HIGH SCHOOL EDITION
Journal of Student Research
Volume 12 Issue 4 (2023)

Assessing the Impact of Climate Change on Characteristics of Tropical Cyclones in Houston, Texas

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ABSTRACT

The objective of this research is to utilize a computational model to assess the impact of climate change on tropical cyclones in the Houston, Texas area. In recent years, it has been observed that tropical cyclones have become more destructive, increasing in intensity and frequency. The current body of knowledge on tropical cyclones has indicated the significant role that climate change plays in the worsening of tropical cyclones. This research focused on studying the characteristics of tropical cyclones potentially affected by climate change in the Houston, Texas area, stemming from the researcher's firsthand experience of Hurricane Harvey which occurred in August of 2017. Nine global climate models were studied and incorporated into a MATLAB computational program in this research to generate a total of 9,000 synthetic tropical cyclones with and without climate change for comparison purposes. The various characteristics of tropical cyclones were analyzed based on the output of the MATLAB program. A comparison of these characteristics yielded the conclusion that climate change plays a key role in increasing the likelihood of destructive characteristics of tropical cyclones. Therefore, it is likely that future tropical cyclones in the Houston, Texas area will demonstrate an increased risk severity, causing more harm to people and more damage to local society. It is highly recommended that future research should focus on mitigation strategies for the Houston, Texas area to reduce the consequence of tropical cyclones and prevent the situation of Hurricane Harvey from reoccurring.

Introduction

Hurricane Harvey

In August of 2017, Hurricane Harvey, one of the most severe hurricanes that the United States has experienced, struck Houston, Texas. Figure 1 illustrates Hurricane Harvey's disastrous effects on the Houston, Texas area. Based on government statistics, Hurricane Harvey costed society nearly 125 billion dollars in damage, alongside 68 civilian deaths, making it the second costliest hurricane in United States history from an economic perspective (*Hurricane Costs*, n.d.). Furthermore, the aftermath of the storm included the displacement of many families and individuals. The impact Harvey had on the infrastructure and people led the recovery of society from this disaster to last for years. Due to the unexpected nature of Hurricane Harvey (given that Hurricane Katrina had only occurred 11 years prior within the same region), it will be beneficial for society to analyze aspects of hurricanes that may reoccur in the future to increase preparedness and develop strategies to protect lives and reduce losses.

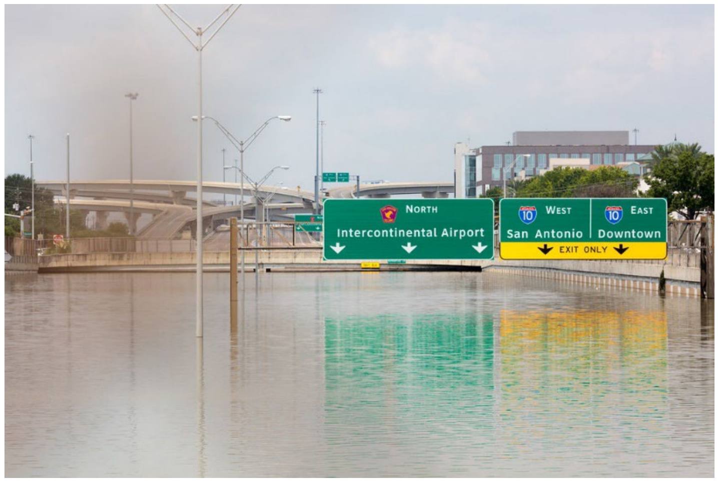


Figure 1. Photo of the Houston area during Hurricane Harvey

Tropical Cyclones

Tropical cyclones are generally referred to as 'hurricanes' in the Atlantic Ocean, so for this academic paper, the terms 'tropical cyclone' and 'hurricane' will be used interchangeably. Tropical cyclones are classified as rotating systems of clouds that form over tropical or subtropical waters (*Tropical Cyclone Climatology*, n.d.). The types of tropical cyclones, which include tropical depressions, tropical storms, hurricanes, and major hurricanes, are classified based on wind speed. Extensive research on tropical cyclones has been conducted to analyze various aspects of these storms, including the study of historical records and the prediction of future events.

Over the past few decades, observations conclude that tropical cyclones have increased in intensity and occurred at more frequent intervals. For instance, 30 hurricanes out of the top 52 economically costliest hurricanes since the year 1900 in the United States have happened between the years 2000 to 2023 (*Billion-Dollar Weather and Climate Disasters*, 2023). Studying the characteristics of tropical cyclones will better prepare society for future storms by allowing various strategies to be implemented to reduce the consequence of tropical cyclones.

