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The Impact of Climate Change on Hurricane Damages in the United States

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Abstract

This paper quantifies hurricane damage caused by climate change across the US. A damage function is estimated from historic hurricane data to measure the impacts at each location given the storm's strength. The minimum barometric pressure of each storm turns out to be a better indicator of damages than the traditional measure of maximum wind speed. A hurricane generator in the Atlantic Ocean is then used to create 5000 storms with and without climate change. Combining the location and intensity of each storm with the income and population projected for each location, it is possible to estimate a detailed picture of how hurricanes will impact each state with and without climate change. Income and population growth alone increase expected baseline damage from $9 to $27 billion per year by 2100. Climate change is expected to increase damage by another $40 billion. Over 85 percent of these impacts are in Florida and the Gulf states. The 10 percent most damaging storms cause 93 percent of expected damage.

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I. Introduction

Hurricanes have become the icon of climate change with pictures from space parading the front covers of many climate change books including the journal of Climate Change Economics. The Intergovernmental Panel on Climate Change (IPCC) argues that hurricanes and other extreme events are an important reason to support greenhouse gas mitigation efforts. Several scientists report an increase in hurricane intensity over the last 30 years (Emanuel 2005, IPCC 2007a). The IPCC (2001) and Swiss Re (2006) report dramatic increases in hurricane damages over time.

And yet despite these findings, the link between climate change and hurricane damage remains controversial. Partly this is due to the fact that highly destructive hurricanes are rare events and so it is difficult to detect changes in underlying frequencies and severity (Landsea et al. 1999; 2006). Over the last 50 years, 111 hurricanes have struck the United States (NOAA 2009). Many things changing over time can influence the damages from storms, most noticeably population and income (Pielke et al. 1998; 2008). Accounting for changes in the vulnerable population and capital in the path of storms, it is not clear that there is any trend in hurricane damages (Pielke et al 1998; 2008). The historic record may simply not be long enough and clear enough to detect how climate may be affecting hurricanes.

Estimates of current hurricane damages in the US are $9 billion/year (0.06% of GDP) (Nordhaus 2010). Using simulations of future hurricanes, Emanuel (2006) predicts that average hurricane intensity in the US would increase with warming. Assuming that every hurricane increases in intensity, several authors have predicted US damages would increase. Assuming that hurricane damages increase with the cube of wind speed, Hallegatte (2007) predicts US damages would increase 54 percent. However, other authors have calculated that damages increase by the fifth power of wind speed or higher and so predict that US hurricane damages would double (Nordhaus 2006; 2010; Pielke 2007.

In this paper, we take a different approach to estimating the impact of climate change on hurricanes by relying on a geographically detailed Tropical Cyclone Integrated Assessment Model (HIAM). The model begins with the A1B SRES global emissions trajectory. Four future climate scenarios in 2100 are then projected using this emissions path and four different climate models. A cyclone generator is then used to predict how hurricanes in the Atlantic Ocean may change (Emanuel et al. 2008). In both the current climate and the future climate, a total of 5000 hurricanes are generated that strike the United States, for each climate model. This provides an extensive data set concerning the distribution of hurricanes that would strike the country. It is equivalent to observing over two thousand years of data on hurricanes in each climate and for each model. Instead of using an average change for all hurricanes, we use the change in the entire distribution of hurricanes to predict the impact of climate change.

We estimate a hurricane damage function using historic data from storms that have hit the United States from 1960 through 2008. The damages are matched with characteristics of the storm, including minimum barometric pressure, maximum wind speed, and location at landfall (NOAA 2009). Estimates of county income and population density are generated from census data. A regression is then used to predict the damages caused by historic storms.

The damage function is then used to predict the damages that would be caused by each storm in the generated data set. The 40,000 storms generate a rich data set that describes the expected value and distribution of hurricane damages. It also describes how the risks vary along the coast of the United States given each climate scenario.

The analysis then compares the damages from hurricanes under the current climate versus the future climate. We perform two analyses. The first analysis examines the growth in hurricane damages caused by higher income and population along the coast. This analysis assumes no climate change. The second analysis examines the additional damages caused by climate change given the future baseline. The change in damages is predicted from the change in the entire set of future storms versus current storms.

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 hurricane is the sum of all the losses caused by it. In this analysis, we focus primarily on lost buildings and infrastructure but we also include an analysis of fatalities in the United States. The economic damage of capital losses is the present value of lost future rents. This should be equal to the market value of the building. Note that the market value of capital is often less than the replacement cost.

In order to model hurricanes, it is critical to recognize that they are rare events. An important component of expected hurricane damages is the frequency or probability (π) the hurricane will occur in each place. In this case, we are interested in the probability that a hurricane with particular characteristics (X) will strike a particular place. For example, important characteristics of the hurricane include minimum barometric pressure (*BP*), maximum wind speed (*WS*), and where the hurricane strikes (*i*). Atmospheric science can help predict the probability a hurricane (*j*) with particular characteristics will strike each place (*i*) given the climate (*C*):

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

The damages associated with any given hurricane (*j*) also depend on the vulnerability (Z) of each place (*i*).

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

For example, the vulnerability in each location (*i*) could depend on its population and income:

Damages will also depend upon the adaptation policies taken to prevent extreme event damage. For example, building codes could encourage homes to be able to withstand high wind speeds, land use policies could discourage development in flood plains, or restrictions could keep people away from vulnerable coast lines. In contrast, mal-adaptation could make matters worse. Poorly conceived policies could increase damages by encouraging people and capital to be in harm's way. For example, policies could subsidize flood insurance in risky places or subsidize disaster relief. Unfortunately, data is not available to measure the effect of adaptation policies and so they are not included at this stage of the analysis.

The expected value of hurricane damages is:

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

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

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

Note that this value is summed across all the storms. It is not the effect of a change in an average storm. For any given time period, climate change could change damages because the frequency of storms change, the intensity of storms change, or the locations of storms change. The calculation of hurricane damages in this study is done for each county which is then aggregated to each state and the entire country.

Note that the calculation of the damages caused by climate change is done holding the characteristics of each affected location constant. Trend line studies fail to control for changes in vulnerability and consequently confuse changes in what is in harm's way with changes in the probability of a particular harm. Climate hazard trend studies often confuse changes caused by economic and population growth with changes caused by climate (Pielke and Landsea 1998; Pielke 2005; Pielke et al. 2008).

Equation 4 calculates the expected welfare loss from climate change. From a policy perspective, it is also helpful to understand the frequency distribution of damages. The frequency distribution describes the probability (Prob) of different levels of damage per storm:

$$\mathrm{Pr}ob(D) = f(D(X)) \qquad (5)$$

The frequency distribution allows policy makers to see the distribution of risks they face. The distribution indicates the level of damage and its chance of occurring. A more intuitive description of frequencies can be seen in the return rate (RR) function of storms causing damage (D). The return rate is defined:

$$RR = 1/\Pr ob(D) = 1/\ f\,(D) \tag{6}$$

The return rate describes the average amount of time between storms causing each level of damage. Examining the tail of the return rate or frequency distribution is particularly helpful to calculate the amount of catastrophic insurance needed to cover large damage.

Damages are also broken down by region within the United States. We examine five regions: Gulf, Florida, Southeast, Mid Atlantic and New England[2]. State specific estimates are presented in Appendix A.

III. Hurricane Integrated Assessment Model

The integrated assessment model has been constructed to project hurricane risks given different climates. The analysis integrates an emission path, the resulting climate change, the impact on hurricanes, and the resulting damage. The analysis relies on the A1B SRES emissions scenario generated by the Intergovernmental Panel on Climate Change (IPCC 2000). The scenario assumes that mitigation is gradually tightened over time so that greenhouse gas concentrations finally peak and stabilize at 720 ppm.

We rely on four climate models: CNRM (Gueremy et al. 2005), ECHAM (Cubasch et al 1997), GFDL (Manabe et al. 1991), and MIROC (Hasumi and Emori 2004) in order to capture the wide range of plausible climate changes that this emission scenario might cause. Each climate model predicts both the current climate and the climate in 2100. Because of differences in the models, they generate a wide range of climate change predictions. The range of temperature outcomes across these four models

[2] The Gulf states include Texas, Louisiana, Mississippi, and Alabama. The Southeast includes Georgia, South Carolina, North Carolina, and Virginia. The Mid Atlantic includes Delaware, Pennsylvania, New Jersey, and New York. New England includes Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine.

