral bleaching levels and the duration of the bleaching. This, in turn, has also increased the levels of coral mortality. Coral reef ecosystems provide habitat to millions of different marine species, protect coastlines from storms and erosion, and provide support to local businesses and recreational use. As the most bio-diverse marine ecosystem, coral reefs have millions of animals depending on them for their survival. Mass bleaching has occurred in the Great Barrier Reef, which is located in Western Australia, during several large-scale events in 1998, 2002, 2016, 2017, 2020, and 2022 [4].

These mass bleaching events involve many coral species and can even lead to the death of these valuable ecosystems. The most recent event in the Great Barrier Reef region occurred in 2022, making it the fourth event in the last seven years. Severe bleaching, which is when more than 60 percent of a coral community is bleached, affected 43 percent of reefs surveyed. (AIMS). Many reefs around the world, in addition to the Great Barrier Reef, saw "the longest, most widespread, and most damaging coral bleaching event on record" between 2014 and 2017" [6].

1.3 Previous Studies on Coral Bleaching Levels

According to a study conducted by the journal OneEarth, about half of living corals have died since the 1950s, and reef biodiversity has dropped by 63%. With some corals being more vulnerable, some corals may be lost before they can be studied and preserved [10]. Coral reefs, such as the Great Barrier Reef, have had a great number of bleaching events at unprecedented frequencies. Coral species more susceptible to coral mortality have become rare, and species that have grown tolerant of increasing temperatures are dominant in reefs. In general, reef diversity and coral cover have decreased immensely since the 1950s. Coral reefs in tropical reefs have suffered an extreme loss of cover in the last 40 years. According to One Earth, "anthropogenic ocean warming has triggered mass bleaching and disease outbreaks," which has significantly decreased the coral cover in all tropical coral reefs" [10].

A study on rising temperatures and coral bleaching conducted by Science Direct stated that coral bleaching could cause mortality, and even if some partially or fully recover, it could take decades. Four general circulation models were created by IPCC IS92a emission scenario [11]. A model that predicts the frequency of coral bleaching was created by a combination of thermal threshold for coral and Sea Surface Temperature (SST) projections. These factors convey that bleaching events are projected to increase rapidly in frequency, with an emphasis on the Caribbean, Southeast Asia, and Great Barrier Reef, and lower amounts in the central Pacific [11]. It was predicted that bleaching events will be annual in most oceans by 2040, and annual in the Caribbean and Southeast Asia in 2020. The study also shows a 50% probability that SSTs will be warm enough to cause coral bleaching in colder regions like Comoros and Chagos in the Indian Ocean by 2030, and in the Saudi Arabian Gulf by 2070.

Corals can recover from bleaching if conditions permit the zooxanthellae to return. Certain coral bleaching events can be directly fixed by addressing local stressors of coral such as polluted waters. However, this is only a short-term fix, and the reduction of greenhouse gas emissions is necessary for maintaining and recovering the world's reefs. There are many conservation organizations that try to address these local stressors to at least alleviate the effects of coral bleaching. For example, NOAA's Coral Reef Conservation Program uses a resilience-based management approach that focuses on supporting corals in the ability to handle and recover stress [16]. They tackle specific problems such as pollution, unsustainable fishing and overfishing, and coral restoration.

A ten-year study from Palmyra Atoll National Wildlife Refuge in the central Pacific Ocean revealed that the coral reef recovered after a widespread bleaching event. This exhibits the fact that reefs outside the proximity of human impacts can recover. "One year after each bleaching event, we did see signs of coral decline at some of the sites, but within two years this was restored," said Adi Khen, a lead author of the study [12]. The study consisted of a long-term time series that provided information from before the event, during the event, and after the event. Palmyra Atoll is habited only by American scientists and researchers and therefore is unaffected by common human stressors such as overfishing and pollution.

The coral bleaching of Palmyra Atoll occurred due to the rising sea temperature and was able to fully recover in as little as two years [12]. Essentially, this indicates that coral reefs in remote locations have a better chance of naturally recovering from bleaching events. "These remote, protected reef systems seem to be able to recover much faster than reefs that are adjacent to dense human populations where overfishing, coastal development, and freshwater runoff containing fertilizers and pesticides all may erode the ability of a reef to recover" said Smith, another author of the study [12].

1.4 A Study on Reef Deterioration

In this study, I will be exploring the amount of damage to notable coral communities such as the Great Barrier Reef and reefs in the Caribbean. I will explore variables such as ocean region, percentage of coral bleached, and percentage of mortality using two different specialized data sets. I will compare and visualize these questions using the data.

First I will explore which ocean regions have the most coral bleaching and which coral communities have the most coral mortality, as observed in the data sets. I will also dive into finding which countries and regions have the highest percentages of coral bleaching events recorded. Next, I will model the relationships between various variables such as temperature and bleaching, distance to shore and bleaching, and depth and bleaching. I will also be exploring the relationships between multiple of these variables together to see if there is a higher correlation with bleaching. Lastly, I will be looking at data from Broward County Florida, and making visualizations and models of the data available.

2 Data

In this section, I will be providing an overview of the data I accessed for this study, the tidying techniques I utilized, and how I prepared my data for analysis.

2.1 Bleaching Data Set

The first data set that I utilized in my study was a subset of mortality and bleach data from a data set named "Bleaching data set" [9]. The data set included 37,774 rows of data and 32 columns. This data set was accessed on the website, Zenodo, which is a multi-disciplinary open repository site. The data includes bleaching event observations ranging from 1963 to 2017. The sources of the data are listed as "literature, International Coral-List outreach, ICRS presentations, Reefcheck, Florida Reef Resilience Program, Coral Cay Conservation, and XL Catlin Seaview Survey" [9]. The Bleaching data set is a compilation of bleaching event observations gathered from all of these sources and then compiled together.

Those behind collecting and organizing the data set are researchers from the University of British Columbia named Donner SD, Rickbeil GJM, and Heron SF. It is the second version of the data set and was released in 2017 with updates from the "Coral Reef Watch 2014-2017 database" [9]. It is a publicly available data set that is in .xlsx format and includes every individual bleaching event with characteristics such as location, dates, bleaching percentages, mortality percentages, severity codes, and maximum depths. There is a README file included in the data set with a legend explaining each variable represented in the data. The data was collected through a targeted search for bleaching events that were not available on ReefBase and through spatial interpolation techniques that developed latitude-longitude global maps.

2.2 Global Bleaching Data Set

The second data set that I used was a data set called "Global Bleaching and Environmental Data" [15]. I accessed it from the Biological and Chemical Oceanography Data Management Office [15] on their website. The principle researchers were Robert van Woesik from Florida Institute of Technology and Deron Burkepile from University of California Santa Barbara. The data set included 62 columns and 41,361 rows of data. This is the second version of the data set and it was released on October 14th, 2022. The data "includes information on the presence and absence of coral bleaching, allowing comparative analyses and the determination of geographical bleaching thresholds, together with site exposure, distance to land, mean turbidity, cyclone frequency, and a suite of sea-surface temperature metrics at the times of survey" [15].

The data was processed using Microsoft Access 2019, R, and QGIS. There is a legend included in the documentation on the website that has a description of all of the variables and the units of measurement, if applicable. The data set is publicly available on the BCO-DMO website as a Matlab file, netcdf file, ODV file and is also obtainable in list format with flat listing, data only listing, and CSV file listing. The data was collected from seven sources: "Reef Check, Donner et al., McClanahan et al., AGRRA, FRRP, Safaie et al., and Kumagai et al." [15]. All of these sources are data recorded by researchers about bleaching events and then all compiled together and organized into the Global Bleaching data set. On the website, it is also possible to manipulate data through math operations, joins, splits, time conversions, production of statistics, and the creation of subsets within the data.

2.3 Data Cleaning Process

My first step in cleaning the Bleaching data set was uploading it on R-studio. All of my code was done with R version 4.2.1 and I used the packages tidyverse, dpylr, tidyr, modelr, skimr, naniar, weathermetrics, and plotly. I uploaded the data set and excluded the columns survey_type, source, citation, comments, database_code, and qc_code, as they served no purpose in my research. I checked what data was available for all variables using the summarize_function, checking the sums of NA values per column, and found that many of the columns had over 50% of NA values. I diverted from using this data set as my principle data set and decided to make a subset of data related to bleaching and mortality percentages of various regions, which I will refer to as the mortality subset. I chose the variables most related to my research and with the least amount of NA values per event. Lastly, I converted all of the temperatures in the data set from Kelvin to Fahrenheit, and all the edits can be found in Figure 1. You can see that most of the data came from the Caribbean and the Pacific Ocean in Figure 2. Furthermore, Figure 3 shows that Florida and Kaneohe Bay have the most bleaching events in the data set.