Literature Review

Previous research indicates that three main factors contribute to the rise in society's vulnerability to tropical cyclones: economic growth, coastal population growth, and climate change.

Economic Growth

First, economic growth within a region essentially means an increase in economic assets. This increase in economic assets will lead to greater vulnerability of more valuable resources and people within that region. According to meteorology and climate scientists, rapid economic growth and development will cause cities to experience a heavier and more damaging impact due to tropical cyclones (Zhang et al., 2013). Urbanization is one main indicator of economic growth. Researchers specializing in spatial analysis state that urbanization is accompanied by industrialization which reinforces economic growth (Di Clemente et al., 2020). Examining trends in the percentage of people living in urban areas illustrates the population growth in urban areas over time. The data from the World Bank shows that in the year 2010, the percentage of the total population living in urban areas in the United States was 80.77% and in the year 2020, it increased to 82.5%. The projected percentage of the urban population in the United States will reach nearly

90% in the year 2050, confirming a very high level of urban growth in the near future (*United States - Urbanization 2020*, 2022). The escalating rate of urbanization will result in an accumulation of both economic assets and the population in the region, leading to a significant rise in the vulnerability of society as the damage caused by storms will have a larger toll, both economically and socially.

Coastal Population Growth

Second, humans are naturally more attracted to coastal cities. Therefore, many megacities have formed in coastal locations, which typically experience more severe and frequent tropical cyclones (Neumann et al., 2015). In fact, as of the year 2018, nearly 40% of the United States population lives in coastal cities, so those populations are constantly subjected to increased risk from tropical cyclones (*What Percentage of the American Population Lives Near the Coast?*, n.d.). Moreover, according to the United States Census Bureau, since the year 2000, there has been significant population growth along the coastline in the United States. From 2000 to 2017, the population has increased by approximately 13.2% in the Atlantic coastline region, 26.1% in the Gulf of Mexico coastline region, and 13.5% in the Pacific coastline region, with a 15.7% increase in all coastal areas (U.S. Census Bureau, 2021). It is apparent that an increase in coastal populations will endanger considerably more citizens during tropical cyclones. This conclusion is supported by Illinois State climatologist and water survey chief Stanley Changnon, who suggests that the escalation of urban sprawl and the growth of the population has caused those in cities susceptible to tropical cyclones to be at even greater risk (Changnon, 2010).

Climate Change

Climate change is the third factor leading to the increasing vulnerability of humans and infrastructure to tropical cyclones. A hurricane's wind speed, pressure, and rainfall are all impacted by climate change, which causes an increase in damage in local regions. Climate and data science researchers Ranson et al. (2014) summarized the relationship between the estimated damages due to tropical cyclones and climate change. They concluded that "approximately 90% of North Atlantic tropical cyclone predictions [and] 91% of Western North Pacific tropical cyclone predictions" show growing destruction by tropical cyclones caused by climate change (Ranson et al., 2014). Additionally, meteorologists have used the concept of return periods to examine the likelihood of extreme weather events with specific intensities occurring within the next year. An event with a 100-year return period has a 1/100 = 1% chance of occurring each year, which can be approximated to roughly one event of a specific intensity occurring within 100 years. The return period of tropical cyclones has generally decreased due to climate change. An example of a characteristic of tropical cyclones that demonstrated decreasing return periods is the total rainfall. Meteorologist and climate scientist Kerry Emanuel predicted that the current return period for tropical cyclones with at least 500 mm of rainfall in Texas is about 100 years when previously it had a return period of 2000 years in the late 20th century (Emanuel, 2017). Lastly, hurricane tracks, or the path a hurricane travels, also change due to climate change.

A cornerstone source that inspired this research was based on analyzing and predicting the rain return periods for events with Hurricane Harvey's amount of rainfall in the future (Emanuel, 2017). A key finding of the study has been discussed above. Emanuel concluded a sixfold increase in the probability of large amounts of rainfall during tropical cyclones, which provided extensive context and background information for this research. Emanuel also developed an important methodology including downscaling synthetic tropical cyclones from climate models, which will be described in detail later in this paper.

Considering the increase in damage by tropical cyclones leads to the research question of this study: will climate change influence the characteristics of tropical cyclones leading to higher intensity and frequency of future tropical cyclone events in the Houston, Texas area? The hypothesis proposed in this research is that climate change will increase the intensity and frequency of tropical cyclones in the Houston, Texas area.