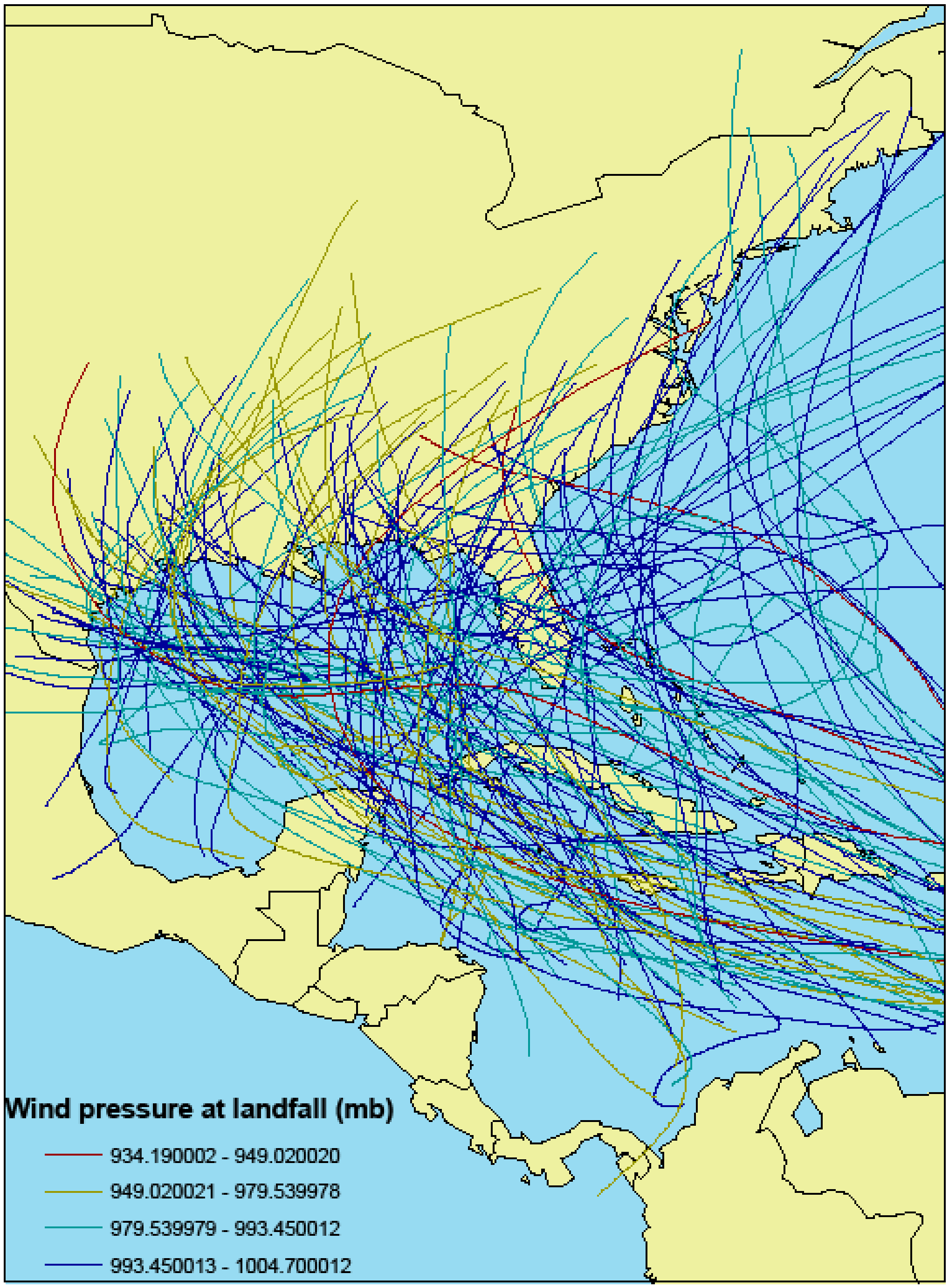
describes the range of temperature outcomes reported for this emissions scenario across many climate models (IPCC 2001). CNRM predicts a global warming of 2.9°C, ECHAM predicts 3.4°C, GFDL predicts 2.7°C, and MIROC predicts 4.5°C. These changes in climate warm sea surface temperatures which in turn fuel the hurricanes. However, there are other changes in wind shear and wind direction that can affect hurricane intensity as well, and changing wind patterns can affect where storms strike and how many storms actually intercept the U.S. coastline.

Using a hurricane generator in the Atlantic basin, thousands of storms are seeded into the Atlantic Ocean. Given the climate conditions projected by each climate model, the storms are allowed to develop. Only some of the seeded storms develop into hurricanes and only some strike the United States. A total of 5,000 hurricane tracks are followed that eventually strike the US for each climate case (Emanuel et al. 2008). This is equivalent to observing over 2000 years of hurricane experience with each climate scenario. For each climate model, there are 5,000 hurricanes for the current climate and 5000 hurricanes for the future climate. Given that there are four climate models, there are a total of 40,000 hurricanes followed in the study. Note that this approach explicitly models the location and intensity of each storm. Most earlier hurricane studies simply assumed that all storms would become more intense by a common percentage (Nordhaus 2006; 2010; Pielke 2007).

We assume that hurricanes that remain at sea cause minimal damage. Most of the damage caused by tropical cyclones occurs when they strike land. The minimum barometric pressure and the maximum wind speed at landfall of each storm are recorded. Storms striking Florida and Long Island, New York can continue and strike another location. We count the damages from these storms in both locations.

A sample of hurricane tracks is shown in Figure 1. The tracks are both more frequent and more powerful (red) near Florida and the Gulf Coast states. As hurricanes move north along the US coast they tend to lose power. This is true for both the current

Figure 1: Sample of Hurricane Tracks Striking the US by Minimum Pressure



climate and the future climate. However, in the future, more powerful storms become slightly more frequent. The bulk of these more powerful storms strike Florida and the Gulf Coast states.

The storms in each climate scenario have different properties. As temperatures warm, hurricane wind speeds increase and minimum pressure decreases, indicating more powerful storms. However, the average change is quite small. Except for the CNRM scenario, average wind speed increases from 4 to 7 percent across the climate models. Average minimum pressure falls 0.01 to 0.33 percent. The overall frequency of hurricanes changes only slightly, except in the GFDL model where it almost doubles. Although the average features of storms do not change significantly, the distribution of storms changes quite a lot. There is a noticeable increase in the intensity of the largest storms. So although all hurricanes do not change, the most powerful storms appear to become even more powerful.

The amount of damage caused by a storm depends on the intensity of the storm and what is in harm's way. Two damage functions are estimated using aggregate damages per storm and storm characteristics at landfall from US storms since 1960 (NOAA 2009). Although earlier storm data is available, there is some question about its validity. Aggregate damages include insured and uninsured private property losses as well as infrastructure losses. Fatalities are not included. Partly, this is because fatalities are low in the US because of sophisticated warning and evacuation plans (Anbarci et al 2005; Dash and Gladwin (2007); Kahn 2005; Lindell et al 2005) and partly because the residual US fatalities appear to be random events. Whether or not losses are insured is beyond the scope of this paper (see Gares 2002; Kriesel and Landry 2004; Kunreuther and Pauly 2004). The paper also does not measure long term effects on real estate (Beracha and Prati 2008) or labor markets (Belasen and Polachek 2008) as these effects would be double counting the damages included.

We estimate two measures of storm intensity: wind speed and barometric pressure[3]. We also examine the population and income of the five coastal counties surrounding the eye of the storm. Many past studies assume that the damages are

[3] We also examine a two stage model that first predicts wind speed on the basis of barometric pressure and then uses the predicted wind speed. However, we do not present this result since it is almost identical to the barometric pressure model.

proportional to the income and population of nearby coastal counties (Pielke and Landsea 1998; Pielke 2007; Pielke et al. 2008). Other studies assume that damages are simply a function of wind speed cubed (Hallegate 2007). The remaining studies assume that damages are proportional to US GDP (Nordhaus 2006; 2010). This study empirically tests the importance of local income and population. Income and population were based on the five coastal counties near where the eye of the storm strikes land. The assumption that damages largely depend on coastal counties is supported by empirical evidence suggesting this is where over 85 percent of aggregate storm damages occur (Pielke and Landsea 1988, Pielke 2007; Pielke et al 2008, Nordhaus 2010; NOAA 2009). Income and population for the historical storm sample was calculated using decennial census data by county (US Census of Population 1960, 1970, 1980, 1990, 2000). Values between Census years were inferred. Dollar values were updated to 2010 USD using the GDP deflator.

The results of the regressions of log damages on the log of the independent variables are shown in Table 1. The regressions reveal that the intensity of the storm is highly significant. Whether measured by maximum wind speed or minimum pressure at landfall, damages are a highly nonlinear function of intensity[4]. Damages increase inversely with the 86th power of minimum pressure. A 1% reduction in minimum pressure almost doubles storm damages. Damages increase with the fifth power of wind speed. A 20 percent increase in wind speed doubles storm damages. These results are much more nonlinear than commonly assumed (that damage is related to the cube of wind speed e.g. Emanuel 2005). However, these values are lower than comparable estimates by Nordhaus (2010) who finds that damages increase with the ninth power of wind speed. Comparing the results of the minimum pressure and wind speed regressions reveals that minimum pressure has a more significant coefficient. The minimum pressure mode also does a better job of explaining the variance in hurricane damages. This is probably due to the measurement error associated with maximum wind speed as measuring the maximum wind speed of a hurricane is very difficult.

[4] We also examine a two stage model that first predicts wind speed on the basis of barometric pressure and then uses the predicted wind speed in the damage function. Damages increase with the sixth power of predicted wind speed. However, we do not present this model since it has almost identical effects as the barometric pressure model.