The final variables included in the data set were the location of the events, the year, severity codes, bleaching percentages, and mortality percentages. After checking all the distinct values per variable using the table function, I found that most of

```{r}
global_final <- global_bleaching %>%
  replace(global_bleaching == -9999, NA) %>%
  select(-c(Site_Name, 60:62)) %>%
  mutate_at(c('Temperature_Kelvin', 'Temperature_Mean', 'Temperature_Minimum', 'Temperature_Maximum'),kelvin.to.fahrenheit)
global_final
```

Figure 1: Tidy Mortality subset

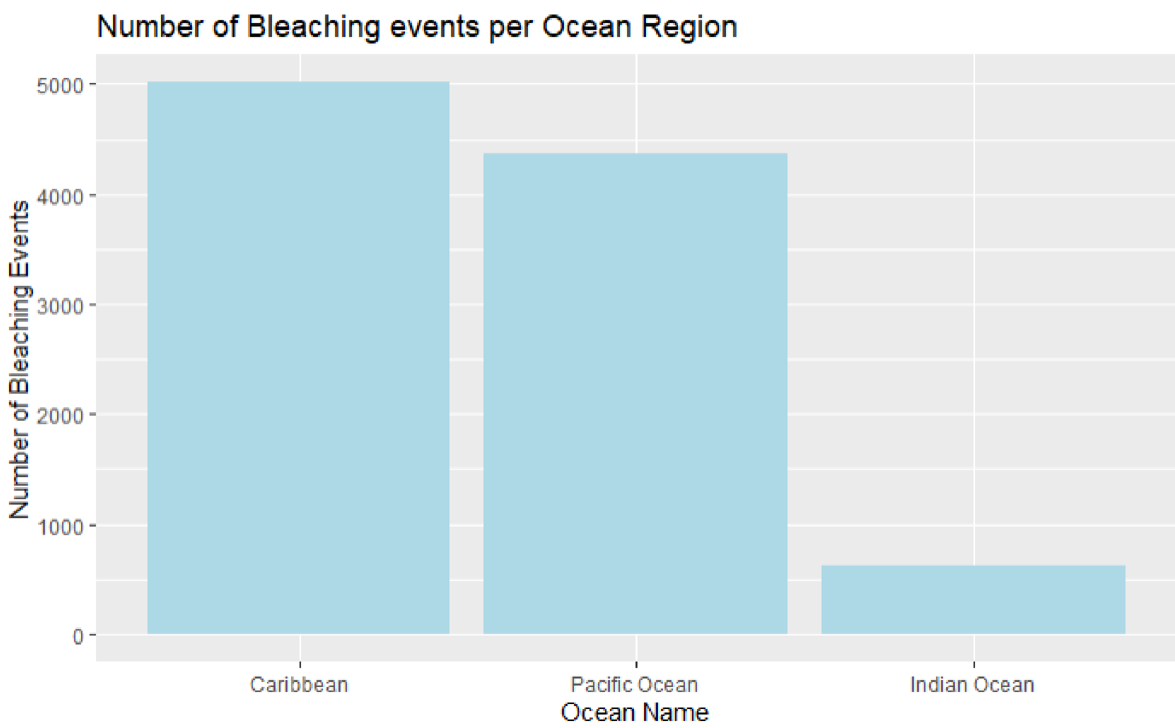

Figure 2: Bleaching events per ocean region in Mortality Dataset

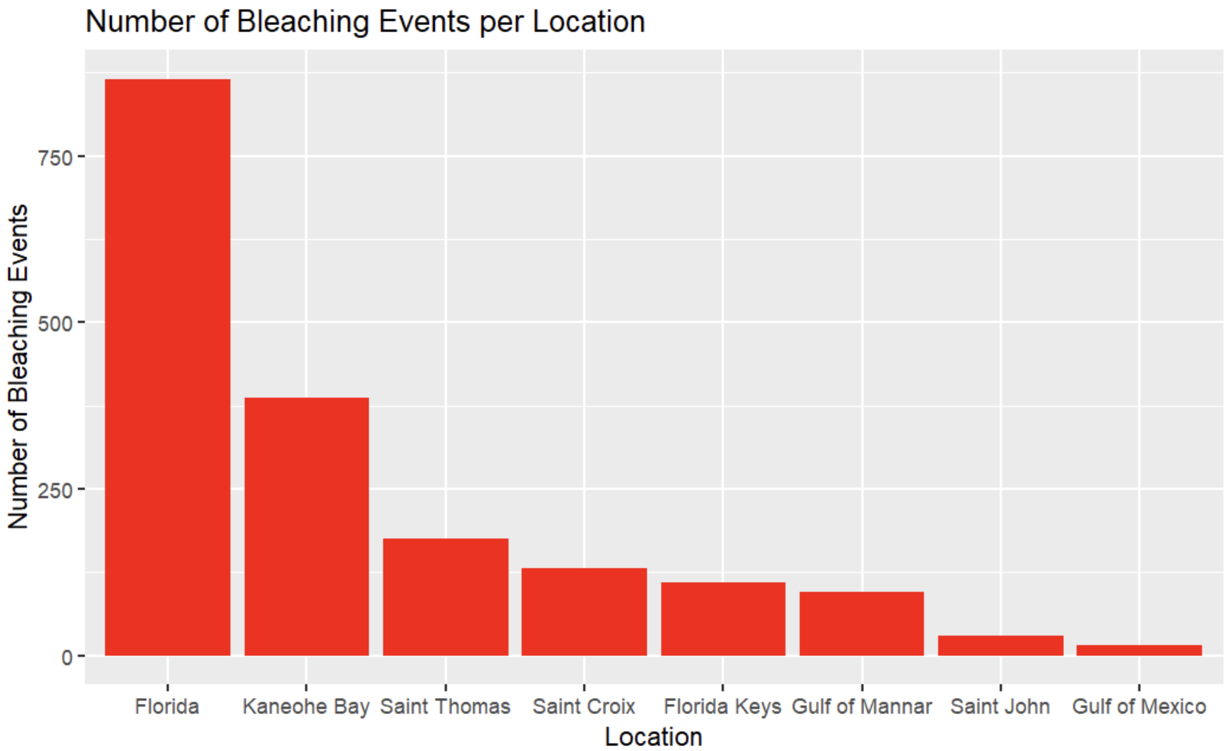

Figure 3: Bleaching events per location in Mortality Dataset

```{r}
global_final <- global_bleaching %>%
  replace(global_bleaching == -9999, NA) %>%
  select(-c(Site_Name, 60:62)) %>%
  mutate_at(c('Temperature_Kelvin', 'Temperature_Mean', 'Temperature_Minimum', 'Temperature_Maximum'),kelvin.to.fahrenheit)
global_final
```

Figure 4: Tidy Global Bleaching Data

the data came from the years 2005, 2006, and 2014-2017, from the ocean regions: Caribbean, Indian Ocean, Pacific Ocean, and North Pacific Ocean. After exploring the areas labeled as North Pacific Ocean, I decided to merge those areas with the value "Pacific Ocean" as they did not have any profound differences. After all of these edits, the subset of data included 10 columns with 10,008 rows of data.

For the second data set, Global Bleaching, I uploaded it onto RStudio using the same version of r and the same packages. I found that there were 0 NA values in the entire data set but after further exploration, found that NA values were actually inputted as -9999. I then proceeded to replace all entries of -9999 with NA and removed the variables site_name, and comments, as they had too many NA values. The code chunk that was used to upload and tidy the Global Bleaching data set can be found in Figure 4.