The gap identified by the literature review is the relevant research focusing on the location of the Houston, Texas area. The body of knowledge on tropical cyclones is vast and contains research in various locations and aspects. However, the Houston, Texas area specifically needs more attention due to the previous severe consequences of Hurricane Harvey in this region. In addition, Houston is the fourth-most populous city in the United States and the potential damage caused by a severe hurricane would be catastrophic for the area if local society is not well prepared. Although there has been previous research done on rainfall in the Houston, Texas area, there has not been any research analyzing the characteristics of tropical cyclones with the consideration of climate change while focusing on the Houston, Texas region.

Conducting research on the gap described previously will lead to a better understanding of what strategies city governments and citizens in Houston should implement to prepare for severe hurricanes in the future. Specific plans to mitigate the threat from hurricanes should be developed and executed based on predicted storm intensity and frequency. Furthermore, becoming aware of the risks and likelihood of future tropical cyclones will allow resources to be allocated to enforcing policies and building infrastructure in a timely manner.

Methods

The methodology of this research is illustrated in the flowchart presented in Figure 2. The methods will be explained in detail in the following section.

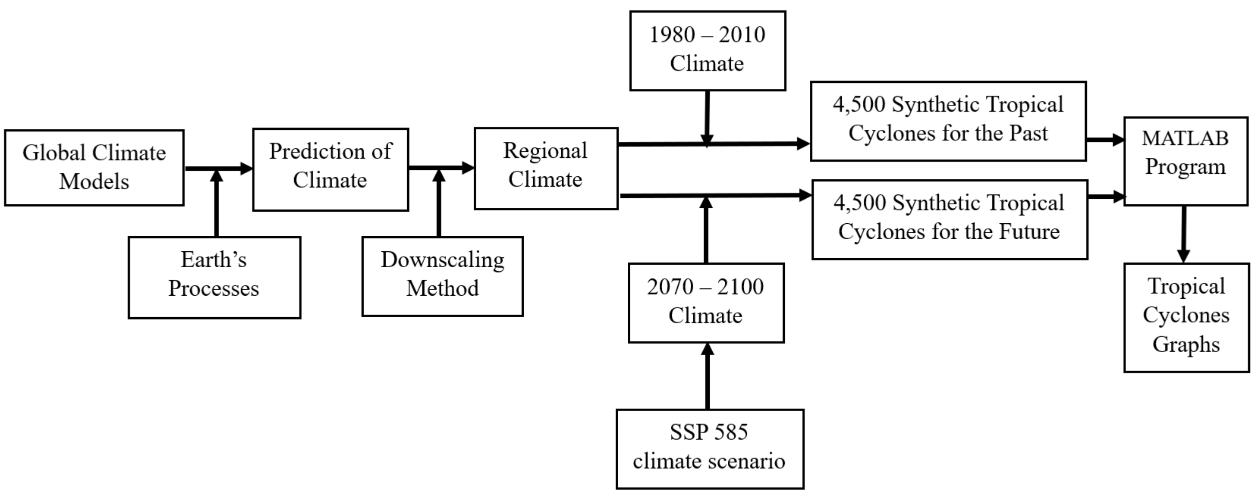


Figure 2. An overview of the methods used in this research

Global climate models have been utilized in this study to simulate climate change in the future. These climate models incorporate information from Earth's processes to generate a system that simulates various climates. Nine popular climate models were examined in this research: the Canadian Earth System Model (CanESM), Centre National de Recherches Météorologiques (CNRM), European Centre Earth (EC Earth), Geophysical Fluid Dynamics Laboratory (GFDL), Hadley Centre Global Environment Model (HadGEM), Institut Pierre Simon Laplace (IPSL), Model for Interdisciplinary Research on Climate (MIROC), Max Planck Institute (MPI), and United Kingdom Meteorological Office (UKMO). These nine global climate models are commonly referenced in research on global climate change by universities and research institutes, so they were chosen for this particular study. Global climate models are generally effective in simulating large-scale atmospheric circulation, however, the resolution is too coarse to provide the same amount of accuracy for hurricanes. Therefore, a downscaling method was implemented to produce synthetic hurricane tracks. Downscaling is a function that narrows the scope of the location of study by applying global climate patterns to a local or regional level, which significantly increases the resolution and accuracy for simulating tropical cyclones.

