The Impact of Climate Change on Tropical Cyclone Damages

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Abstract

This paper constructs an integrated assessment model of tropical cyclones in order to quantify the additional damage that climate change might cause by 2100 around the world. The paper begins with the A1b SRES emission trajectory from the Intergovernmental Panel on Climate Change (IPCC). The trajectory approaches a stable concentration of greenhouse gases of about 720ppm by 2100. This emission trajectory is used in four general circulation climate models: CNRM, ECHAM, GFDL, and MIROC. The climate models are used to predict hurricanes in the 1980-2000 climate and the 2180-2200 climate. The models predict a range of future global temperature changes from 2.9°C to 4.5°C. The climate outcomes from these models are then fed into a regional climate model that is capable of predicting hurricane behavior in each ocean basin.

A tropical cyclone generator creates potential hurricanes randomly in each basin for both the current climate and the future climate. The model follows these storms across each ocean and determines which storms develop into hurricanes and which do not. A total of 17,000 tropical cyclones are generated in each of the 8 climate scenarios (current and future climate with each of 4 climate models). The model does a reasonable job of predicting the frequency, intensity, and location of the hurricane distribution observed in the current climate.

We detect the influence of climate change by comparing the results of current predicted hurricanes versus future predicted hurricanes. Except in the GFDL scenario which predicts a

doubling of hurricanes, the frequency of hurricanes is not predicted to change because of warming. However, in the western North Atlantic and the western North Pacific, hurricane intensity consistently increases in all four climate scenarios. In the other ocean basins, the change in hurricane intensity is inconsistent, sometimes increasing and sometimes decreasing across the climate scenarios. Whether climate change has an effect on hurricane intensity in the other basins is therefore highly uncertain.

This paper advances on the underlying science of hurricanes by examining the damages that hurricanes might cause. Beginning with observed hurricanes and observed levels of damages, the paper calculates a damage function of tropical cyclones. Using US data, the study calculate a relationship between storm damages and storm intensity. The analysis confirms earlier results suggesting a highly nonlinear relationship between storm intensity and storm damages. The study finds that the minimum pressure of a storm is a better predictor of damages than maximum wind speed (the measure used in the damage literature). Using international data, the study then examines the link between storm damages and the characteristics of the affected areas. The study finds that damages increase with both income and population density as expected. However, damages increase less than proportionally with both variables contrary to assumptions made by previous authors.

Current predicted tropical cyclone damages are then calculated using the current income and population density of each country and the distribution of tropical cyclones predicted in the current climate. Damages are calculated for each storm that is predicted to strike each country or come close enough to cause significant damage. The expected value of damages is adjusted to equal the observed damages in each country over the last 20 years. The global damages from tropical cyclones are currently $26 billion (0.043 percent of Gross World Product (GWP)).

The analysis then calculates what damages would occur if income and population density were to increase as projected by 2100. Given the projected growth rates for each country, damages are calculated again using the current distribution of tropical cyclones. Global damages are projected to double to $55 billion just because of the increase in income and population in each country. Damages increase faster in Asia because of the projected faster growth rate of income in that region. Tropical cyclones damages as a fraction of GWP are expected to fall by 2100 to 0.01 percent of GWP because damages increase less than proportionally with income.

The final step in the analysis is to compute the effect of climate change. The damages from the future economy with storms from the current climate are compared to the damages from the future economy with storms from the future climate. Warming doubles the global damage caused by tropical cyclones. Warming causes an additional $54 billion of damage per year (0.01 percent of GWP). Looking across the different climate models, warming increases damages between $28 and $68 billion/yr.

The effects are not uniformly felt across the world. The increase in storm intensity in the North Atlantic and North Pacific lead to substantial damages in the northeastern edge of the Western Hemisphere and in the eastern edge of Asia. The United States, China, and Japan account for 88 percent of the expected global damages. The countries with the biggest damages as a percent of GDP are predominantly small islands in the Caribbean.

Warming also changes the distribution of damages. With current climate, the top 10% worst storms (measured by damage) cause 90% of the total damage and the top 1% worst storms cause 58% of the damage. With the future climate, the top 10% worst storms cause 93% of the damage and the top 1% of storms cause 64% of all the damage.