After checking all the distinct values per variable using the table function, I found that most of the data came from the years 1997-2019, with most of the data in 2005, and from the ocean regions: Arabian Gulf, Atlantic Ocean, Indian Ocean, Pacific Ocean, and Red Sea. I also found the top 10 eco-regions with the most bleaching events. You can see that most bleaching events recorded are found in the Pacific Ocean and Atlantic Ocean in Figure 5. Moreover, Figure 6 shows that the eco-regions Bahamas and Florida Keys, Belize and West Caribbean, and Hispaniola Puerto Rico and Lesser Antilles had the most bleaching events recorded. These were my initial

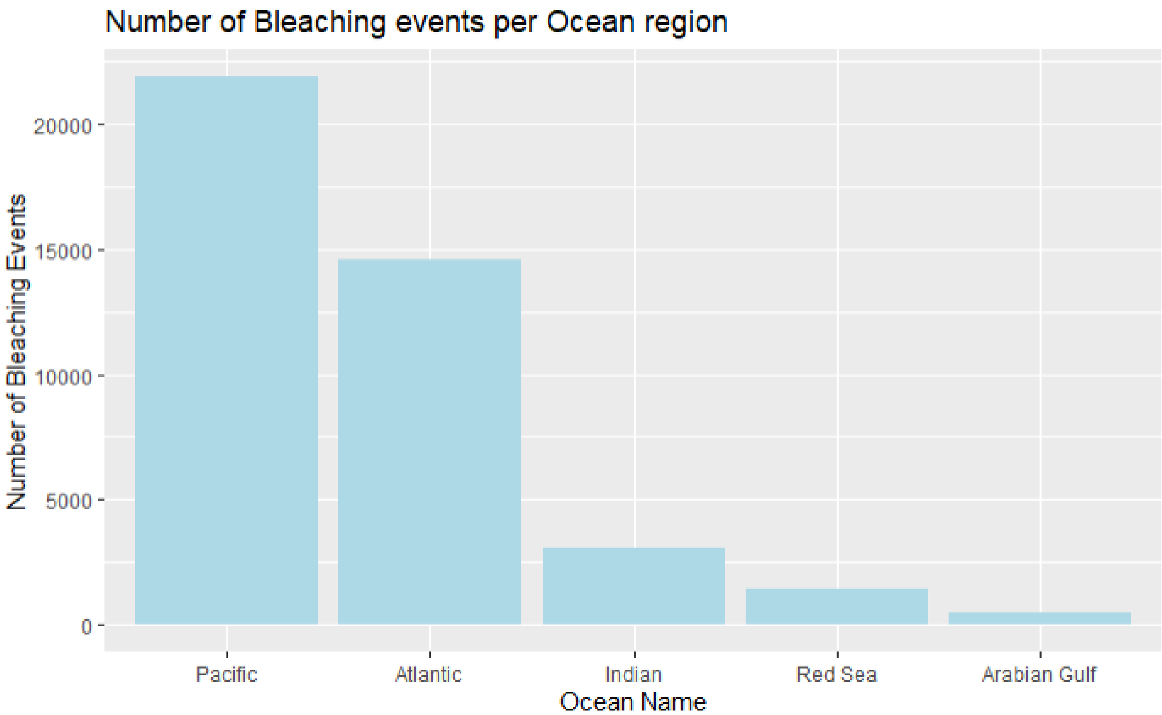

Figure 5: Bleaching events per ocean region in Global Bleaching Dataset

observations before I started preparing my data and variables for modelling.

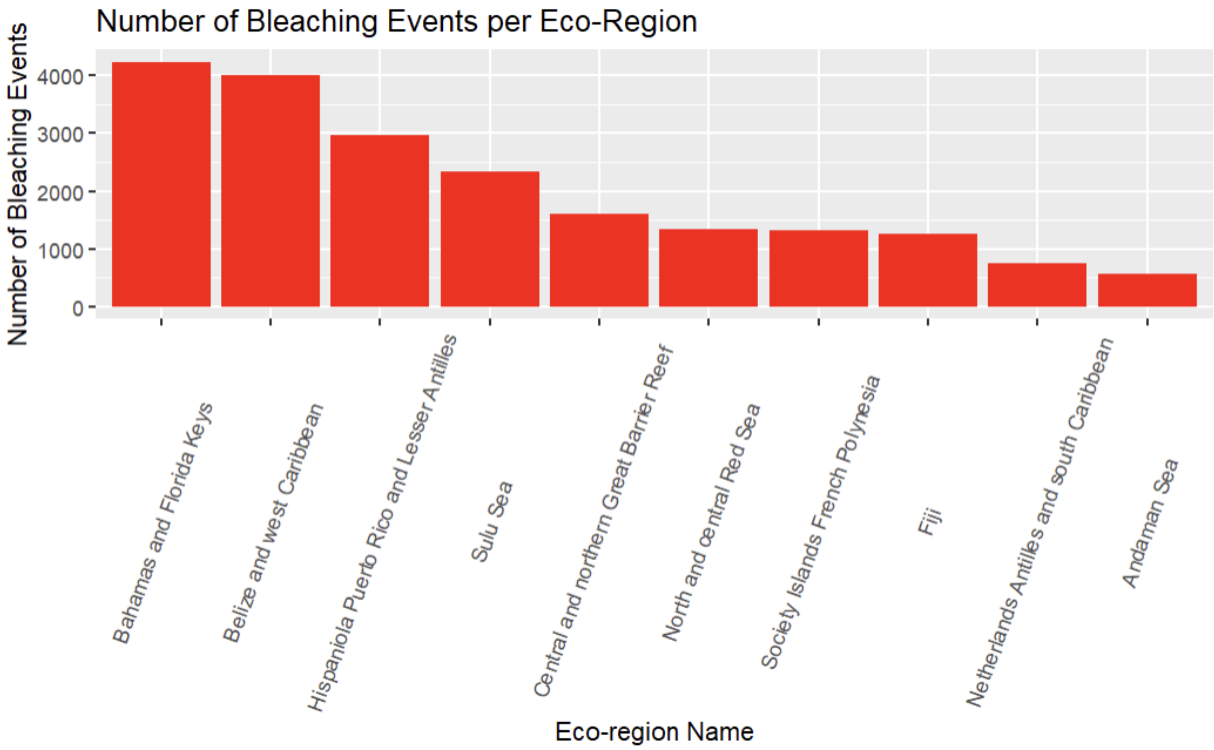

Figure 6: Bleaching events per eco-region in Global Bleaching Dataset

3 Model and Results

In this section, I will be discussing the steps taken to analyze variables and their relationships using various types of models and visualizations.

3.1 What percentage of coral mortality is there by region in the mortality dataset?

To approach this question, I first filtered for the number of observations per location to find which locations have the largest average mortality percentages overall. I then filtered for the largest average mortality percentages per year and location. This gave me insight into which years had the most mortality events and how often mortality events occurred for each location. I utilized the top 8 locations with the largest percentage of mortality events and created plots to display these observations. The 8 locations found in my plots are Florida, Saint Croix, Saint Thomas, Saint John, Gulf of Mexico, Florida Keys, Gulf of Mannar, and Kaneohe Bay. For each location, I made line charts for the mortality events that occurred per year. You can see mortality events for Florida per year in Figure 7 and per month in Figure 8. I did not include the rest of the plots because they do not provide much new information and can be repetitive but you can find the rest of my plots at my github link at https://github.com/emjuliet/thesis.

I also made line plots and box plots to display the mortality events that occurred per month. In these visualizations, I saw that Florida, Saint Thomas, Saint John, and Saint Croix have the most mortality events ranging from the years 2000-2015. Florida even had observations recorded as early as 1987 and 1988. Distinctively, the

Florida Keys only had observations recorded in 2005, 2011, and 2015 and the Gulf of Mannar only had observations recorded in 1988 and 2016. This is an interesting finding because that means that many large-scale mortality events happened in these locations during these years. However, because we don't have data from other years, we don't know whether there was no bleaching or if there were bleaching events that weren't recorded and didn't make their way into the data set. In the box plots, I found that most mortality events per month happened at an average of 5-10%, with a few outliers of 0%. In the line plots for months, I also found that mortality percentages peak at seemingly random months. However, these findings may be due to observations only being collected in certain sites on certain years and months, so we can not make any conclusions based on these visualizations.