Typically, if there are adequate records, one might choose to use data from historical events. However, in many locations, such as the Houston, Texas area, there are simply not enough historical records on tropical cyclones to produce precise results. Within the Houston, Texas area, from the 20th century to the 21st century, only around 30 tropical cyclones occurred and could be used for potential analysis. There is also a notable lack of extreme hurricanes, which is often necessary to include in predictions due to society's concern for predicting more dangerous storms. A sample size of 30, or an even smaller sample for extreme hurricanes, is too small to make accurate generalizations or analyze trends within the data. Moreover, using hurricane data from years earlier than the 20th century might result in inaccuracies, due to the data being based on eyewitness accounts or less accurate means of measurement. To increase the precision of the results, synthetic tropical cyclones, also known as artificial tropical cyclones, were generated in this research instead of using the historical records of tropical cyclones. These synthetic tropical cyclones include all characteristics of real tropical cyclone events, including a hurricane track, or the path a hurricane travels. Synthetic tropical cyclones are formed using a combination of ocean models and a pre-existing hurricane model. Each cyclone is assigned a random seed and then input into calculations to simulate the characteristics of the storms.

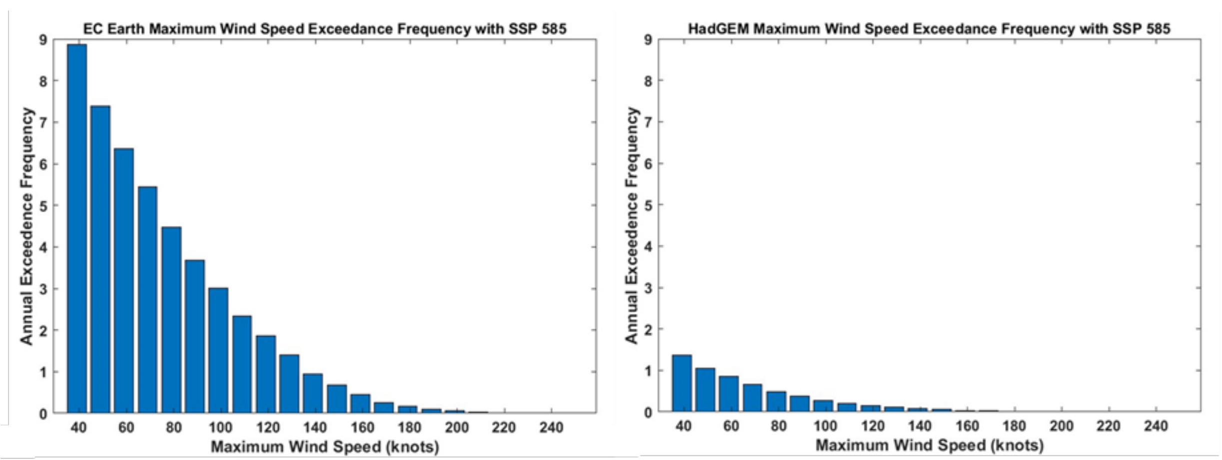
For each climate model, 4,500 synthetic tropical cyclones were generated from the years 1980 to 2010 using a global climate model and climate data respective to those years. 4,500 separate synthetic tropical cyclones were generated using the SSP 585 climate scenario under the same global climate model from the years 2070 to 2100. The synthetic tropical cyclones from the years 1980 to 2010 do not take climate change into account, while the synthetic tropical cyclones from the years 2070 to 2100 incorporate climate change through the implementation of the SSP 585 climate scenario. The years 2010 to 2070 are not considered because the purpose of this research is to provide a comparison between the historical climate and the effects of climate change on tropical cyclones in the far future, which reduces the need to include those years. SSP, or Shared Socioeconomic Pathway, scenarios are included to predict the socioeconomic conditions of the Earth up to the year 2100. Out of the 5 SSP climate scenarios, the SSP 585 climate scenario was chosen for this research. The SSP 585 climate scenario is characterized by "[f]ossil fueled development", with an 8.5 watt per meter squared increase in radiative forcing by the year 2100 (Harrisson, 2021). Radiative forcing, a measurement that is heavily affected by changes in greenhouse gas emissions, is the difference between the amount of the Sun's energy entering the Earth's atmosphere and the amount of the Sun's energy exiting the Earth's atmosphere (*Radiative Forcing*, n.d.). The scenario can be further described as society experiencing "an intensified exploitation of fossil fuel resources with a high percentage of coal and an energy-intensive lifestyle worldwide" (*The SSP Scenarios*, n.d.). The SSP 585 climate scenario was selected due to its similarities with a possible future of the Earth that is characterized by the growth of fossil fuels. Lastly, the tropical cyclones were put into a computational model in MATLAB to summarize various characteristics of the tropical cyclones. MATLAB is a programming language used for computational models and data analysis, making it a good fit for this study.