Further work is required to fully understand how to adapt to tropical cyclones. There are three mechanisms that cause damage: storm surge, high winds, and flash flooding. Further research is needed to predict the consequences of each of these mechanisms and how different adaptation strategies might change the distribution of damages. The fact that so much of the damages are concentrated in rare (once in a century or millennium) but very powerful events makes adaptation difficult.

Capsule

Climate science and economics are combined to estimate the future tropical cyclone damages from economic growth and from climate change.

Main Text

I. Introduction

Tropical cyclones (hurricanes, typhoons) have become an icon of climate change. Scientists report an increase in tropical cyclone intensity over the last 30 years[1,2] and a dramatic increase in tropical cyclone damages over time[3,4]. And yet despite these findings, the link between climate change and tropical cyclone damage remains controversial. Tropical cyclones are rare events and appear to be subject to long term variability so it is difficult to detect changes in underlying frequencies and severity[5]. The people and assets in harm's way is also increasing over time, which may explain the trend in tropical cyclone damage[6,7,8]. The historic record may simply not be long enough and clear enough to detect how climate may be affecting tropical cyclones.

The average current global damage from tropical cyclones is $26 billion per year[9]. A tropical cyclone model predicts there will be an increase in tropical cyclone intensity in the Atlantic Ocean[10]. Using this average change in intensity, several authors predict that damage will double[11,12,13] .

This paper takes a different approach that captures the full range and distribution of tropical cyclones to estimate the impact of climate change on the damages caused by tropical cyclones. The paper relies on an integrated assessment that combines the insights of a hurricane generator with the consequences of a damage model. Beginning with an emissions trajectory, four climate models predict future climate scenarios. A tropical cyclone generator is then used to seed potential storms in each ocean basin[10]. The storms are then permitted to develop given the conditions predicted by each climate model. A total of 17,000 storms are generated with and without climate change. The model is able to capture the different outcomes in each ocean basin and measure how storm intensity and location changes. For each storm, a damage model is then used to predict the damages upon landfall.

The analysis begins by forecasting how current baseline damages from tropical cyclones would change because of future increases in what is in harm's way. From this future baseline, we then evaluate the effects of climate change. We predict how the change in tropical cyclones generated by the current versus future climate affect damages. The analysis captures changes in the frequency of storms, the landfall of storms, and the intensity of storms. The analysis carefully controls for what is in harm's way before estimating the impact of climate change. The results provide the first geographically detailed estimates of how storm damages change around the world.

The next section of the paper describes the methodology in more detail. The empirical findings of the paper are then reviewed in Section III. The paper concludes with a review of the major findings and some policy observations.

II. Theoretical Methodology

The economic damage (*D*) from each tropical cyclone is the sum of all the losses caused by it. In this analysis, we focus on economic damages primarily from lost buildings and infrastructure. In order to model tropical cyclones, it is critical to recognize that they are rare events and depend on the frequency or probability (π) of each storm in each place. The characteristics (*X*) of each storm are also important. Damages also depend upon where the tropical cyclone strikes (*i*). Atmospheric science can help predict the probability a tropical cyclone (*j*) with particular characteristics (*X*) will strike each place (*i*) given the climate (*C*):

$$\pi_{ij} = \pi(X_{ij}, C) \tag{1}$$

The actual damage associated with any given tropical cyclone (*j*) also depends on the vulnerability (*Z*) of each place (*i*):

$$D_i = D(X_i, Z_i) \tag{2}$$

The expected value of tropical cyclone damages is:

$$E[D] = \sum_j \sum_i \pi(X_{ij}, C) D(X_i, Z_i) \tag{3}$$

Because the damage function is highly nonlinear, the expected damage is the sum of the damages caused by every storm. It is very important to model the entire distribution of damages in order to capture the true effect of tropical cyclones.

The damage caused by moving from the current climate C0 to a future climate C1 is the change in the expected value of the damages:

$$W = E[D(C1)] - E[D(C0)] \quad (4)$$

For any given time period, climate change could change damages because the frequency, intensity, or the location of storms change. In this study, we compute tropical cyclone damages in each country of the world and then aggregate the results to larger regions. Country specific results are reported in Appendix A.