Table 1: Regressions of US Hurricane Damages on Intensity and Vulnerability

Magnitude measure	Constant	Intensity	Income	Population Density	Adj Rsq/ F Stat
Minimum Pressure	607.5 (10.39)	-86.3 (9.96)	0.370 (0.45)	0.488 (1.53)	0.501 35.76
Wind Speed	-12.9 (1.42)	4.95 (7.83)	0.903 (0.96)	0.458 (1.28)	0.371 22.61

Note: There were 111 observations in each regression. t statistics are in parenthesis.
Source: NOAA 2009.

The vulnerability variables (income and population density) are not significant in Table 1, which poses a dilemma for the analysis. It is difficult to know how large the effect of increasing income and population might be from these regressions alone. But it is not realistic to treat these impacts as negligible just because they do not have statistical significance in these particular regressions. Accordingly, we carry out the analysis using several different possible parameter values. Note that the minimum pressure regression places the income elasticity closer to 0.4 whereas the wind speed model places the income elasticity closer to 1. We pursue both models in the analysis. We also test the importance of these coefficients in the sensitivity analysis.

Figure 2 displays the shape of the Minimum Pressure Damage Function. It is very nonlinear and quickly gets into ranges of damages that are not plausible because they more than destroy everything in their path. Figure 3 displays the results for the wind speed regression. It also is nonlinear but does not increase as sharply as the Minimum Pressure Damage Function.

Figure 2 Minimum Pressure Damage Function

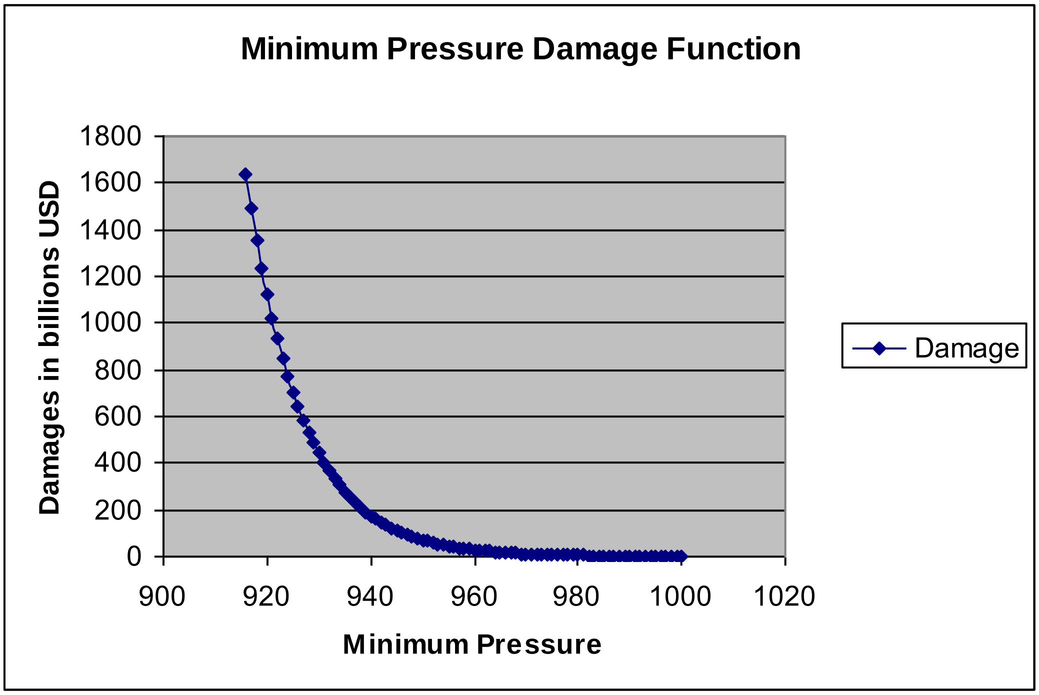
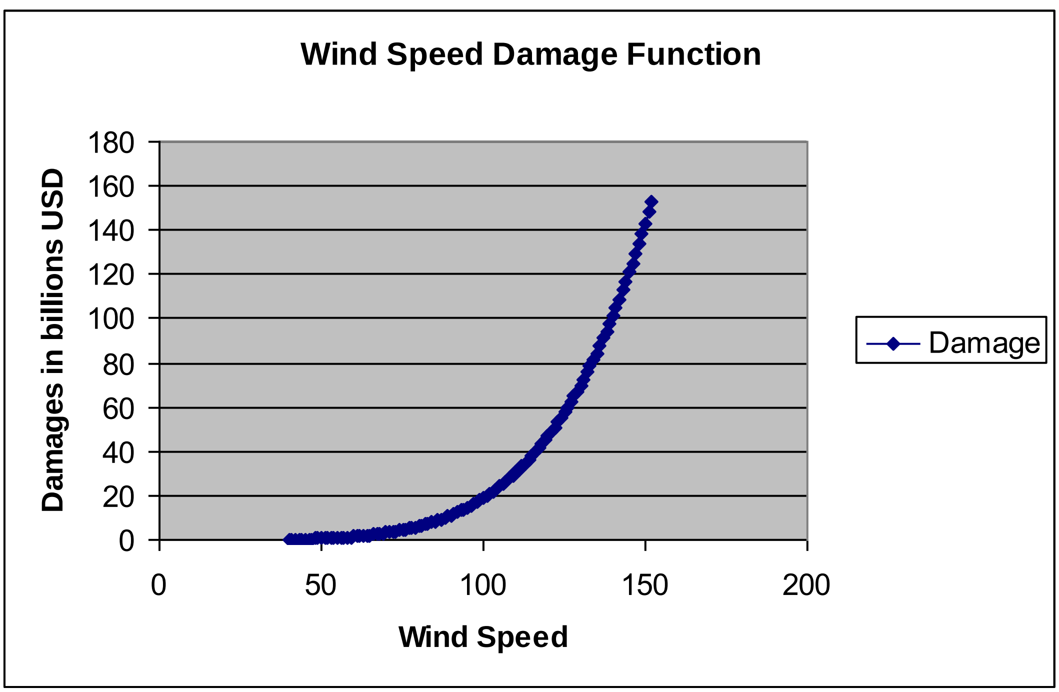
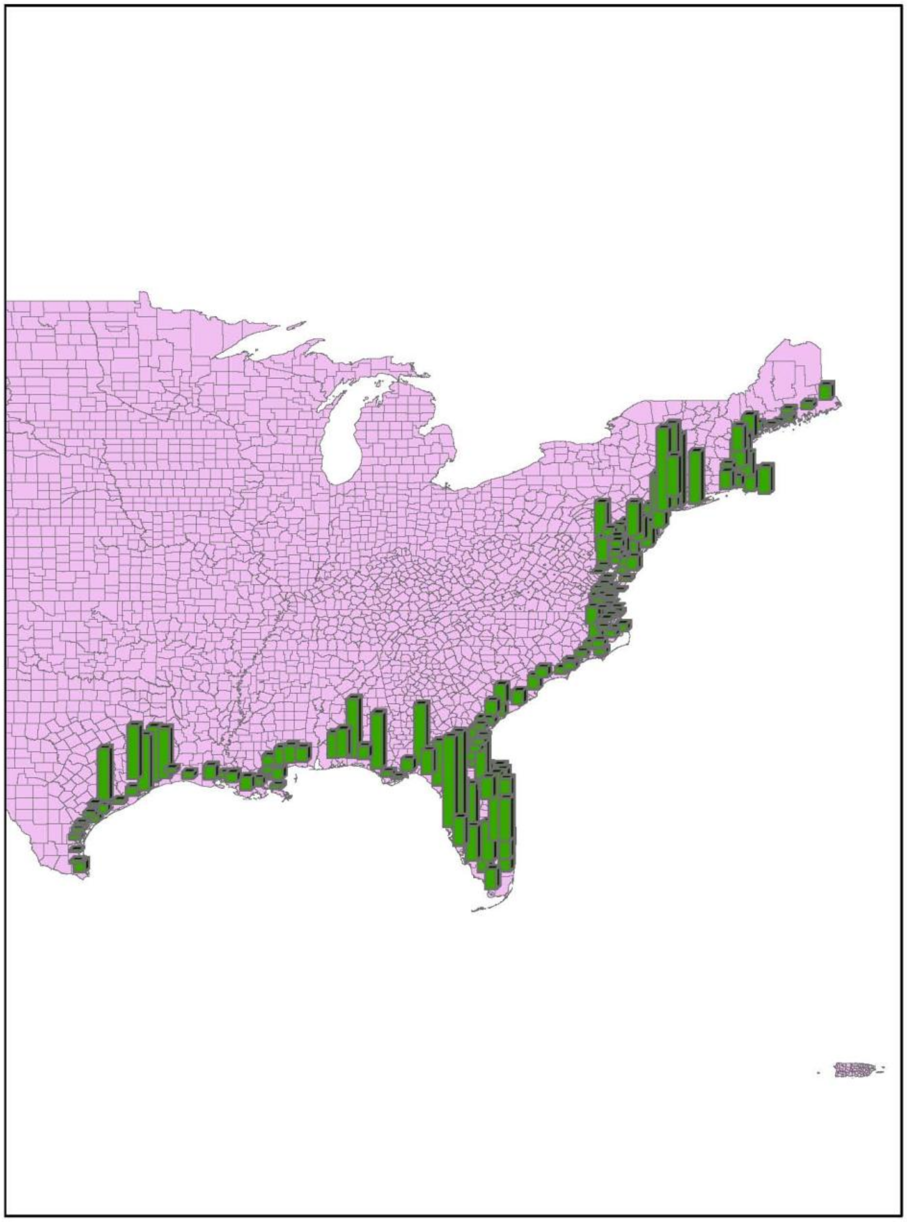


Figure 3: Wind Speed Damage Function



Some storms were predicted to cause so much damage that damages exceeded the capital stock in the path of the storm. Storm damages therefore are truncated at a maximum where all the capital in the five coastal counties where the storm came ashore is destroyed. A map of these maximum damages in the future baseline for 2100 is shown in Figure 4. The height of the green bars provides a sense of the relative magnitude of damages caused by storms along the Eastern coast of the US. Given future storm characteristics and future vulnerability, the expected value of damages from maximum destruction storms is $172 billion per storm. This is more than twice the damage caused by Hurricane Katrina. But the value could be much higher when the storm strikes a major metropolitan area. The future damages from a maximum destruction storm can reach a trillion dollars if it strikes a major metropolitan area.