To focus on a smaller region, only points within 500 kilometers of Houston, Texas were considered in this research. Restricting the area of study reduces bias, potential errors, and variance, as points further away from the point of interest may demonstrate differing trends from points closer to the point of interest. Four characteristics of tropical cyclones that represent the levels of intensity and frequency in storms were focused on for analysis in this research: maximum wind speeds, wind speed return periods, rainfall return periods, and storm frequencies.

The method of implementing global climate models and generating tropical cyclones has been utilized by researchers in the past who wanted to simulate and predict future extreme weather events. As mentioned in the literature review, the method in this research focused on tropical cyclones in the Houston, Texas area and was inspired by the methods used by Emanuel (2017) in his research on rainfall return periods.

Results

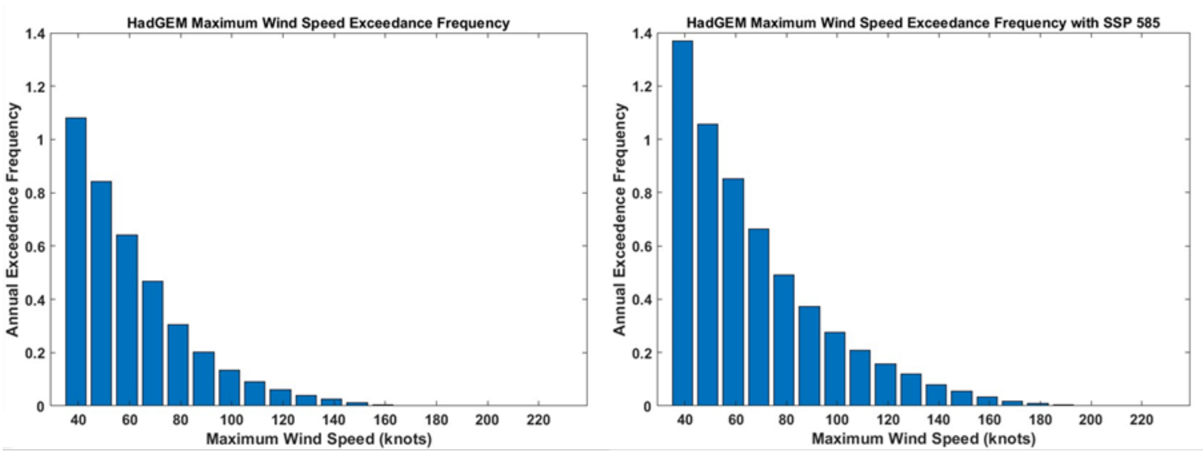
The MATLAB program was implemented to compute the various characteristics of tropical cyclones based on the nine global climate models. After reviewing the results from the various models, the Hadley Centre Global Environment Model, also known as HadGEM, was selected to compare the characteristics of tropical cyclones for this research. In general, the HadGEM model produced less extreme results compared to the other eight climate models that may have the potential to create biased results, i.e. over or underestimation. For instance, the European Centre Earth Model (EC Earth) contained many overestimated values that were significantly different from the predictions by the rest of the models. Figure 3 compares the EC Earth climate model with the selected HadGEM climate model for the maximum wind speed annual exceedance frequencies. The annual exceedance frequency in this data illustrates the number of times that a maximum wind speed during a tropical cyclone will be exceeded within one year. Figure 3 (a) shows an annual exceedance frequency of nearly 9 for a cyclone with a maximum wind speed of 40 knots, based on the EC Earth climate model. However, Figure 3 (b) indicates an annual exceedance frequency of 1.4 for a cyclone with a maximum wind speed of 40 knots, based on the HadGEM climate model. These results imply that the EC Earth model predicts a frequency of 9 cyclones per year with a maximum wind speed exceeding 40 knots, while the HadGEM model only predicts a frequency of 1.4 cyclones per year with a maximum wind speed exceeding 40 knots. The comparison exemplified an overestimation from the EC Earth model, which was consistently observed throughout the other characteristics of tropical cyclones studied. This situation also occurred in the other climate models, therefore, HadGEM was selected for this study, since it tended to be the median or center value of all the predictions generated by all the climate models.