Equation 4 calculates the expected welfare loss from climate change. We also calculate the return rate for storms causing each level of damage. This is a relationship between the average years between tropical cyclones that cause specific amounts of damage:

$$return = 1 / prob(D) = g(D(X)) \quad (5)$$

Policy makers may be interested in the return rate because it provides information about the distribution of damages. Insurers would also be interested in the return rate because it provides information about how much catastrophic insurance to buy.

III. Methodology

The integrated assessment predicts tropical cyclone damages given different climates. The analysis relies on the A1B SRES emission scenario generated by the Intergovernmental Panel on Climate Change[14]. The emission scenario assumes that mitigation is tightened gradually over time so that greenhouse gas concentrations finally peak and stabilize at 720 ppm.

We rely on four climate models: CNRM[15], ECHAM[16], GFDL[17], and MIROC[18]. Each climate model predicts both the current climate and the climate in 2100. CNRM predicts a global warming of 2.9°C, ECHAM predicts 3.4°C, GFDL predicts 2.7°C, and MIROC predicts 4.5°C. These changes in climate raise sea surface temperatures which in turn fuel the tropical cyclones. However, there are other changes such as wind shear and humidity that can affect tropical cyclone intensity. In addition, changing atmospheric winds can alter the tracks of tropical cyclones.

Using a tropical cyclone generator in each ocean basin, the climate data is used to project tropical cyclone tracks[10]. A total of 17,000 tropical cyclone tracks are generated across the five oceans with and without climate change for each climate model (8 sets of 17,000 tropical cyclones). For each track, we follow where the tropical cyclone makes landfall or passes close enough to land to create damage. The minimum barometric pressure and the maximum wind speed at landfall of each storm are recorded. The hurricane generator also predicts the expected frequency of tropical cyclones in each ocean basin.

Figure 1 presents a sample of the tracks generated in each ocean basin. The figure reveals that there is a zone just north and south of the equator where the storms are the most intense. As storms veer off to middle and high latitudes, they tend to lose power.

Figure 2 shows the changes in power by ocean basin attributable to climate change. Power consistently climbs in the North Atlantic and the North Western Pacific ocean basins across all four climate models. These predicted changes in tropical cyclone power will especially influence damages in North America and eastern Asia respectively. Changes in the other ocean basins are not consistent across the climate models.

A damage function is then estimated to predict the damages that each storm will cause. The coefficient for storm intensity was estimated using aggregate damages per storm and storm characteristics at landfall from US storms since 1960[19]. This historic data was matched with coastal population density and income[20] near landfall. The log-log regressions in Table 1 reveal the elasticities of each variable with respect to damage. The first two columns using US data reveal that damages are a highly nonlinear function of wind speed and minimum barometric pressure. The regressions also reveal that minimum pressure provides more accurate estimates of damages than maximum wind speed. It is likely that minimum pressure is a better predictor of storm intensity because it is difficult to measure maximum wind speed accurately. The literature relies solely on wind speed to measure damages[11,12,13,21].

The third column of Table 1 presents a damage regression using international data[9]. Damages increase with income but fall with population density. The elasticities of these variables are significantly less than 1 (contrary to assumptions in the literature[6,8,11,12]). Storm damages consequently do not rise proportionally with income or population.

Given the empirical results above, the preferred damage function has the following form:

$$D = A_D * MP^{-86} Y^{0.06} Pop^{-0.2} \qquad (6)$$

The expected damages for each country were calculated by summing the product of the probability of each storm times the damage it causes for each country. Storm damages are truncated so that they cannot exceed the complete destruction of all the capital in the five counties near landfall. The parameter A_D is calibrated for each country so that the damage from the current predicted set of storms striking each country equal the observed damage in recent history.

IV. Results

The annual observed global damage from tropical cyclones is $26 billion (0.043 percent of GWP)[9]. Our first task is to project how these damages would increase with future economic growth, holding climate constant. Both population and income are projected to 2100. The population in each country is assumed to follow projections that lead to a global population of 9 billion[22]. GDP is assumed to grow an annual rate of 2 percent in developed countries, 2.7 percent in developing countries, and 3.3 percent in emerging countries. Dividing GDP by population yields a future prediction of income per capita for each country in 2100. The damages from the set of storms given current climate are then recalculated using the damage function and future levels of population density and income. With future baseline conditions in 2100, the global expected damage more than doubles to $55 billion per year (0.01 percent of GWP). Damage grows more slowly than GDP because the coefficients on income and population in the damage function are less than 1.