Figure 4: Maximum potential damage from future US Hurricanes in billions USD



Note: the proportion of the maximum values remains roughly the same for the current and future baseline but the mean of the distribution is $29 billion for the current baseline and $172 billion for the future baseline.

IV. Results

The current annual rate of hurricanes striking the US is 2.3/year. These storms cause annual average damages of $9 billion/year (Nordhaus 2010). The damages per storm given the current level of annual damages and the current climate are calibrated so that annual damages are equal to this observed amount.

The economic conditions over the next century are then projected. GDP is assumed to grow 6 fold between 2010 and 2100 (GDP grows at 2%/yr). The US population is expected to increase by 50% (United Nations 2004). We use the historic growth of income per capita and population in each county between 1960 and 2000 to predict how income and population in each coastal county will grow compared to US average income and population. This yields a future baseline of population and income for each county in 2100.

Table 2 reports hurricane damages for both the current and future baseline given the current climate. The analysis shows how baseline damages would change just because of income and population growth but without climate change. According to the minimum pressure model, the increase in income and population in the coastal counties is expected to triple hurricane damages from an expected value of $9 billion/yr to $27 billion/yr. The wind speed model, however, has a much higher elasticity of income and so it predicts that baseline damages will increase to $55 billion, a six fold increase. Note that the aggregate results from the wind speed model are similar to the results by Pielke et al 2008 but the minimum pressure results are much lower.

The current and future baseline damages are not evenly distributed across the Eastern seaboard. The bulk of the current damages are in the Gulf region (56 percent) and Florida (33 percent). Most of the remaining damages are in the Southeastern states (11 percent). The Middle Atlantic and New England regions bear only 0.4 percent of national damages. With the minimum pressure model, the relatively high growth rates along the Florida coast compared to the Gulf coast reduce the future share of damages in the Gulf to 44 percent but increases Florida's share to 44 percent. With the wind speed model, the share of the Gulf falls slightly to 52 percent whereas the Southeast share increases to 14 percent.

Table 2: Change in Baseline Hurricane Damages Because of Income and Population Growth (billion USD/yr)

Region	Current Damages	Damages 2100 Minimum Pressure	Damages 2100 Wind Speed
Gulf states	$5.0	$12.0	$28.8
Florida	$2.9	$12.1	$18.3
Southeastern States	$1.0	$3.2	$7.7
Middle Atlantic States	$0.02	$0.04	$0.17
New England states	$0.02	$0.05	$0.22
United States	$9.0	$27.4	$55.2

Given the future baseline of damages, we then calculate the impact of climate change. The damages from climate change are the predicted hurricane damages in 2100 with future climate minus the predicted hurricane damages in 2100 with current climate. Both estimates use the future baseline of income and population. The expected additional damages caused by climate change in 2100 are shown in Table 3. With the minimum pressure model, average damages per year increase by $42 billion, a 150 percent increase over the future baseline. This amount is equal to 0.05% of US GDP in 2100. Across the different climate models, the estimates range from $15 billion to $57 billion per year. The percentage increase and absolute damages caused by climate change are larger than the results predicted in the literature because this analysis uses minimum pressure while previous studies have relied on wind speed. The absolute size of the additional damages estimated predicted by the wind speed model ($40 billion) are about the same size as the additional damages predicted by the minimum pressure model. The increase in damage over the baseline with the future wind speed baseline is just 72 percent. The wind speed model gives a higher baseline but a lower percentage increase in damages to come out with the same overall damage. With the wind speed model, the damages range from $17 to $75 billion/yr depending on the climate model. The impacts from GFDL and MIROC are generally higher than the other climate models because they both predict a greater reduction in minimum pressure and higher wind speeds. The GFDL damage estimates are also higher because GFDL predicts a large increase in hurricane frequency.

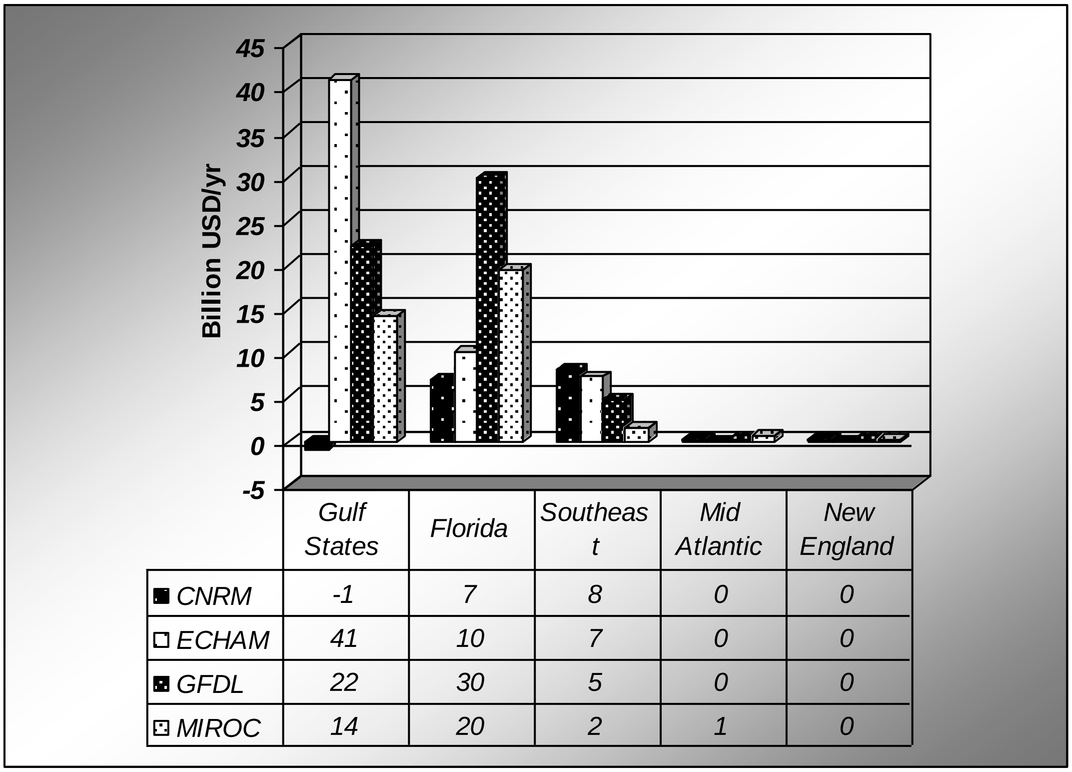
Table 3: ADDITIONAL US Hurricane Damages Caused By Climate Change in 2100

Damage Model	CNRM	ECHAM	GFDL	MIROC	Average
Minimum Pressure	+14.6	+58.3	+57.3	+36.2	+41.6
Wind Speed	+17.0	+34.6	+75.3	+31.2	+39.5

Note: Change in US damages caused by warming for each climate scenario in billions USD/yr from future baseline.

The predicted distribution of additional hurricane damages caused by climate change is not even across the US coastline. Figure 5 displays the additional damage caused by climate change in each coastal region. The damages are expected to be much higher along the Gulf Coast (Texas, Louisiana, Mississippi and Alabama) and Florida. The damages could then trail away as one moves north. On average, 43 percent of the climate change damages are expected to hit the Gulf Coast states and another 44 percent are in Florida. The Southeast (Georgia, South Carolina, North Carolina, Virginia, Maryland, and Delaware) would come in a distant third with 12%. Although more powerful hurricanes can reach the Mid-Atlantic (New Jersey, and New York) and New England (Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine) regions, they would account for less than 1% of national damages.