(a) (b)

Figure 3. A comparison of the EC Earth climate model and the HadGEM climate model for the annual exceedance frequencies of the maximum wind speeds with the SSP 585 climate scenario

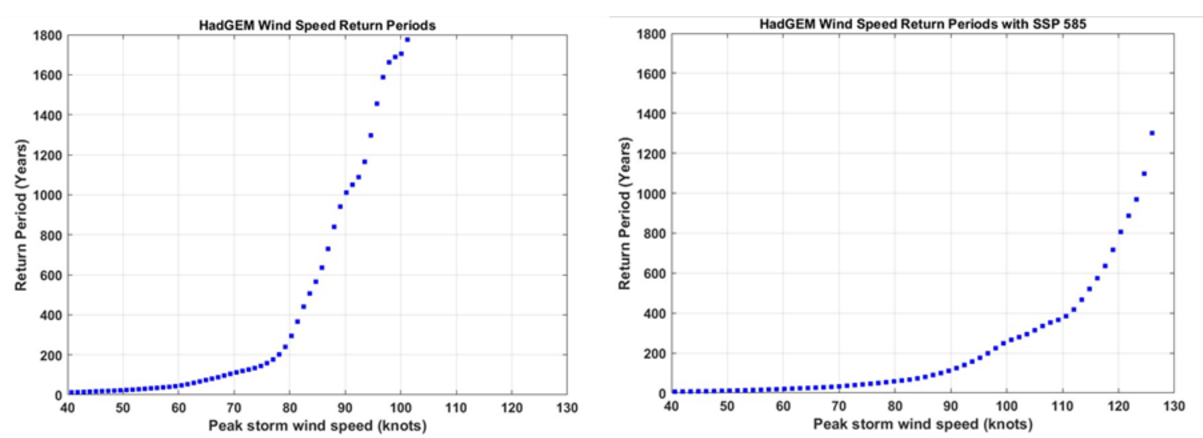
As described above, Figures 4 to 7 are based on the selected HadGEM climate model. The first characteristic examined was the annual exceedance frequency of maximum wind speeds of tropical cyclones. Figure 4 (a) and (b) both demonstrate an inverse relationship between maximum wind speed and annual exceedance frequency, however, there is a visible difference between the exceedance frequencies of the wind speeds regarding the historical synthetic tropical cyclones (as shown in Figure 4 (a)) and the climate change-induced synthetic tropical cyclones (as shown in Figure 4 (b)). For every maximum wind speed on the climate change induced tropical cyclones, there is a greater annual exceedance frequency when compared with the tropical cyclones without climate change. To illustrate this difference, a maximum wind speed of 100 knots in a tropical cyclone generated around a 0.2 annual exceedance frequency when climate change is considered (as shown in Figure 4 (b)) and it generated only around a 0.1 frequency for historical years (as shown in Figure 4 (a)). The increase in annual exceedance frequencies when climate change is considered indicates that future storms will only increase in frequency for higher wind speeds, which in turn, increases the damage and intensity.



(a) (b)

Figure 4. A comparison of the annual exceedance frequencies of the maximum wind speeds using the HadGEM climate model with and without the SSP 585 climate scenario

Next, the wind speed return periods for the peak wind speed of a storm were analyzed. As discussed previously, return periods describe how likely an extreme weather event is to occur at or above a specific intensity within a time frame, which in this case is one year. Both Figure 5 (a) and (b) indicate a positive, exponential relationship between peak storm wind speed and return period (note: the exponential scale has been used on the y-axis to fit most data points). A comparison between Figure 5 (a) and (b) exhibits a decrease in return periods for peak wind speeds. For example, if there is a peak storm wind speed of 80 knots, the tropical cyclones from the year 1980 to the year 2010 (as shown in Figure 5 (a)) would generate a return period of around 300 years, whereas the synthetic tropical cyclones from the future years 2070 to 2100 (as shown in Figure 5 (b)) would generate a return period of around 60 years. This is a significant decrease in the length of the return periods, demonstrating that there is an increased probability of higher peak storm wind speeds occurring in the future, caused by climate change.



(a) (b)