In order to calculate the impact of climate change, a new set of tropical cyclones is generated given the 2100 climate predicted by each of the climate models. The impact of climate change is the difference in damages caused by the new set of cyclones versus the original set of cyclones. Both measures of damage use future economic conditions. By evaluating the impact of climate change using future conditions rather than current conditions, the impacts are larger because more is in harm's way in the future. Damages are computed from all 17,000 storms before and after climate changes.

The results reveal that climate change by 2100 is expected to cause tropical cyclone damages to increase $54 billion/yr (a 100% increase above the future baseline). This additional damage is equal to 0.01 percent of GWP. Looking across the different climate models, damages rise between $28 and $68 billion/yr. These aggregate global results are very consistent with most of the findings in the literature that climate change would double tropical cyclone damages.

However, the new results reveal that the distribution of damages is not even across the world. Figure 3 displays the damages caused by climate change in each continent. Asia and North America are the two continents that are consistently predicted to be damaged by warming across all four climate models. The increased intensity of North Atlantic and Western Pacific storms are causing these effects. The additional damage in North America is equal to $30 billion/yr and the additional damage in Asia is equal to $21 billion. The additional storm damage in the rest of the world is just $3 billion. For some regions and models, the damages from tropical storms actually fall with warming.

Figure 4 displays climate change tropical cyclone damages as a fraction of GDP in 2100. The figure illustrates how burdensome the change in tropical storm damage will be to the economies in each region. The global average damage per unit of GDP is 0.01 percent. North America (0.03 percent of GDP) and Asia (0.01 percent of GDP) have the largest additional impacts per unit of GDP. The tropical cyclone damages per unit of GDP caused by climate change are low in the remaining continents.

The continental averages, however, hide disproportionate effects in individual countries. Damages to all affected countries and each model are shown in Appendix A. The countries with the largest average impacts from climate change are the United States ($30 billion), Japan ($9 billion), and China ($8 billion). The damages from these three countries account for 88 percent of the global damages. The impacts are above 0.2 percent of GDP only in Antigua-Barbados, Cayman Islands, Dominica, Grenada, Honduras, Montserrat, St. Kitts-Nevis, Turks-Caicos, and the US Virgin islands. All but Honduras is an island in the Caribbean.

Although expected damages reveal long term damages, they hide changes in the distribution of damages. Figure 5 displays the relationship between damage and return rates for the GFDL climate scenario. The results for the other climate scenarios are similar. The figure reveals that common small storms are not different before and after climate change. Climate change increases the intensity of large storms. With the nonlinear damage function, this increased intensity translates into a significant increase in damages. The return period for the most powerful storms becomes shorter.

A surprisingly large fraction of the expected damages of tropical cyclones is caused by the most harmful storms. With current climate, the top 10% worst storms (measured by damage) cause 90% of the total damage. The top 1% worst storms cause 58% of the damage. With the future climate, the top 10% worst storms cause 93% of the damage and the top 1% of storms cause 64% of all the damage.

V. Conclusion

This study constructs an integrated assessment model to predict the tropical cyclone damages caused by climate change. The paper relies on a tropical cyclone generator and four climate models to predict thousands of tropical cyclones with and without climate change. The results indicate that tropical cyclone intensity will consistently increase in both the North Atlantic and North West Pacific ocean basins but not in the other ocean basins. The study then estimates a damage function associated with tropical storms from United States and international data. The analysis suggests that minimum pressure provides a more accurate measure of storm intensity than maximum wind speed and that damages are a highly nonlinear function of storm intensity. The results also suggest that damages increase with income but less than proportionally.

Increasing future income and population is predicted to increase annual tropical cyclone damages from $26 billion to $55 billion even with the current climate. However, damages as a fraction of GWP are expected to fall from their current rate of 0.04 percent in 2010 to 0.01 percent in 2100.