3.2 Is there a relationship between global temperatures and the levels of bleaching?

To find the relationship between global temperatures and levels of bleaching I used various different models. My hypothesis was that the higher the temperature, the higher the bleaching levels. The increases in heat could increase the chances of coral bleaching. First I created a linear model using Temperature_Mean as my predictor variable for Percent_Bleaching, which displays bleaching percentages over certain areas. In this model, I created a grid and added predictions and residuals. I then plotted the linear regression line on the data. The r-squared value was 0.00421, which is very low. I used p-values and r-squared values to analyze the results of the models. A p-value describes whether relationships are significant in a model and the closer the p-value is to 0, the higher the significance. The r-squared value "is a measure

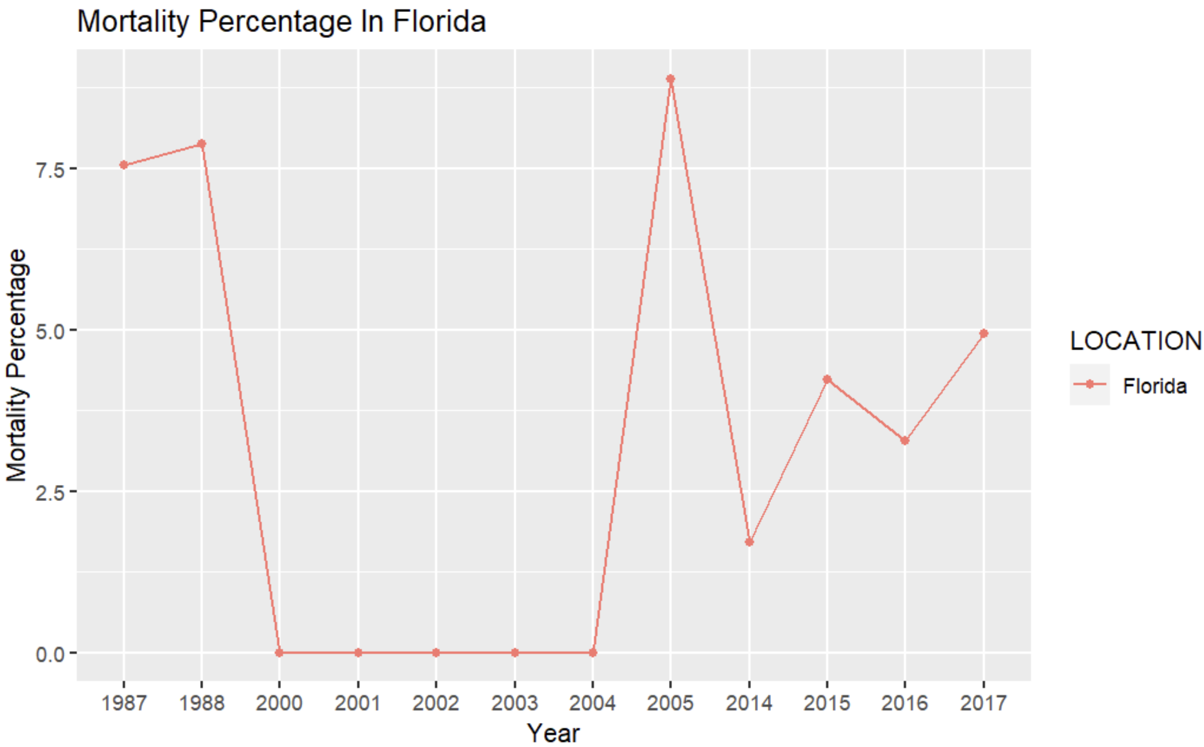

Figure 7: Mortality over the years in Florida.

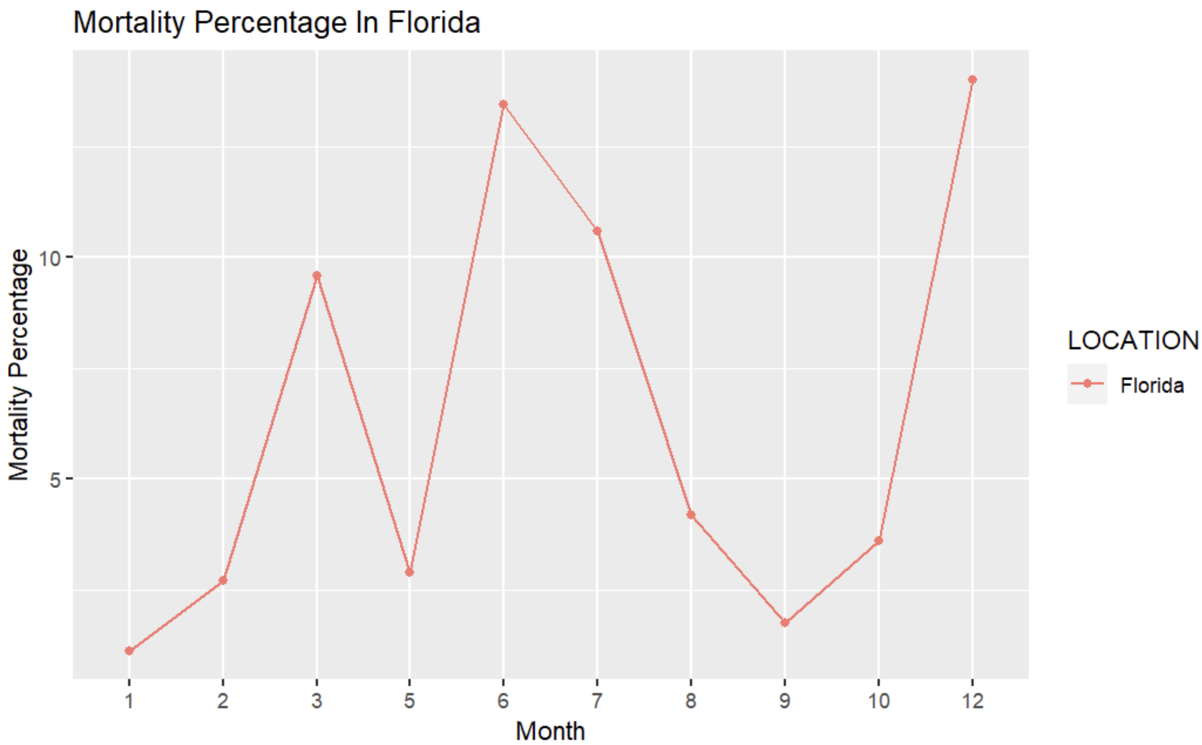

Figure 8: Mortality over months of the year in Florida.

that provides information about the goodness of fit of a model. In the context of regression, it is a statistical measure of how well the regression line approximates the actual data“ [2]. The closer the value is to 1, the more reliable the model is. The p-value was $p < 0.001$, which means we can claim temperature has a significant effect on bleaching percentages but due to the low r-squared value this effect is extremely small. The model for global temperatures and bleaching can be seen in Figure 9. As you can see, the line is negative which means that higher temperature is associated with lower levels of bleaching, this result seems very counter-intuitive. This can be due to the fact that the data is incomplete and inconsistent.

I also attempted to make a quadratic model, a spline model, and a logistic model. I did not find any significant results in any of these models. The data seemed to be very random, with the points having no pattern, as you can see in the figures below. I then attempted these models on data only ranging from 2010 to 2023 to see if this changed things. Finally, I attempted these models on specific eco-regions, those being the Bahamas and Florida Keys, Belize and west Caribbean, Hispaniola Puerto Rico and Lesser Antilles, Sulu Sea, and Central and Northern Great Barrier Reef. Similarly to the overall model, I found low P-values and low r-squared values for the regions: Belize and West Caribbean, Hispaniola Puerto Rico and Lesser Antilles, and Central and Northern Great Barrier Reef. You can see the model for Belize and West Caribbean in Figure 10, and this line is also slightly negative, which was not the expected result.

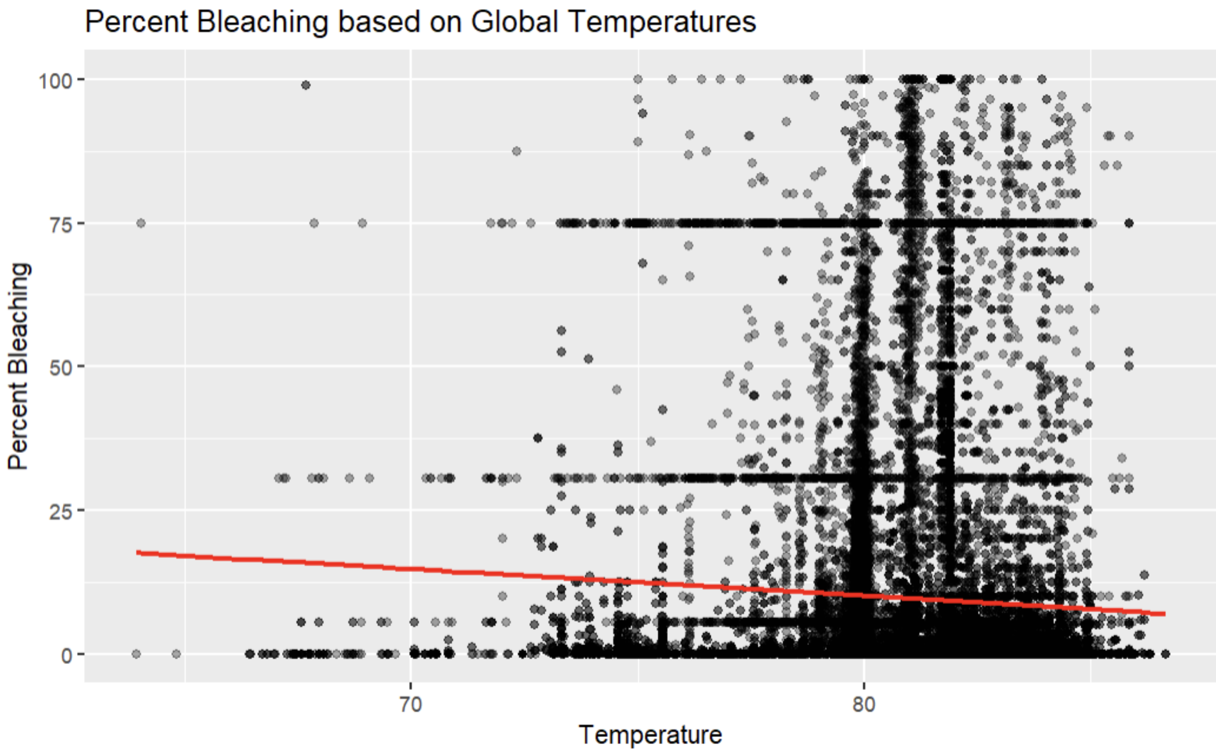

Figure 9: Linear regression of percent bleaching and global temperatures.