Figure 5: Additional Hurricane Damage from Climate Change in 2100 using the Minimum Pressure Model

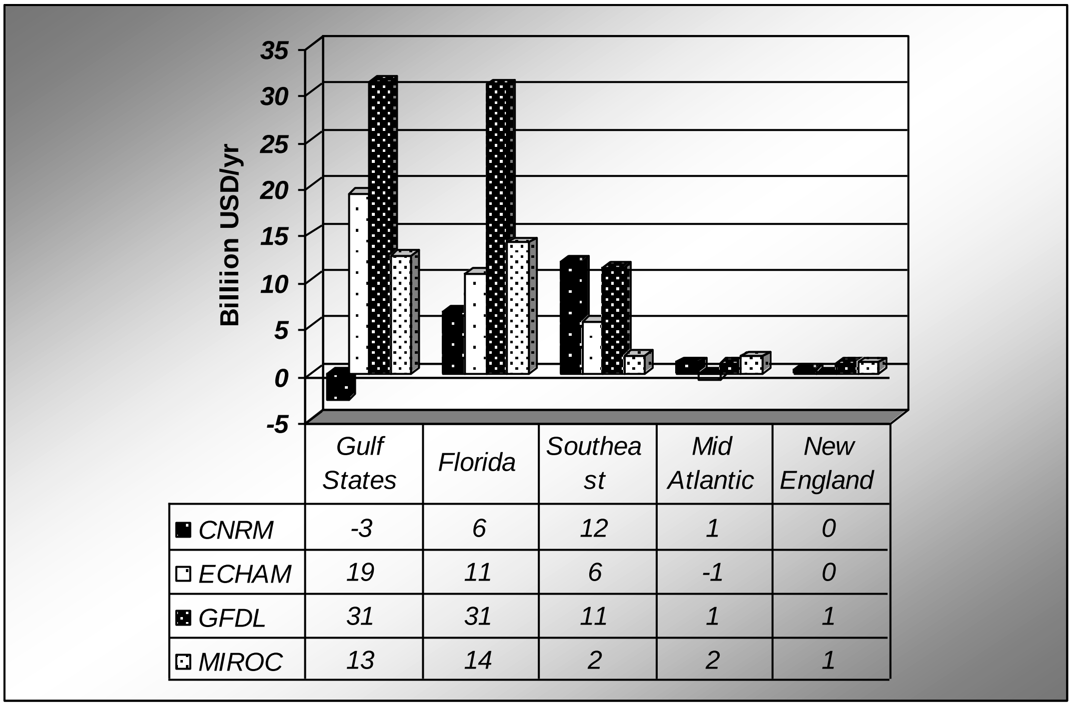


	Gulf States	Florida	Southeas t	Mid Atlantic	New England
CNRM	-1	7	8	0	0
ECHAM	41	10	7	0	0
GFDL	22	30	5	0	0
MIROC	14	20	2	1	0

Note: Predicted expected damages from climate change measured in billions USD/yr.

Figure 6 displays the same regional results using wind speed instead of minimum pressure to predict damages. The results in Figure 6 are based on the identical set of storms as in Figure 5. The different prediction of damages is due solely to the damage function. The overall damages are lower with the wind speed model. The regional distribution of damages is also slightly different. The impacts in the Gulf Coast would be relatively lower and the impacts in the Southeast relatively higher with the wind speed model. The relative damages in the rest of the regions remain similar.

Figure 6: Additional Hurricane Damage from Climate Change Predicted by Wind Speed Damage Model

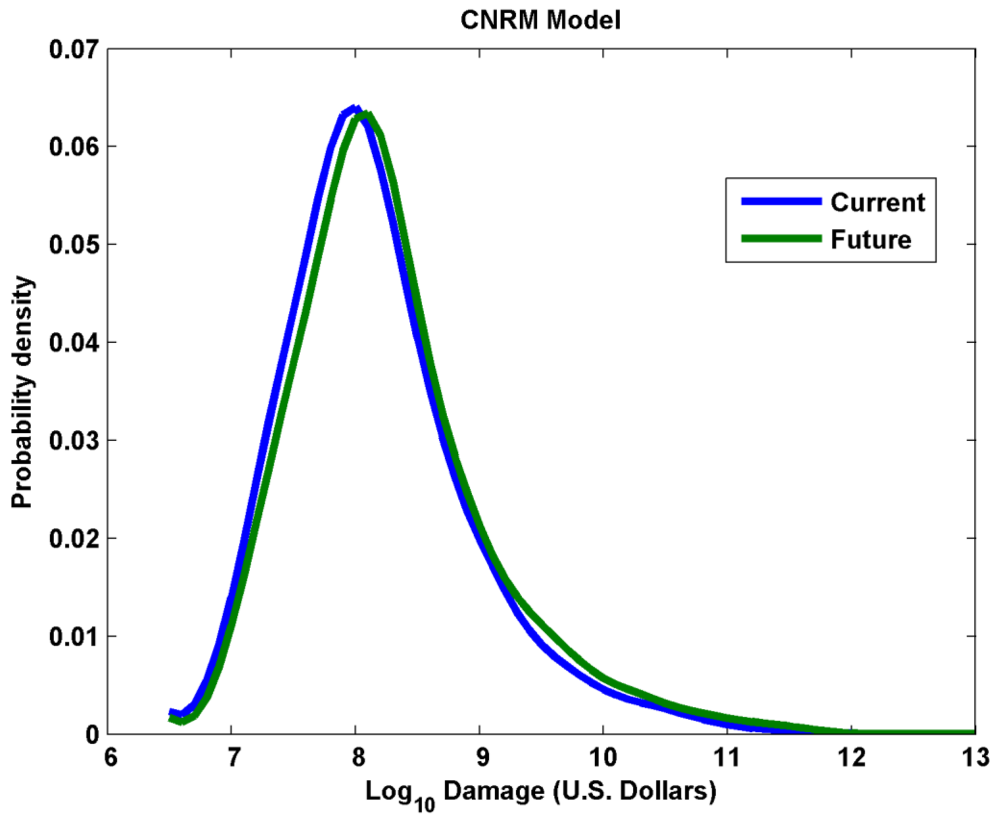


	Gulf States	Florida	Southeast	Mid Atlantic	New England
CNRM	-3	6	12	1	0
ECHAM	19	11	6	-1	0
GFDL	31	31	11	1	1
MIROC	13	14	2	2	1

Note: Predicted expected damages from climate change in 2100 measured in billions USD/yr.

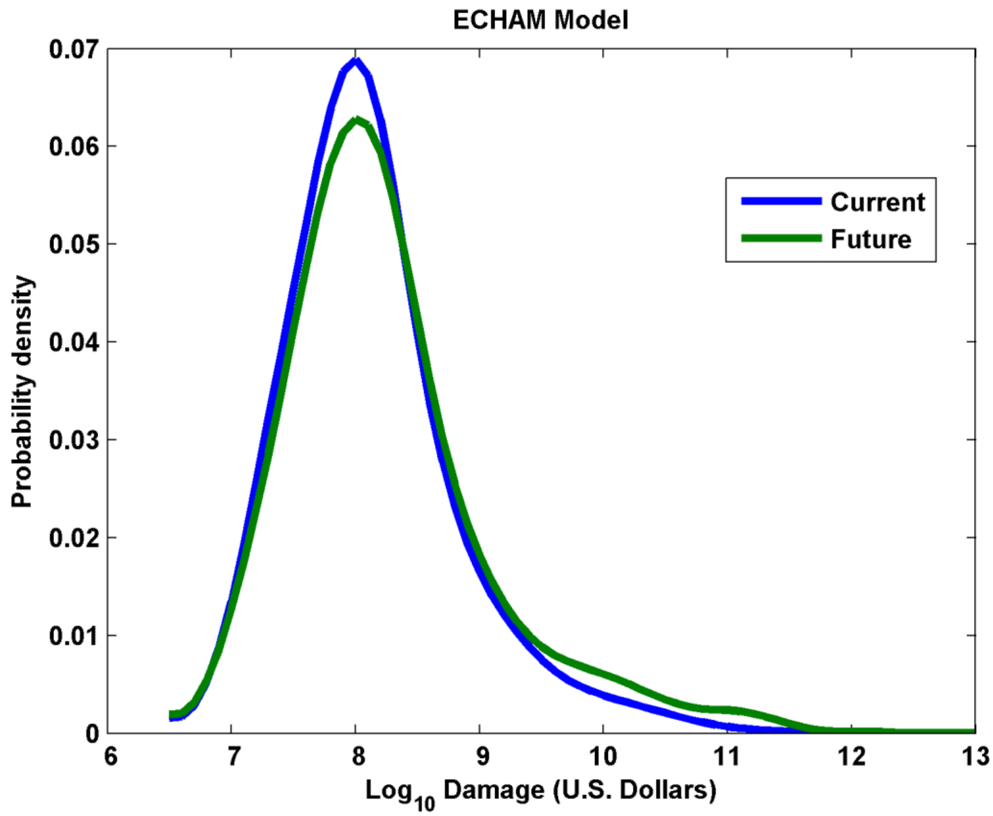
Table 2 explains the baseline expected damage from hurricanes in 2100 and Table 3 shows the expected additional damage from hurricanes caused by climate change. These expectations are calculated over 40,000 hurricanes. However, the expected values of damages do not reveal the skewed nature of the probability distribution of hurricane damages. Many storms cause relatively little damage. However, a few storms cause very large impacts. Figures 6, 7, 8, and 9 display the probability density function of damage for the CNRM, ECHAM, GFDL, and MIROC climate models respectively using the minimum pressure damage function. Both distributions are based on the US population and income in 2100. The distributions are highly skewed to the right. The worst storms in each climate scenario are above a trillion dollars for both current and future climate. Warming causes a shift in the distributions making them more skewed. Bad storms in particular become more harmful. Only the GFDL scenario implies that all storms will be more harmful. The highly nonlinear damage functions cause bad storms to become significantly worse. Only the CNRM distributions hardly shift at all. With the CNRM distribution, hurricane damages are still high but climate change causes only a small additional effect. In contrast, the distribution of damages shifts noticeably for the GFDL and MIROC climate models leading to the higher observed expected damages. The cost of catastrophic insurance will rise as the probability distribution becomes more skewed.