The impact of climate change is expected to double the damages from tropical cyclones by 2100 by $54 billion. This is equal to 0.01 percent of GWP. The estimated impact of climate change ranges from $28 to $68 billion depending on the climate model. The findings confirm the rough results of earlier tropical cyclone studies that relied on cruder methods.

The damages, however, are not evenly spread across the planet. Because tropical cyclones in the North Atlantic and North West Pacific Oceans consistently increase in intensity with warming, North America and eastern Asia have the largest and most consistent impacts. The average impact in Asia is an additional damage of $21 billion and the average impact in North America is an additional damage of $30 billion. Damages to the United States, Japan and China account for 88% of global damage. Climate change causes small damages in the rest of the world because the remaining continents see both small harmful and beneficial impacts depending on the climate model. Even controlling for GDP, North America and eastern Asia bear the highest damages per unit of GDP. However, the most vulnerable countries are relatively small Caribbean islands.

The results reveal that the damages from tropical cyclones are quite skewed. Even with the current climate, the 10 percent worst storms (measured by damage) account for 90 percent of the total damage. With warming, these powerful storms get even more harmful and the 10 percent worst storms account for 93 percent of the total damages. These especially large storms explain most of the damages caused by climate change and yet they occur very rarely. It may well take several centuries of observations to see whether the changes predicted in this paper actually have occurred.

There are many uncertainties associated with the forecasts made in this study. The emission path of greenhouse gases is highly uncertain because it depends upon the long term growth of the economy, the long term relationship between GDP and energy, and mitigation policies that may be adopted over the next century. The relationship between climate change and greenhouse gas concentrations is also quite uncertain as revealed by the results from the four climate models. Exactly how tropical cyclones will react to climate change is also uncertain as it depends upon many factors that are difficult to predict. The magnitude of the damages that future tropical storms will cause is uncertain. The damages with respect to storm intensity are very sensitive to minimum pressure and to the elasticity of population and especially income. Better international records of storm tracks and intensities and storm damages would help increase the accuracy of these estimates. How damages might change if there is both a change in tropical cyclones and sea level rise is uncertain (although they may be just additive[23]).

Finally, how society will adapt to tropical cyclones in the future is not yet clear. Currently, many countries have mal-adaptation policies that make matters worse by encouraging assets to remain or be placed in harm's way. For example, subsidizing flood insurance and capping the cost of catastrophe insurance makes it cheaper to live in risky locations. Even providing emergency disaster relief reduces the overall cost of developing a risky location. Reducing the implicit subsidies in these policies and actively discouraging development in risky locations could reduce damages significantly. In contrast, physical protection strategies such as building sea walls may be ineffective as protection against tropical cyclones. Most of the damage is caused by rare but very powerful storms. Walls would have to be very high to prevent inundation. These would be hard to justify if powerful storms are very infrequent at each location (once in a thousand years). Developing effective adaptation strategies to tropical cyclones is an important policy and research topic.

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Figure and Table Captions

Table 1: Regressions of Tropical Cyclone Damages

Figure 1: Storm tracks by minimum pressure (mb)

Figure 2: Change in Tropical Storm Power by Ocean Caused by Climate Change

Figure 3: Climate Change Impacts on Tropical Cyclone Damages by Region by 2100

Figure 4: Tropical cyclone damage in 2100 as a fraction of GDP

Figure 5: Return period in 2100 by US damage for ECHAM

Table 1: Regressions of Tropical Cyclone Damages

	US	US	International
Constant	12.19 (1.42)	607.5 (10.39)	15.17 (22.77)
Log (Wind Speed)	4.95 (7.83)	…	…
Log(Minimum Pressure)	….	-86.3 (9.96)	….
Log(income)	0.903 (0.96)	0.370 (0.45)	0.415 (6.44)
Log(Population Density)	0.458 (1.28)	0.488 (1.53)	-0.210 (3.04)
Adj Rsq	0.371	0.501	0.158
F Statistic	22.61	35.76	103.2
Observations	111	111	807

Note: T-statistics in parentheses. The functional form of the regression is log log. Source of US data is NOAA 2009 and the source of the international data is EMDAT 2009.