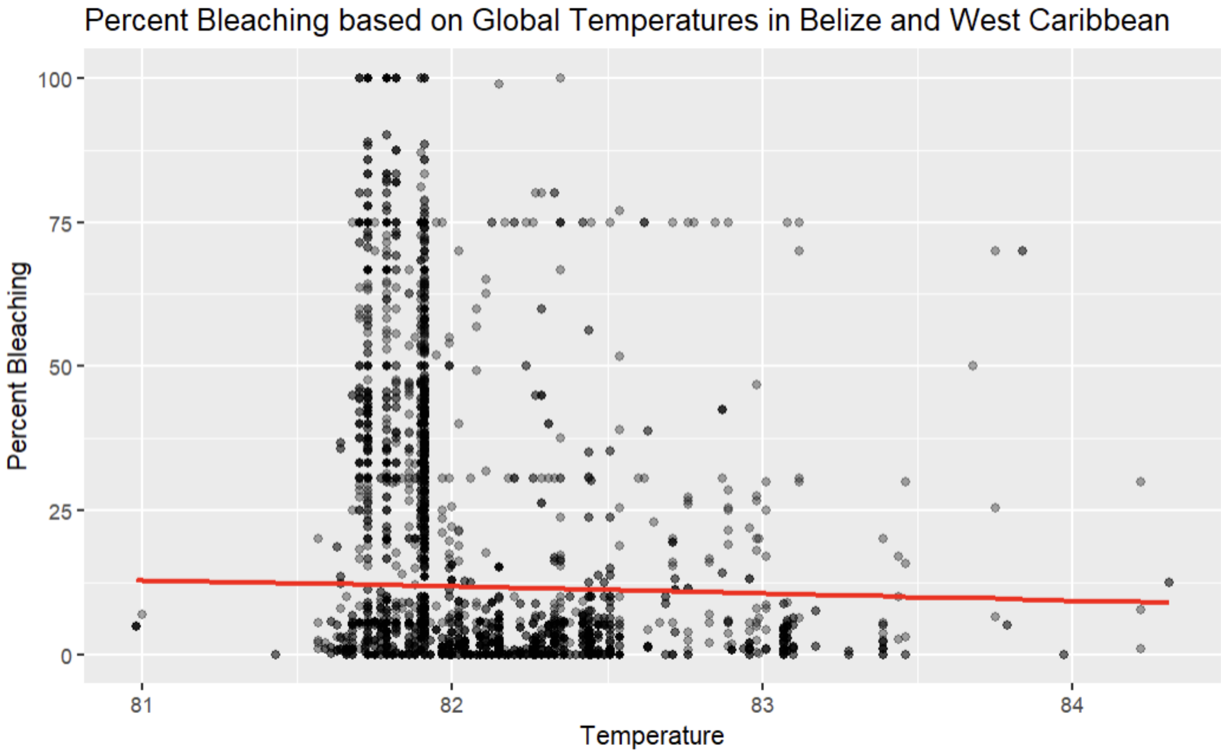

Figure 10: Linear regression of percent bleaching and global temperatures In Belize and West Caribbean.

3.3 Is there a relationship between distance to shore and the levels of bleaching?

For this question, I sought out to see if the distance of coral reefs to shore is a good predictor variable for bleaching levels. My hypothesis was that the farther reefs are from land, the less susceptible they are to coral bleaching due to less exposure to human activity. I created linear models using Distance_to_Shore as my predictor for Percent_Bleaching. I also made quadratic models, logistic models, and splines. Lastly, I attempted these models on data only ranging from 2010 to 2023 and on specific eco-regions, those being the Bahamas and Florida Keys, Belize and West Caribbean, Hispaniola Puerto Rico and Lesser Antilles, Sulu Sea, Central and northern Great Barrier Reef.

Unfortunately, most of these models were not a good fit for the data and there were few significant results. This may be due to the fact that most of the distance to shore data is close to 0 and it is hard to create models on data that is very condensed. However, the overall model with all of the data had a p-value of $p < 0.001$ and a low r-squared, which signified a relationship but no explanation for the variation of the model. The linear regression can be found in Figure 11, this model shows that as the distance to shore gets larger, the higher percentage of coral bleaching. This can be due to data inconsistency and a lot more data available for reefs that are farther from shore. This was also true for the models of the eco-regions, Belize and the West Caribbean, Hispaniola Puerto Rico and Lesser Antilles, and central and northern Great Barrier Reef.

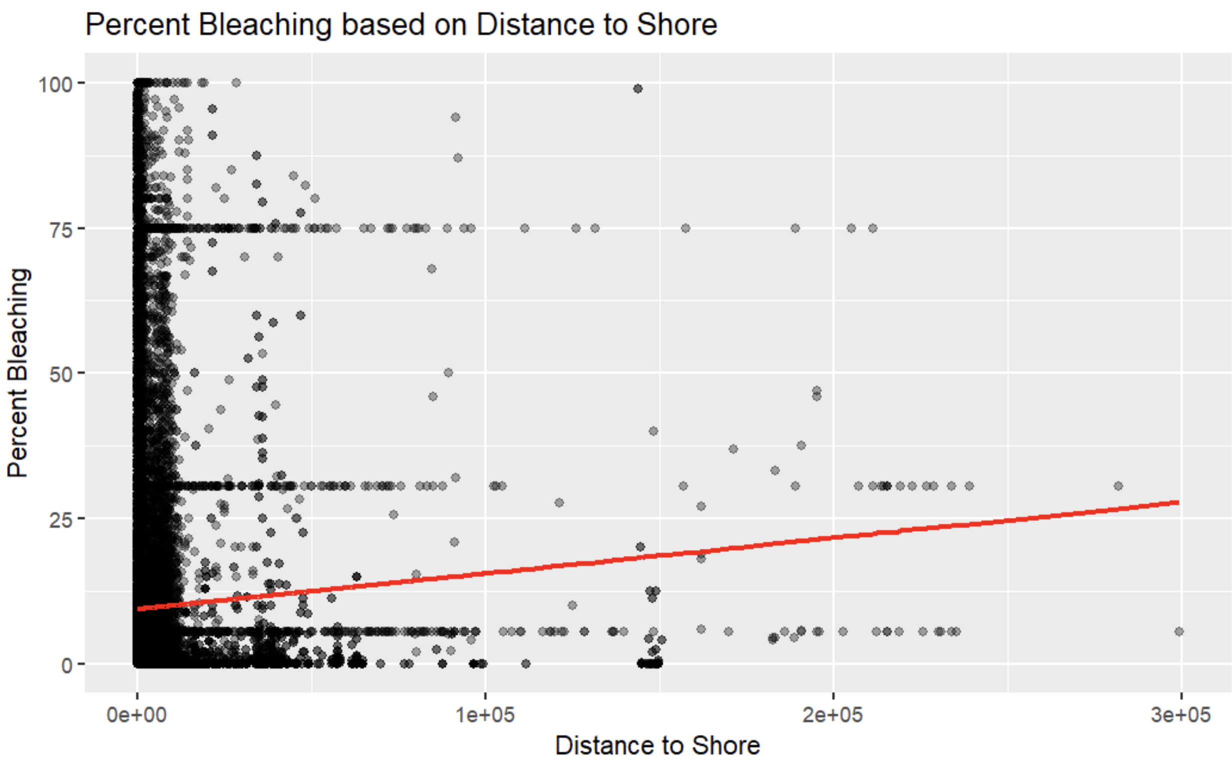

Figure 11: Linear regression of percent bleaching and distance to shore.