Figure 6: Probability Density Function of Damages per Storm from CNRM Model



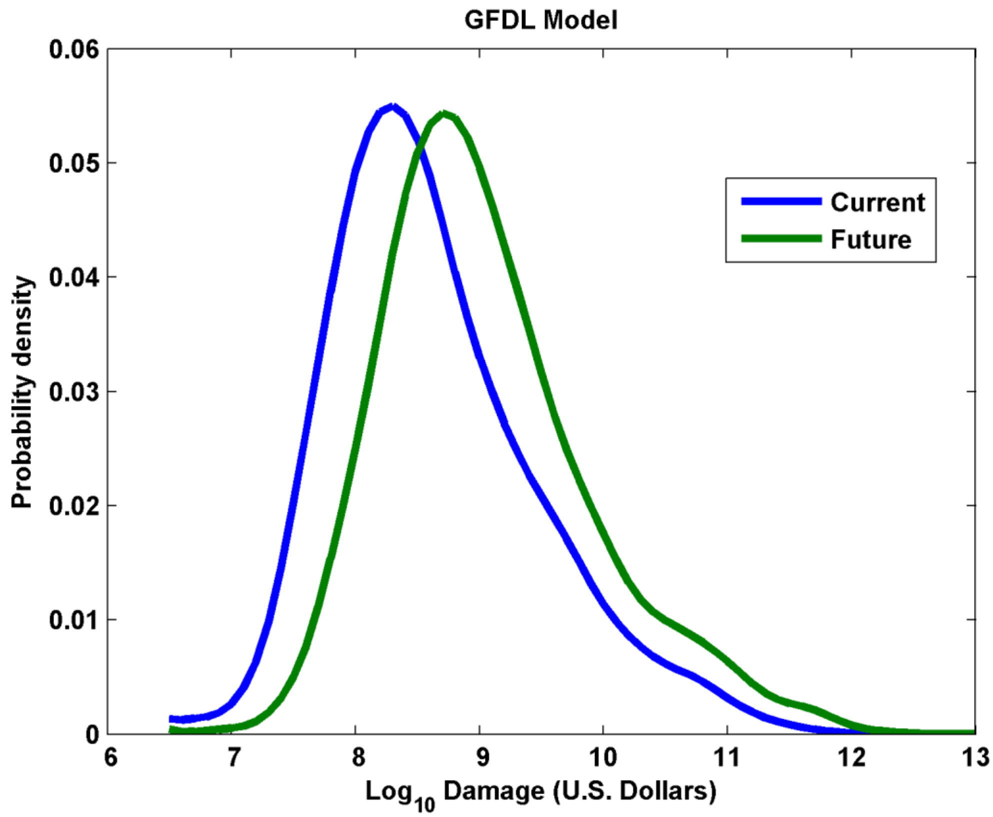
Note: Assumes Minimum pressure Damage Function and Future Baseline in 2100. Transforming the horizontal axis using the $\log_{10}$ is purely for presentational purposes. Note that $\log_{10}$ equal to 9 is equivalent to $1 billion dollars and $\log_{10}$ equal to 10 is equivalent to $10 billion dollars.

Figure 7: Probability Density Function of Damages per Storm from ECHAM Model



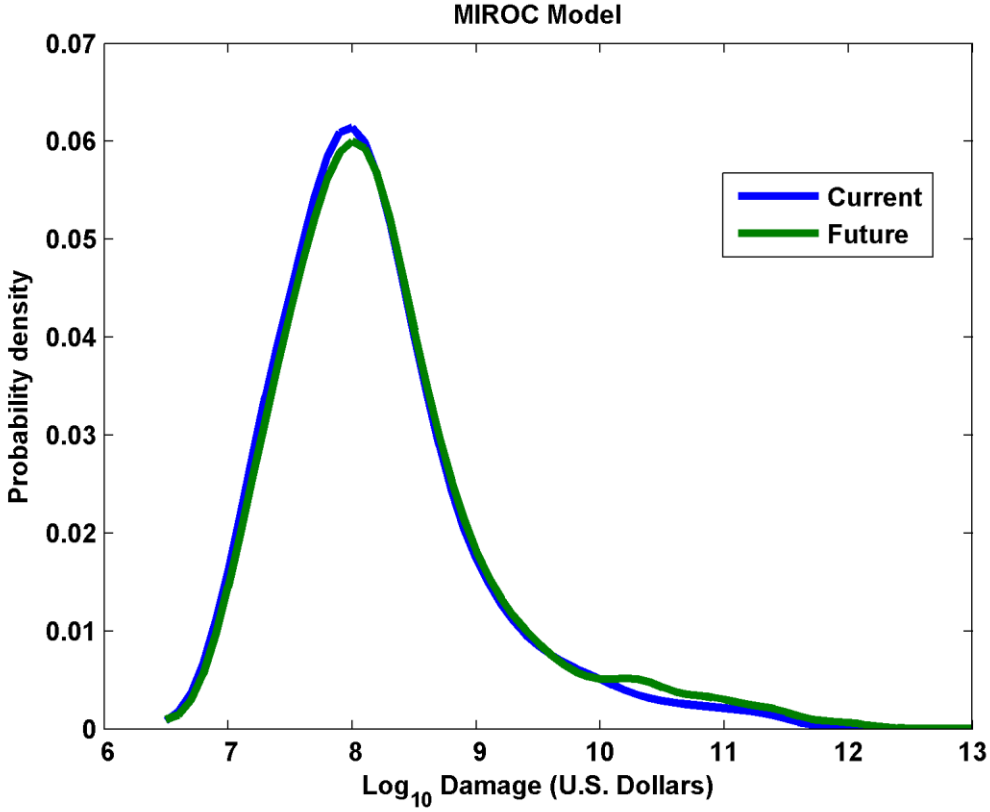
Note: Assumes Minimum pressure Damage Function and Future Baseline in 2100. Transforming the horizontal axis using the $\log_{10}$ is purely for presentational purposes. Note that $\log_{10}$ equal to 9 is equivalent to \$1 billion dollars and $\log_{10}$ equal to 10 is equivalent to \$10 billion dollars.

Figure 8: Probability Density Function of Damages per Storm from GFDL Model



Note: Assumes Minimum pressure Damage Function and Future Baseline in 2100. Transforming the horizontal axis using the $\log_{10}$ is purely for presentational purposes. Note that $\log_{10}$ equal to 9 is equivalent to $1 billion dollars and $\log_{10}$ equal to 10 is equivalent to $10 billion dollars.

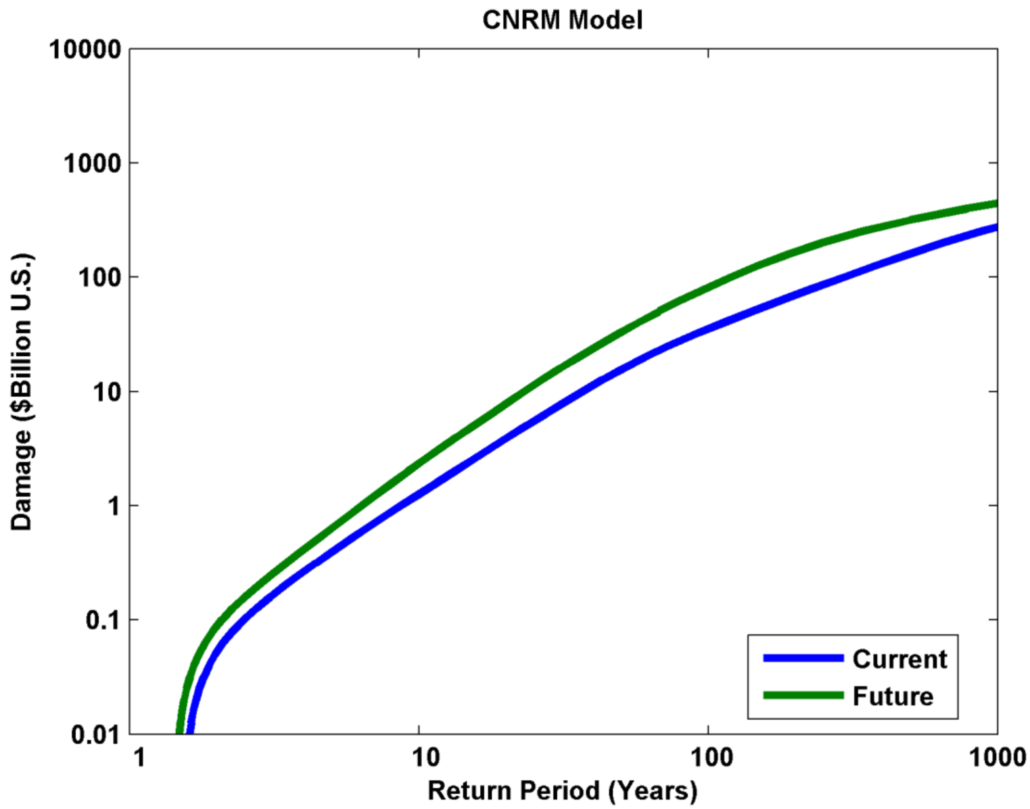
Figure 9: Probability Density Function of Damages per Storm from MIROC Model



Note: Assumes Minimum pressure Damage Function and Future Baseline in 2100. Transforming the horizontal axis using the $\log_{10}$ is purely for presentational purposes. Note that $\log_{10}$ equal to 9 is equivalent to $1 billion dollars and $\log_{10}$ equal to 10 is equivalent to $10 billion dollars.