Figure 1 Storm tracks by minimum pressure (mb)

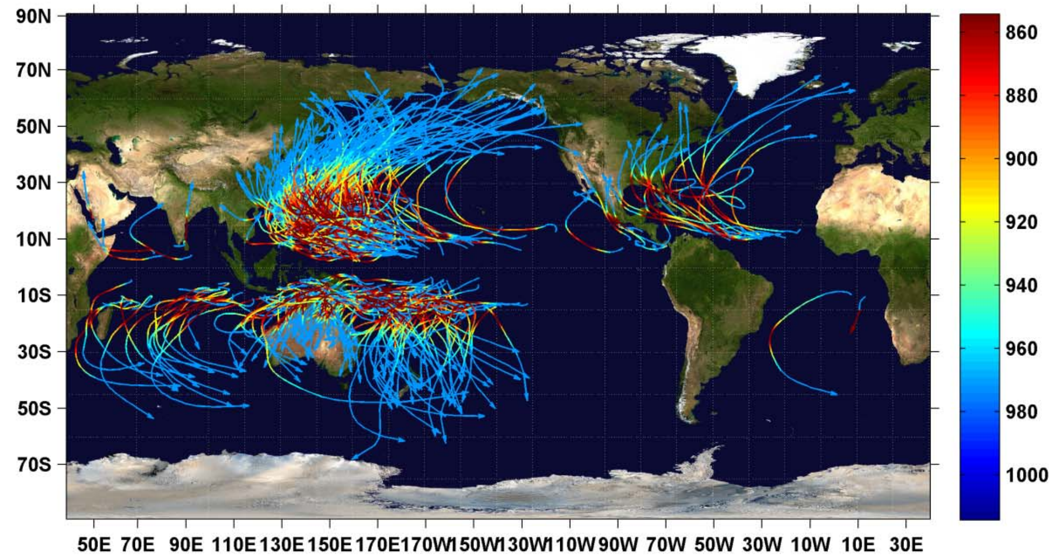