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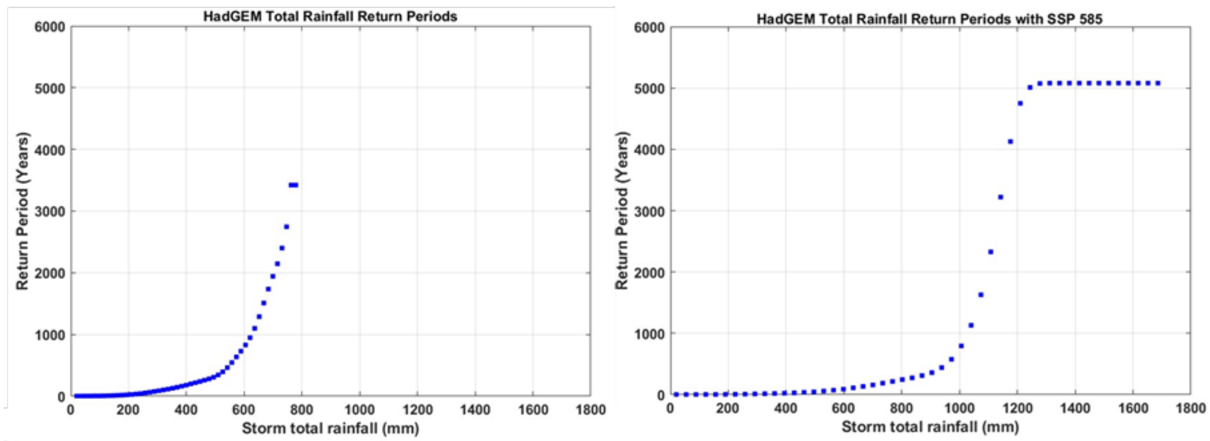
Volume 12 Issue 4 (2023)

Figure 5. A comparison of the return periods of the peak wind speeds using the HadGEM climate model with and without the SSP 585 climate scenario

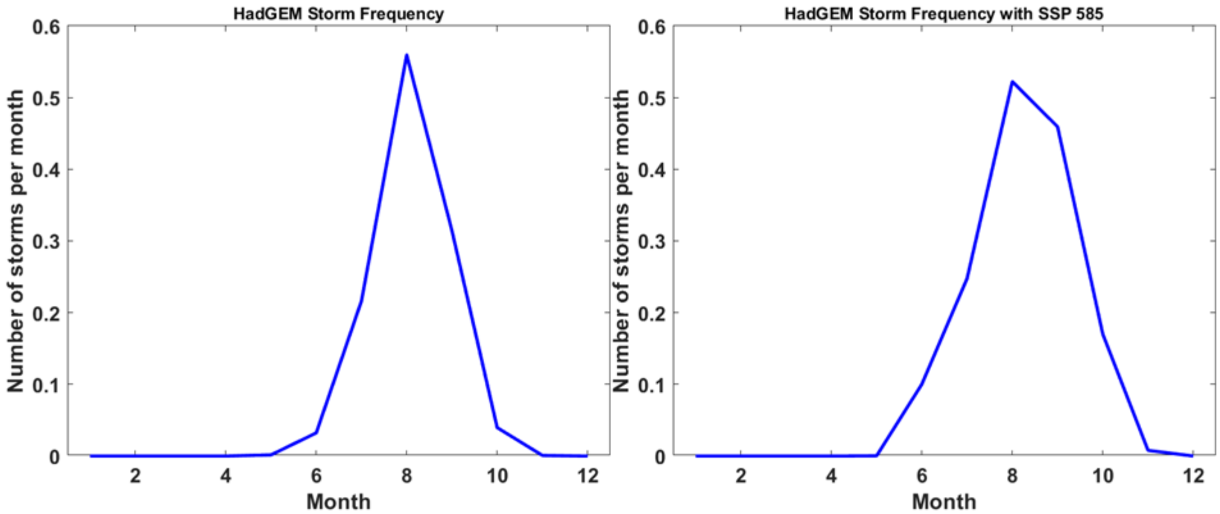
The return periods of the total rainfalls with and without climate change followed a similar trend as the return periods of the peak wind speeds: a significant decrease in return periods for the same amount of rainfall between the two sets of data. As seen on the graph with the historical synthetic tropical cyclones (as shown in Figure 6 (a)), storms that had a total rainfall of 800 mm were pretty much unheard of, as those storms would have a return period of around 3000 years. This changes when climate change is applied, as a 500 mm total rainfall historical tropical cyclone (as shown in Figure 6 (a)) would have the same return period as a 1000 mm total rainfall tropical cyclone when climate change is considered (as shown in Figure 6 (b)), which is a return period of around 1000 years. This illustrates climate change's impacts on the amount of rainfall in the future, as there are higher chances of greater precipitation. An interesting point to note in Figure 6 (b) is that the return periods of the storm's total rainfall plateaus to a return period of 5000 years near the total rainfall of 1250 mm. This indicates that a total rainfall of above 1250 mm is nearly impossible to occur in the future.