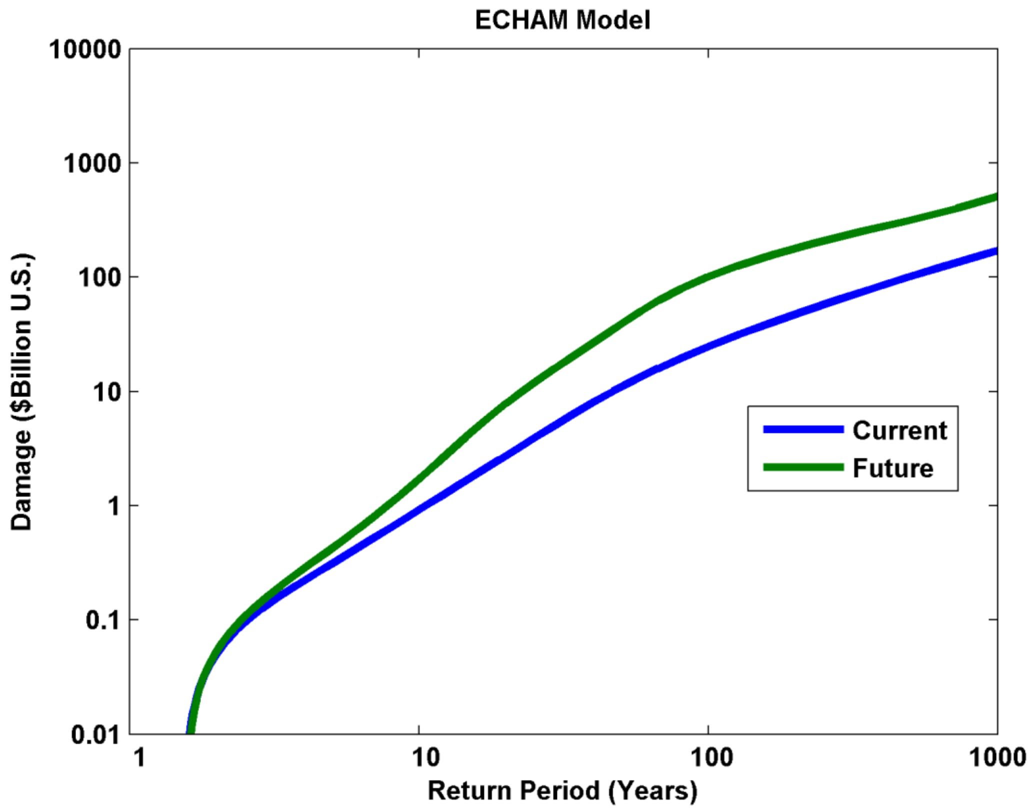
Although the return period graph contains the same information as the probability density functions, some readers may find it is more intuitive. The return period measures how many years would pass on average between storms causing a particular level of damage. Figures 10, 11, 12, and 13 show these return period graphs for 2100 for the United States according to the CNRM, ECHAM, GFDL, and MIROC models respectively. Looking across all four graphs, one consistent result is that the return period for highly destructive storms will be shorter in the future. Although very large storms will still be rare, they will be more frequent. The increased frequency of large storms increases the expected damages. The shape of all the figures, however, is not identical. Figure 12 (GFDL) predicts a reduced return period for hurricanes of every intensity. The remaining models tend to predict only the return period of large storms will be substantially shorter. Figure 10 (CNRM) predicts only a small change between the future and the current distribution and so it predicts a small change in expected damages.

Figure 10: US Return Period Analysis for CNRM Outcomes



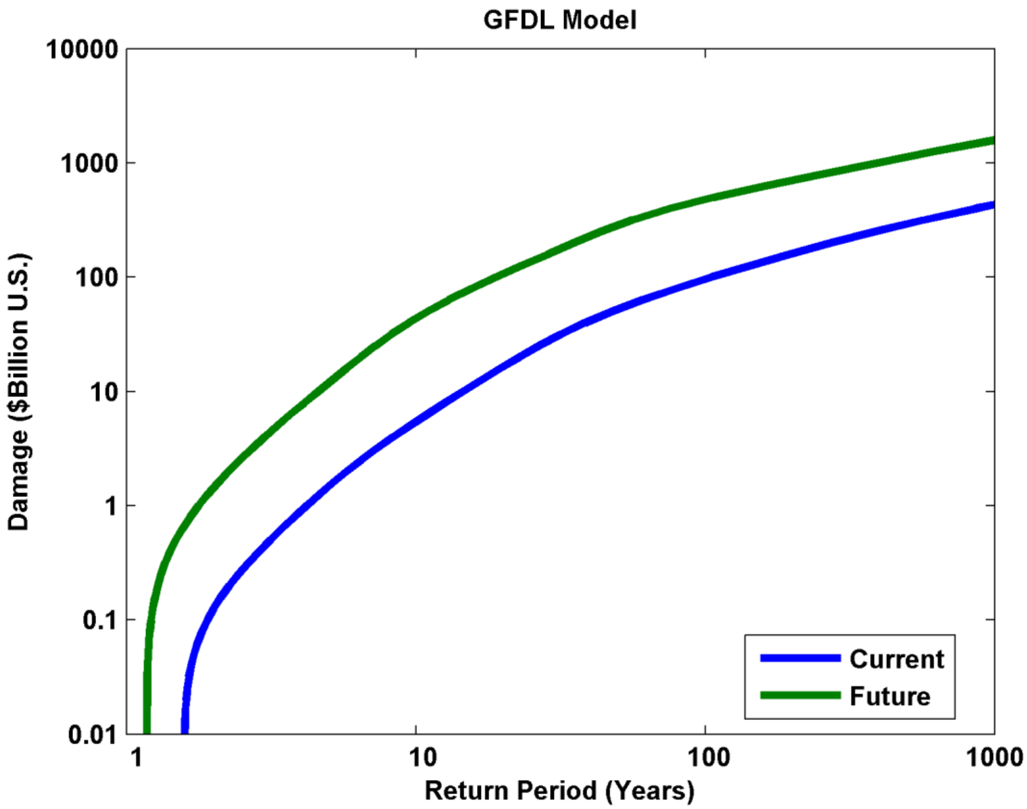
The return period shows the average number of years between storms causing a particular level of damages. The vertical axis is shown using the $\log_{10}$ purely for presentational purposes.

Figure 11: US Return Period Analysis for ECHAM Outcomes



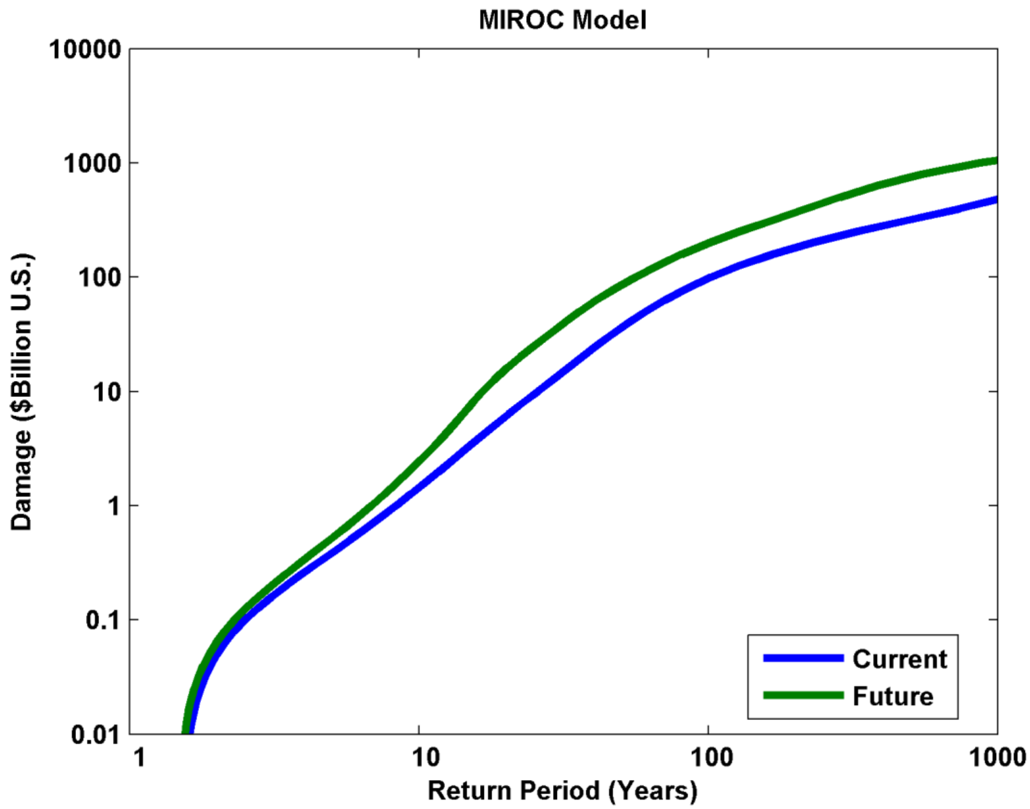
The return period shows the average number of years between storms causing a particular level of damages. The vertical axis is shown using the $\log_{10}$ purely for presentational purposes.