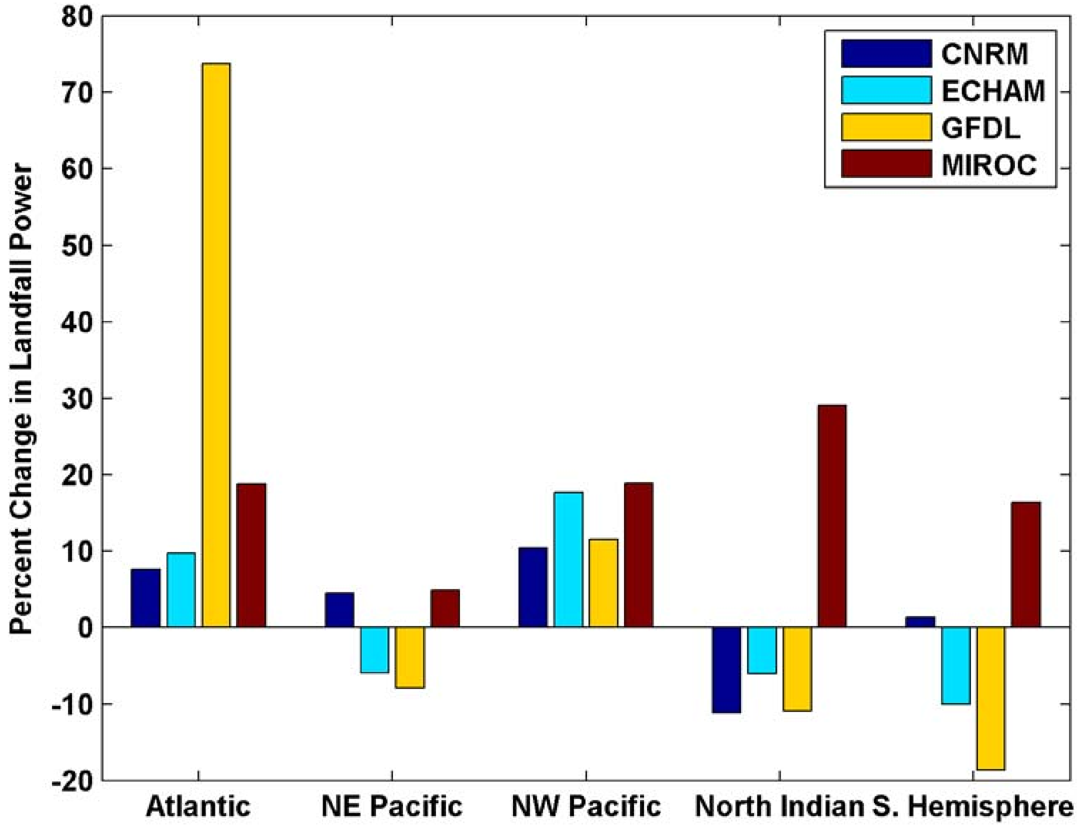
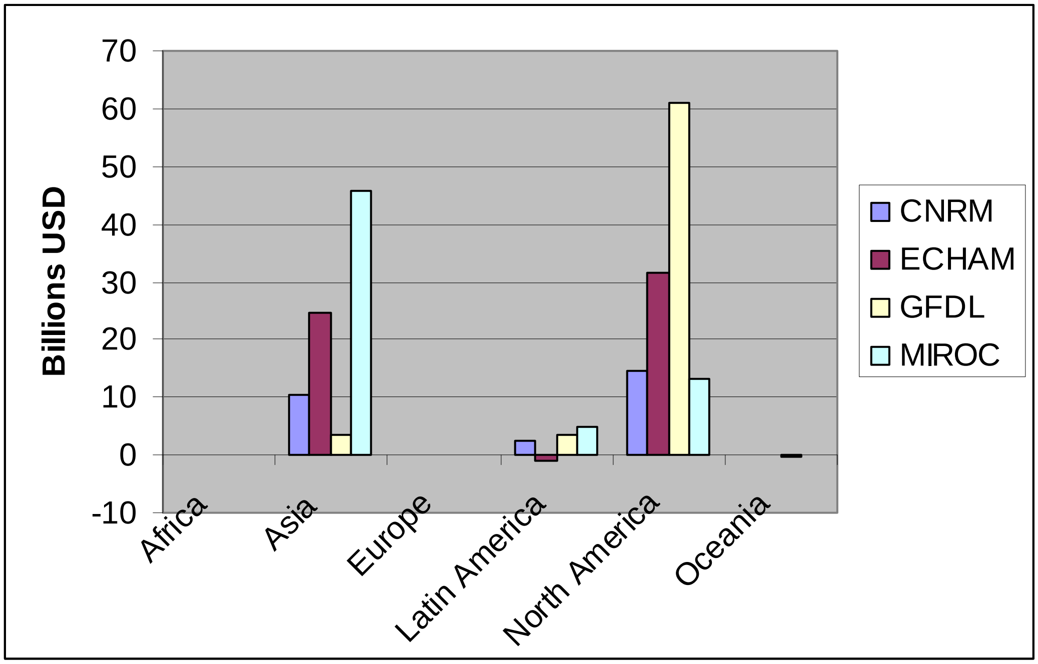