(a) (b)

Figure 6. A comparison of the return periods of the total rainfall using the HadGEM climate model with and without the SSP 585 climate scenario

Lastly, the data regarding the frequency of storms occurring by month was examined. The Atlantic hurricane season typically occurs from June to November. The results from the climate modeling and prediction as seen in Figures 7 (a) and (b) indicate little difference regarding the number of storms per month, except for specific months, such as September and October. Both graphs show the same peak of the frequency of storms around August in both cases, with a storm frequency of around 0.5 to 0.6 for both. It can be noted that the scope of time during which tropical cyclones occurs has widened in Figure 7 (b), as mentioned previously around September to October, which may be attributed to climate change.



(a) (b)

Figure 7. A comparison of the number of storms per month (storm frequency) using the HadGEM climate model with and without the SSP 585 climate scenario.

Discussion

The results of the research have validated the hypothesis described previously. There is indeed a significant difference in the characteristics of tropical cyclones due to climate change: society can expect more frequent storms with higher maximum winds and total rainfalls, as concluded from Figure 4, Figure 5, and Figure 6, as well as a wider range of months that storms could occur during, as shown in Figure 7.

Two main findings have been discovered from this research. First, in the future, storms in the Houston, Texas area will increase in destructiveness and create greater damage due to higher probabilities of more dangerous characteristics of storms occurring, such as stronger winds, higher storm surges, and heavier rainfall. Storm surges are changes in water levels caused by winds in oceans due to a tropical cyclone. From an analysis of the data, it can be concluded that there are shorter return periods for higher maximum wind speeds and higher total rainfalls, which contribute to the catastrophic impacts of tropical cyclones. Second, it can be concluded from the results that climate change plays a key role in this intensification, according to the impact of climate change on the studied characteristics of tropical cyclones in the Houston, Texas area.

A limitation of this study is the use of synthetically generated tropical cyclones. Although these tropical cyclones are generated based on well-developed climate models, it is understandable that tropical cyclones are complex environmental phenomena and it is extremely challenging to precisely model all characteristics of tropical cyclones with or without the consideration of the climate change scenario. Also, the location of Houston is a narrow area of study. The results of this research may not be 100% applicable to other areas affected by tropical cyclones. Further replication of this study using other climate models or methods to generate synthetic tropical cyclones may be beneficial to reduce the probability of confounding variables and validate the results of this study.

Conclusion

Tropical cyclones are complex environmental phenomena that can have a significant impact on local society. Back in 2017, Hurricane Harvey costed the Houston region nearly 125 billion dollars in damage and 68 civilian deaths. The objective of this research was to utilize a computational model for assessing the impact of climate change on tropical cyclones in the Houston, Texas Area. Nine global climate models were studied and incorporated into a MATLAB computational program in this research to generate a total of 9,000 synthetic tropical cyclones with and without climate change for comparison purposes. The various characteristics of tropical cyclones were analyzed based on the outputs of the MATLAB program. A comparison of these characteristics yielded the conclusion that climate change plays a crucial role in increasing the likelihood of destructive characteristics of tropical cyclones. Therefore, it is likely that future tropical cyclones in the Houston, Texas area will demonstrate an increased risk severity, causing more harm to people and more damage to local society. It is highly recommended that future research should focus on mitigation strategies for the Houston, Texas area to reduce the consequence and risks of tropical cyclones and prevent the situation of Hurricane Harvey from reoccurring.

In addition, this research provides important insight into various trends for the future that can be applied to places around the world affected by tropical cyclones. Future research directions may consider the factor of urbanization, which influences the magnitude of the impact of tropical cyclones. Area-specific mitigation strategies need to be developed after considering the results of this study. For instance, strategies such as implementing building codes to protect important infrastructure or building storm walls to minimize flooding can be incorporated into government policies to reduce the severity of hurricanes (Aerts et al., 2014). In the future, it is also important to consider how to raise awareness in society, so that people can be emotionally prepared for potential tropical cyclone events. Regardless of what methods or strategies society chooses, society must take action now in order to better prepare for the future impacts of tropical cyclones on urban areas.

Acknowledgments

I would like to express my sincere gratitude to my research mentor, Professor Kerry Emanuel, a Professor Emeritus from the Massachusetts Institute of Technology (MIT), for his guidance and motivation to me throughout my research project. As one of the 100 most influential scientists named by *Time* Magazine in 2006, Professor Emanuel has always been very patient in answering all of my questions, teaching me how to access the climate models and run MATLAB simulations during this research experience. I am very grateful that Professor Emanuel has inspired me to carry on his passion and curiosity for scientific research in the future. Additionally, thank you to Mr. Frishman for teaching me and always supporting my research. Mr. Frishman has taught me how to have a researcher mindset and allowed me to truly enjoy the research process.

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