Figure 12: US Return Period Analysis for GFDL Outcomes



The return period shows the average number of years between storms causing a particular level of damages. The vertical axis is shown using the $\log_{10}$ purely for presentational purposes.

Figure 13: US Return Period Analysis for MIROC Outcomes



The return period shows the average number of years between storms causing a particular level of damages. The vertical axis is shown using the $\log_{10}$ purely for presentational purposes.

The most powerful storms are predicted to destroy everything in their path. We assume that these storms destroy all the capital in the five coastal counties nearest the first point of contact. Table 4 presents the fraction of complete destruction storms in each simulation assuming a future baseline and the minimum pressure damage model. These complete destruction storms are present in all the simulations, including those from the present climate. However, there are consistently more of these storms in the future climate than the current climate. The climate models predict that these maximum damage storms currently range from 0.09% to 1.14% of all storms. Given the historic frequency of US storms of 2.3/yr, this implies maximum destructive storms would come to the US every 38 to 480 years given the current climate. With the future climate, the return period for the US would fall to between 18 years to 89 years. Of course, the return period of a maximum destruction storm for any specific location is much higher than the US value. It will depend on how frequently such a storm hits that specific location.

Table 4: Percent of Complete Destruction Storms

Climate Model	Current Climate	Future Climate
CNRM	0.23%	0.49%
ECHAM	0.09%	0.89%
GFDL	0.18%	0.71%
MIROC	1.14%	2.44%

Note: Uses future baseline and minimum pressure damage function.

The use of four climate models provides a good sense of the role that climate uncertainty plays in this analysis. One can compare the results with each climate model to see what role that source of uncertainty contributes. The results are also sensitive to assumptions about economic growth and the damage function. As the economy grows faster or population increase more rapidly, there will be more in harm's way. The minimum pressure model suggests that damages will increase less than proportionally with these changes. The wind speed model suggests that damages will increase proportionally at least with respect to income. The elasticity of storm intensity is also a source of uncertainty. The minimum pressure model suggests that damages are a more elastic function of storm intensity than the wind speed model suggests.

In Table 5, we explore several additional sensitivity analyses using the minimum pressure model. We examine how changes in economic and population growth influence the final results. Increasing future 2100 US GDP from $88 trillion to $138 trillion (increasing the growth rate from 2 percent to 2.5 percent) increases both future baseline damage and the additional climate change damage by 63 percent. If population growth increases by 60 percent, future baseline damage and the additional climate change damage increase by 24 percent. Changing the damage function also matters. Increasing the elasticity of income to unity increases future baseline damage and the additional climate change damage by 250 percent. Increasing the elasticity of population to unity doubles future baseline damage and the additional climate change impact.

Table 5: Sensitivity Analysis of US Hurricane Damages Using Minimum Pressure Model

Experiment	Future Baseline (no CC) Damages	With-Climate Change Damages
Baseline	$27	$42
Population increases 60 percent	$33	$52
GDP Growth: 2.5 percent	$44	$68
Population Elasticity=1	$54	$84
Income Elasticity=1	$68	$105

Note: All values are in billions USD/yr. Current damages are $9 billion/yr. Baseline assumptions: GDP growth =2%, population growth 50%, income elasticity=0.4, population elasticity=0.5.

V. Conclusion

This study relies on an integrated assessment model to predict the economic damages that climate change may cause on hurricanes in the United States. Current and future climates are compared using the A1B emission scenario and four climate models. A hurricane generator is then used to create about 5000 hurricanes in the Atlantic Ocean that will strike the United States in each climate scenario and for each model. A set of estimated damage functions then calculate the resulting damages. The study is the most spatially detailed analysis of climate damages that has yet been undertaken. It is also the most careful analysis to combine the science and economics of hurricanes to date.

The study finds that hurricane damage in the United States is a highly nonlinear function of both minimum pressure and wind speed. A 1.2 percent drop in minimum pressure and a twenty percent increase in wind speed double hurricane damage. The current literature (with the important exception of Nordhaus 2010) has underestimated the elasticity of damages with respect to hurricane intensity. This paper favors the damage model with minimum pressure rather than maximum wind speed because it does a better job of explaining observed damage

The study is based on earlier observations that the current damage from hurricanes is equal to $9 billion/yr. The analysis confirms earlier findings that hurricane damages will increase substantially because more people and assets will be in harm's way even without climate change. By 2100, overall damages should increase three fold to $27 billion/yr according to the minimum pressure model and increase six fold to $55 billion/yr according to the wind speed model just because of increases in income and population in the eastern United States seaboard. The bulk of these baseline damages are along the Gulf Coast and Florida.

The study also finds that climate change is likely to increase US damage from hurricanes. The average additional damage that climate change could cause by 2100 is equal to $42 billion/yr according to the minimum pressure model and $40 billion/yr according to the wind speed model (about 0.05 percent of GDP). The additional damage with the minimum pressure model ranges from $15 to $58 billion/yr and the additional damage with the wind speed model ranges from $17 to $75 billion/yr depending on the climate model.

The study also finds that the increased expected damages from climate change are not uniformly distributed across the United States. The damages occur where hurricanes strike: along the Eastern seaboard of the country. Florida and the Gulf region are likely to endure 87 percent of the total additional US damage from climate change, the Southeast will endure another 12%, and the Middle Atlantic and New England regions will suffer less than 1 percent.

There are several sources of uncertainty in the estimation: the emission scenario, the climate scenarios, the hurricane response, the hurricane damage function, and the vulnerable assets and population. The factors that appear to contribute the most to the range of predicted damages are the climate models and the parameters of the damage function. The results across the climate models are quite different. Changing the magnitudes of the income and intensity elasticities in the damage function can make a huge difference.

There remains considerable work to be done. Improving the damage functions should be possible with more spatially explicit data. Including the effect of sea level rise in combination with hurricanes is likely to prove important. One study predicts sea level rise and storms to have an additive effect (Nicholls et al. 2008). Including adaptation is likely to be critical. The current model captures private adaptation but no adaptation policies. Yet adaptation policies are very important since they can reduce vulnerability by discouraging assets from being located in harm's way. Unfortunately, a great deal of current policy may have the opposite effect because assets in harm's way are often subsidized by public insurance and free disaster relief. Further, insurance regulations often prohibit insurers from charging fair actuarial insurance on highly risky locations such as the shoreline along Florida and the Gulf Coast.

One important policy result from this analysis concerns the concentration of damages in rare but powerful storms. With sea level rise, it is relatively easy to build sea walls that can limit the flooding from gradually rising seas. It is likely that most urban coastal areas will be protected from SLR with built up coast lines and sea walls. However, with severe storms, flooding will occur only rarely and at very high levels. The cost benefit ratio of building high walls is less obvious for an impact that occurs so infrequently. The appropriate adaptation strategy for hurricanes is likely to be quite different from the best adaptation strategy for SLR. Given that climate change will cause both SLR and more frequent strong hurricanes, it is critical that the best adaptation strategy for both problems be identified before excessive capital is invested in a problematic solution.

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Appendix A: State Hurricane Damages

State	Future Baseline Damages	CNRM	ECHAM	GFDL	MIROC
Alabama	347	1,053	2,393	8,804	1,366
Connecticut	69	35	-32	53	98
Delaware	21	10	2	12	61
Florida	12,989	7,062	10,141	29,887	19,533
Georgia	379	828	2,737	1,298	194
Louisiana	3,366	299	7,539	4,569	1,785
Maine	17	1	-4	11	4
Maryland	24	26	18	22	16
Massachusetts	64	27	-5	94	88
Mississippi	552	1,184	5,172	6,291	1,579
New Hampshire	1	1	0	0	-2
New Jersey	76	41	-12	46	208
New York	222	121	-128	136	443
North Carolina	512	2,698	1,036	2,554	1,076
Rhode Island	15	9	2	47	35
South Carolina	1,705	4,503	3,559	1,008	-890
Texas	6,229	-3,397	25,931	2,503	9,416
Virginia	165	94	-23	-58	1,214