Figure 2: Change in Tropical Storm Power by Ocean Caused by Climate Change



Note: Power is the cube of the maximum wind speed. The change in power is the difference between the power with the future climate and with the current climate.

Figure 3: Climate Change Impacts on Tropical Cyclone Damages by Region by 2100



Note: Calculated using minimum pressure damage model with future baseline.

Figure 4: Tropical cyclone damage in 2100 as a fraction of GDP

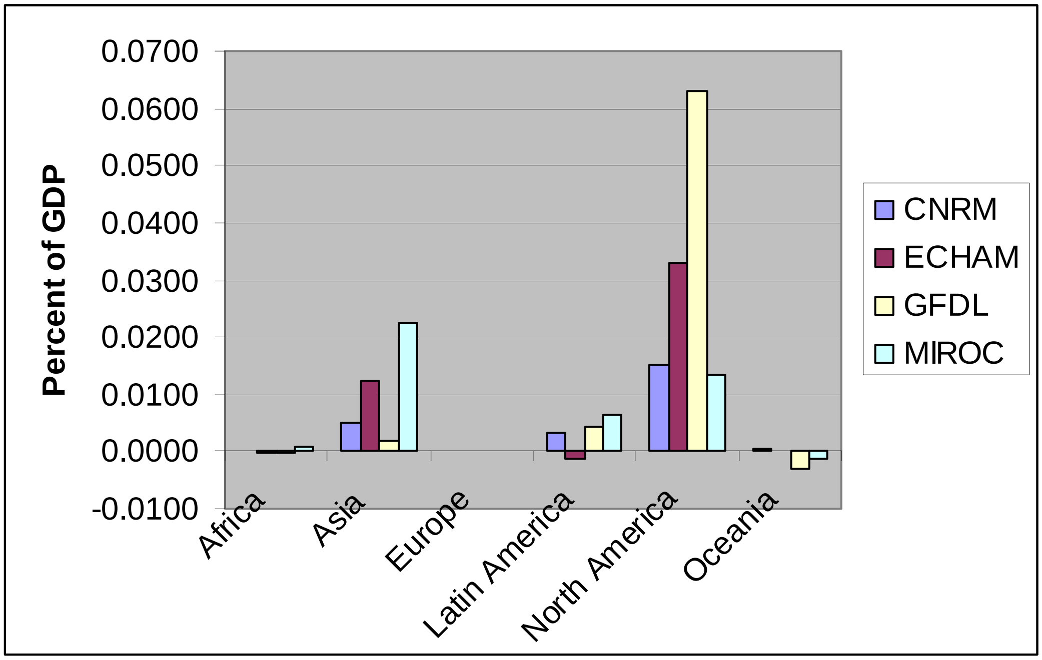
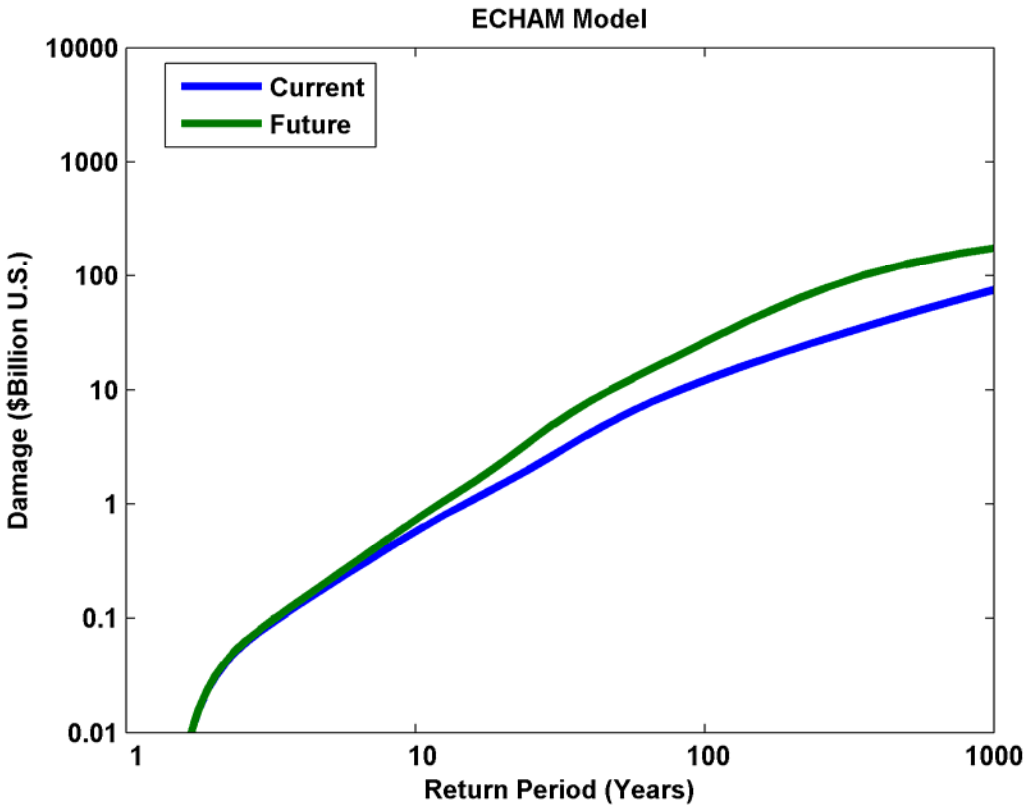


Figure 5: Return period in 2100 by US damage for ECHAM



Note: Damage calculated in 2100.