3.4 Is there a relationship between depth and the levels of bleaching?

For this question, I was trying to see if the depth of the coral reefs had any relationship with the levels of bleaching. My hypothesis was that the deeper the coral was, the less bleaching levels there were. I created linear models using Depth_m as my predictor for Percent_Bleaching. I also made quadratic models, logistic models, and splines. None of these models had any significance and this is likely due to most of the data points being between 0 and 25 meters with outliers in the 50-meter range. However, the r-squared value, while still being close to 0 at 0.027, was farther to 0 than observed in the previous questions, where the values were extremely close to 0. This still means that there is no statistical significance of depth and bleaching levels having a correlation, and the model can be found in Figure 12.

Similarly to my other questions, I attempted these models on data only ranging from 2010 to 2023 and on specific eco-regions. I found there to be only two models that showed any type of correlation. The model using the observations coming from the eco-region, Belize and West Caribbean, had a p-value of $p < 0.001$ and an r-squared value of 0.06. The p-value indicates that there is a significant correlation between depth and coral bleaching levels in this area. The r-squared value, however, is low which indicates that the model doesn't strongly explain the variation. This also occurred with the model based on the eco-region Hispaniola Puerto Rico and Lesser Antilles, where there was a significant p-value but a low r-squared.

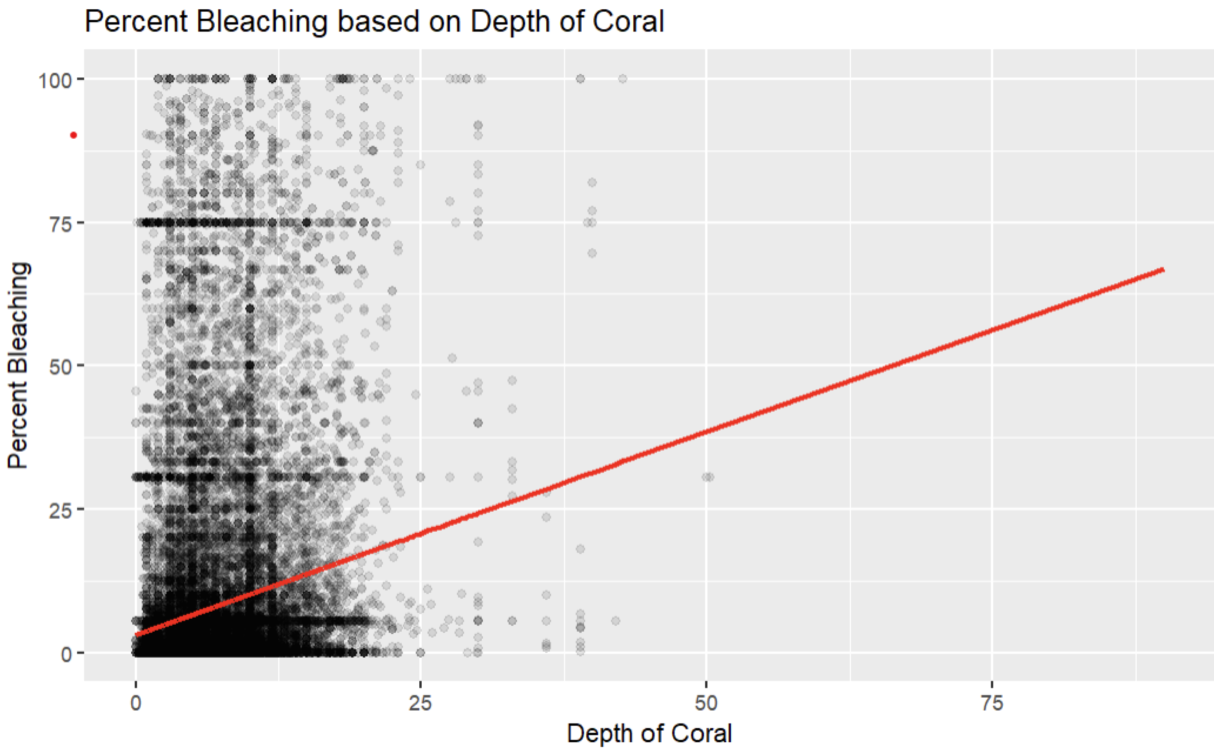

Figure 12: Linear regression of percent bleaching and depth.

3.5 Multi-variable models to predict bleaching events

After not finding any significant results from any of the previous models I decided to create multi-variable models using the variables Depth_m, Distance_to_Shore, and Temperature_Mean as predictors for Percent_Bleaching. Due to the large amount of data that all of these combinations would create, I split the data into 6 sections using the function seq_range, which gave a total of 216 values for the model visualizations. The p-value of the model was $p < 0.001$ but the r squared was low which shows that there is a significant relationship but a very small one. The linear, quadratic, spline, and logistic models had no significant results. As you can see in Figure 13, as depth increases and temperature decreases the predictions for percent bleaching get lower. This is the expected result as higher temperatures and lower depths would be susceptible to coral bleaching. It is also important to note that each regression is based on a different distance to shore and as the distances get larger the relationships get stronger.

Next, I removed outliers in the variables that measured depth and temperature to see if this would create a better model, which can be found in Figure 14. I only utilized depths of 25 and below and temperatures of 75 and above. Even after removing these outliers, I did not see an improvement or vast differences in the fit of the model.

Lastly, I explored a new variable in my data, Exposure which consists of three categories: Exposed, Sometimes, and Sheltered. The variable is an observation of the coral area's exposure level. I made a model using Exposure and Temperature_Mean as the predictors for Percent_Bleaching. I got the same results as in the previous multi-variable model with a p-value of $p < 0.001$ and a low r-squared variable, which ultimately means there is a relationship but no explanation for variation, and the

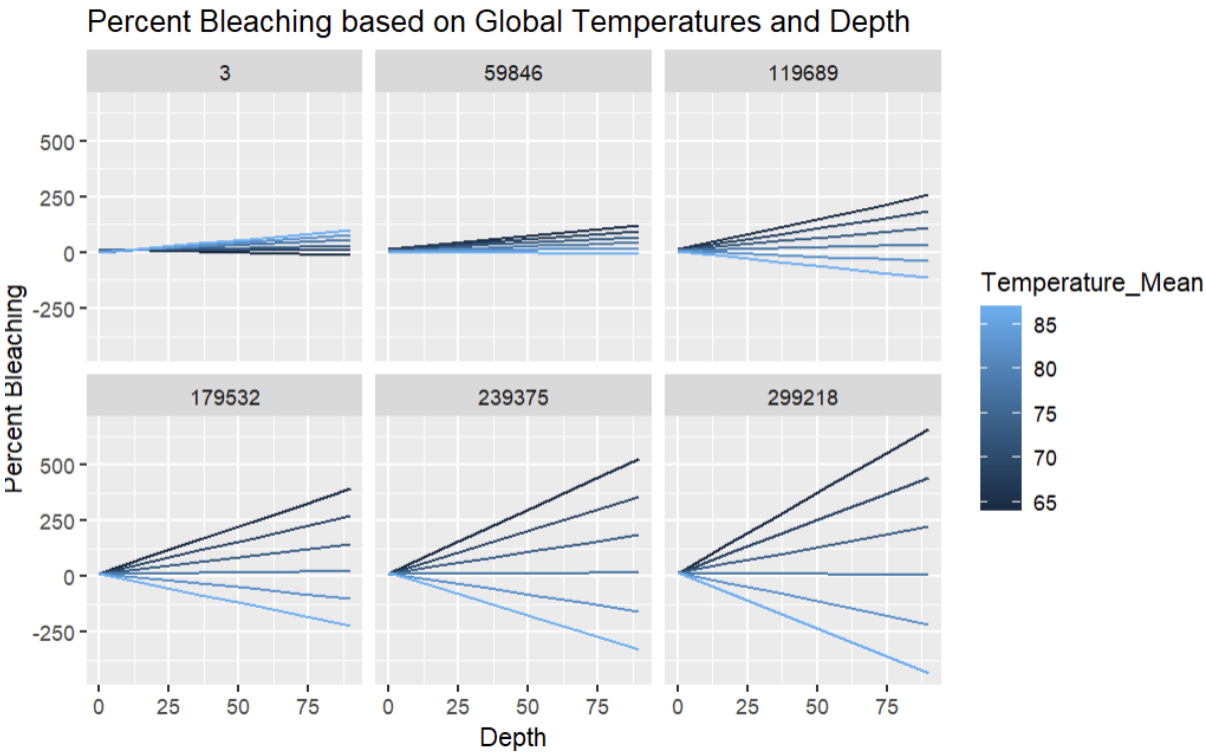

Figure 13: Linear regression of percent bleaching based on depth and temperature with different facets of distance to shore

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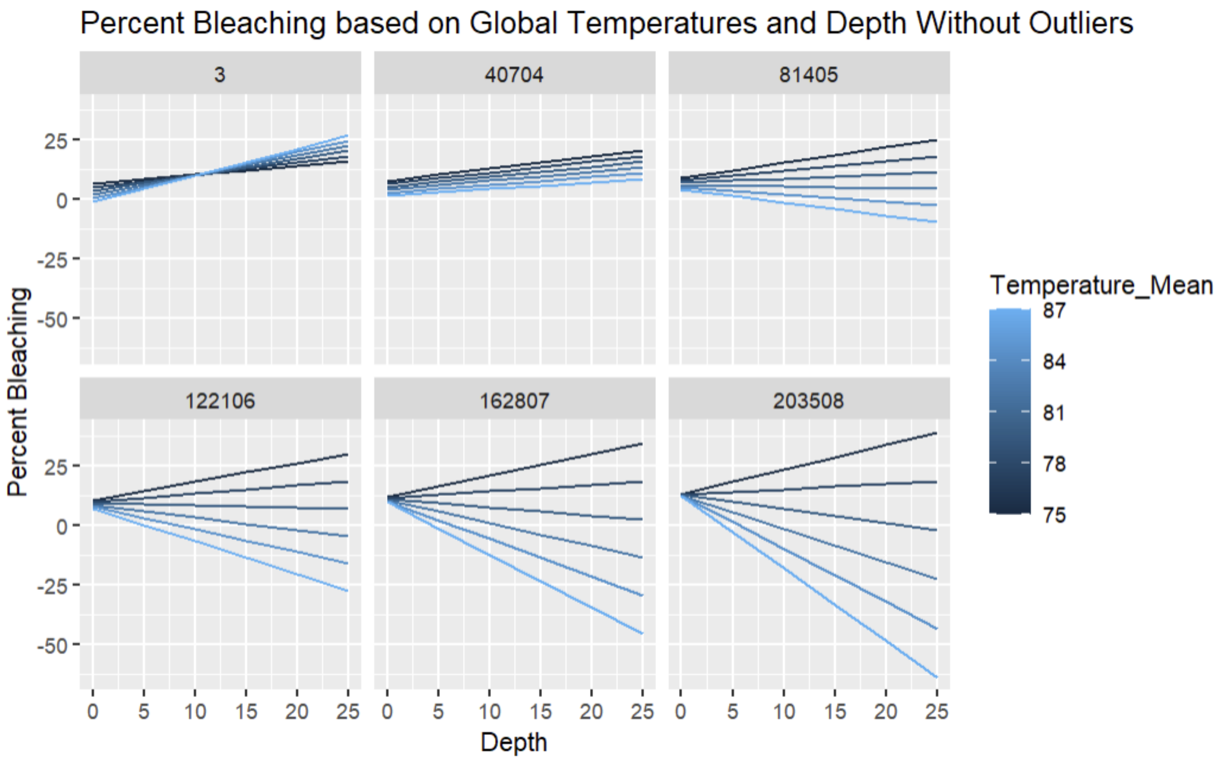

Figure 14: Linear regression of percent bleaching based on depth and temperature after removing outliers with different facets of distance to shore.

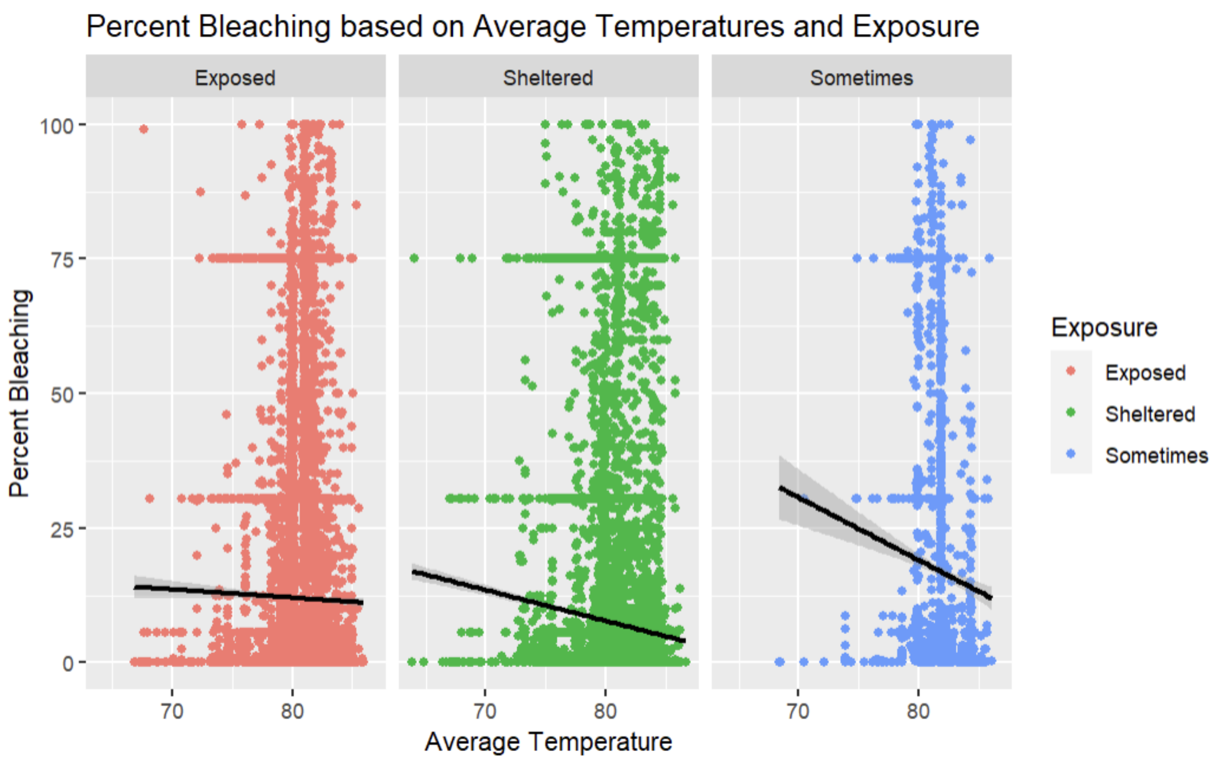

Figure 15: Linear regression of percent bleaching based on temperature and exposure.

linear model can be found in Figure 15. Seemingly, the linear regressions are not a good fit for the data.

3.6 Broward County case study

For my final exploration, I used the Mortality data set to filter out reefs found in only Broward County, which is a county in south Florida on the Atlantic side. There were 6 different reefs found in Broward County in different areas, and their locations can be found in Figure 16. Secondly, I gathered data on the mean temperatures in Broward County from another data set and merged it with the subset of mortality data in Broward County. I made a linear regression and found that there is a slight positive relationship between temperature and Mortality levels in Broward County, as seen in Figure 17. Although the linear visualization seems to point to a significant relationship between temperature and mortality percentage, the r-squared value was low, which signifies an unreliable model. I did not have access to the depth of the reefs and could not model this relationship.

4 Discussion

In this section, I will discuss observations made from my analyses, the reliability of my models, limitations, and short-term and long-term next steps.

4.1 Observations

In my first exploration, I found that most bleaching events occur in the Pacific Ocean and Atlantic Ocean and in the eco-regions Bahamas and the Florida Keys, Belie and West Caribbean, Hispaniola Puerto Rico, and the Lesser Antilles. I also explored which locations had the most mortality events over the years. These ended up being Florida, Kaneohe Bay, Saint Thomas, Saint Croix, and the Florida Keys. It is interesting to note that with the exception of Kaneohe Bay, these countries and eco-regions are all in the area surrounding Florida and the Caribbean. The bleaching and mortality events that these areas have been experiencing have been happening as early as the 1980s. Although these are just recorded observations, it could be something worth looking into, to find why this area is so susceptible to coral bleaching and coral mortality. However, it is important to note that this could be that there have been more recorded observations in these areas in comparison to other regions

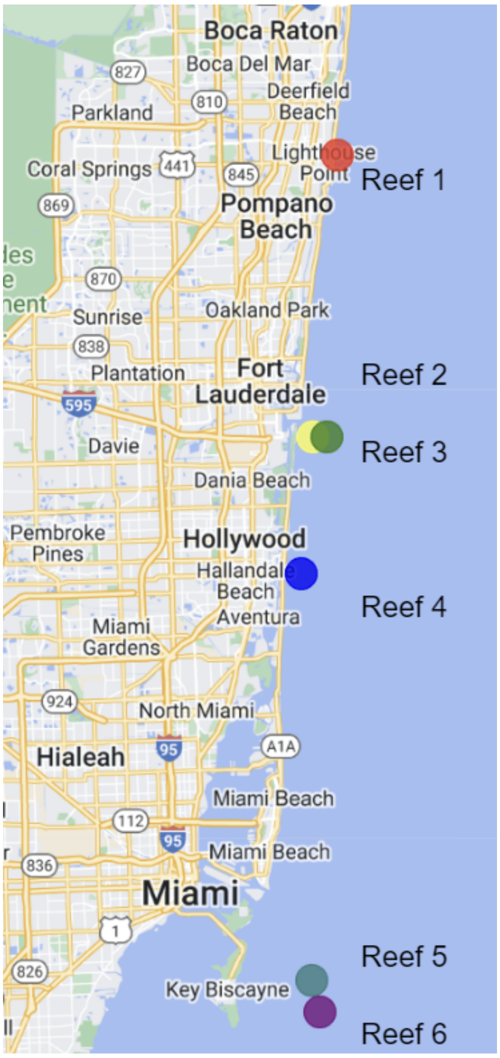

Figure 16: Locations of the 6 reefs in Broward County.

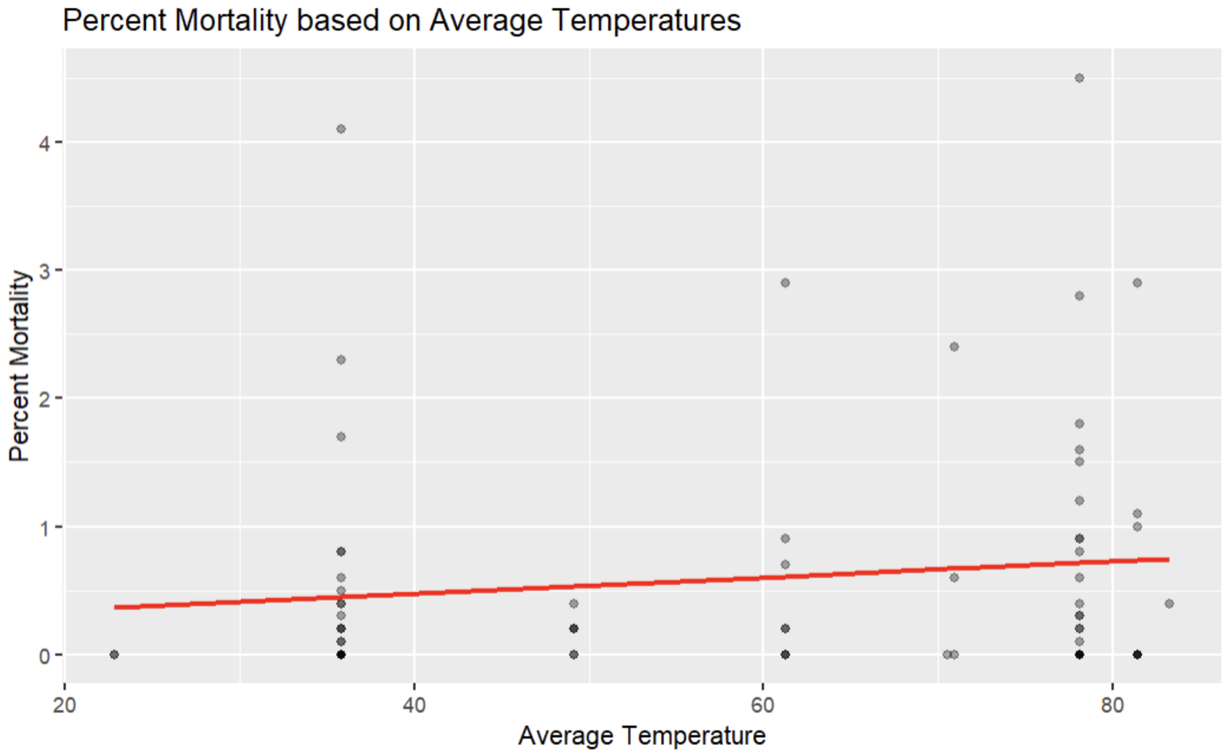

Figure 17: Linear regression of percent bleaching based on temperature in Broward County.

of the world. This may be due to a lack of resources or researchers in other areas.

4.2 Model reliability

Overall, most of the models I created display significant relationships but that doesn't necessarily mean that the models are reliable and can provide an explanation for any of the variations between the variables. The models were not good fits for most of the data, as the data seemed to be very random and condensed at certain points. We can not make any conclusions or confirm any hypotheses with the models.

4.3 Limitations

There were various limitations in the data. The data set is not very consistent and has a lot of gaps within years, months, and locations. This may be to a lack of researchers in those areas or within those time frames or just that there was no data to observe in these gaps. A lot of the data was collected from different sources and compiled into one data set, this can cause issues in the quality and format of the overall data set. Extreme outliers in the data in variables such as distance to shore and temperatures also pose a problem with model reliability. There were many NA values and inputs that made no sense that I had to remove from the data set as well. I also had a time constraint of one semester as a full-time college student, which did not allow me to explore everything I would have wanted to.

5 Conclusion

5.1 Key takeaways

Coral reefs experience coral bleaching due to various factors which can lead to coral mortality if the bleaching is over a long period of time. Global warming has a very large impact on coral bleaching events, as well as other things such as human activity and extreme weather. In my study, I explored various questions and observations found in two different data sets. I found which regions had the most bleaching and mortality events and also explored the relationships between various variables and the percent bleaching of coral. Although none of the models I created were significant and reliable, there were many observations made in which areas had the most bleaching events, and also how the bleaching events increased and decreased throughout the years. Many of the eco-region models had low p-values and low r-squared values, so we can not make any strong conclusions about the models or the direction of the relationships.

5.2 Further work

If I or anyone else were to continue this research, I would recommend using other variables in the data set such as sea surface temperatures, windspeeds, and cyclone frequencies as a short-term step. For someone pursuing a longer project, I would look at smaller regions in the data, possibly using latitude and longitude, and create models using different variables of these smaller regions. The relationships between predictor variables and the percent bleaching of coral may be easier to find in smaller data sets or more specific data.

The Broward County case study can be further explored by searching for more data since I only had access to data from 2005 and 2006. A long-term step I would take to further explore this case study is to find more mortality data and explore the relationships between more variables in the data set such as %_BLEACHED_RAW and %_MORTALITY_RAW. With more time I would also try to find more observational data such as depths, distance to shore, and exposure for each reef. For a short-term exploration, I would make a model using the mortality percentages and use variables such as depth, distance to shore, or extreme weather from the global bleaching data set as my predictors.

Overall, it is very important that research continues on global warming and coral bleaching and that efforts increase to work on these environmental issues.

References

[1] Cities and climate change. *UN Environmental Programme.*

[2] Coefficient of determination, r-squared. *Numeracy, Maths and statistics - academic skills kit.*

[3] Coral bleaching. *Great Barrier Reef Foundation.*

[4] Coral bleaching events. *AIMS.*

[5] Generating power. *United Nations.*

[6] Great barrier reef mass bleaching event. *NASA.*

[7] How does climate change affect the ocean? *Natural History Museum.*

[8] Nick Bradford. A warming ocean.

[9] Simon D. Donner, Gregory J. M. Rickbeil, and Scott F. Heron. A new, high-resolution global mass coral bleaching database. *PLOS ONE*, 12:1–17, 04 2017.

[10] Tyler D. Eddy. Global decline in capacity of coral reefs to provide ecosystem services.

[11] et al. James C. Crabbe, Bessat F. Climate change, global warming and coral reefs: Modelling the effects of temperature. *Computational Biology and Chemistry*, May 2008.

[12] Steven Koppes. Central pacific coral reef shows remarkable recovery despite two warm-water events. *Scripps Institution of Oceanography*, Jul 2022.

[13] Rebecca Lindsey. Climate change: Global sea level. *NOAA Climate.gov*.

[14] Smithsonian Magazine. The planet has lost half of its coral reefs since 1950. *Smithsonian.com*, Sep 2021.

[15] Simon Urcelay, Donner. High resolution global mass coral bleaching dataset version 2.0. June 2022.

[16] National Oceanic US Department of Commerce and Atmospheric Administration. What is ocean acidification? *NOAA's National Ocean Service*, Aug 2012.