POLICY RESEARCH WORKING PAPER 5562

The Impact of Climate Change on Global Tropical Storm Damages

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Abstract

This paper constructs an integrated assessment model of tropical cyclones in order to quantify the impact that climate change may have on tropical cyclone damages in countries around the world. The paper relies on a tropical cyclone generator in each ocean and several climate models to predict tropical cyclones with and without climate change. A damage model is constructed to compute the resulting damage when a cyclone strikes each country. Economic development is expected to double global tropical cyclone damages because more will be in harm's way. Climate change is expected to double global damage again, causing an additional $54 billion of damage per year. The damage is projected to be concentrated in North America and eastern Asia but many Caribbean islands will suffer the highest damages per unit of GDP. Most of the increased damage will be caused by rare but very powerful storms.

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Produced by the Research Support Team

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I. Introduction

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

And yet despite these findings, the link between climate change and tropical cyclone damage remains controversial. Partly this is due to the fact that tropical cyclones are rare events and appear to be subject to long term cycles so it is difficult to detect changes in underlying frequencies and severity (Landsea et al. 1999; 2006). There are approximately 50 tropical cyclones a year globally but some years can have very few and others over a hundred. 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 tropical cyclone 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 tropical cyclones.

The average current global damage from tropical cyclones is currently $26 billion/year (EMDAT 2009). Several authors have relied on the general result by Emanuel et al. (2005) that tropical cyclone intensity (wind speed cubed) would increase for the US with warming. Assuming damages increase with the cube of wind speed, US damages would increase by 56 percent (Hallegate 2007). However, most authors find that damages are proportional to a higher order power of wind speed and they predict that tropical cyclone damages in the US would double (Nordhaus 2006; 2010; Pielke 2007). Narita et al. (2008), using the FUND model, estimate that global tropical cyclone damages would also double. These analyses assume that every storm becomes more intense by a constant percentage.

In this paper, we take a different approach to estimating the impact of climate change on tropical cyclones by relying on a geographically detailed Tropical Cyclone Integrated Assessment Model (TCIAM) (Mendelsohn, Emanuel, and Chonabayashi 2010). The model begins with the A1B SRES global emissions trajectory that stabilizes greenhouse gas concentrations at 720 ppm (IPCC 2000). This path is one of the well established scenarios used by the IPCC in their Fourth Assessment Report (IPCC 2007a). There are consequently several climate model runs that were available using this scenario. We use this emission path in conjunction with four climate models to predict four global climate scenarios for both the present and the future (2100). These climate scenarios are then used to predict how tropical cyclones may change into the future using a newly developed tropical cyclone simulator (Emanuel et al. 2008). Potential storms are seeded into each ocean basin. Given both current climate and future climate conditions, the storms then either develop into tropical cyclones or they die off. A total of 3000 tropical cyclones are generated per basin[2]. This provides an extensive data set of tropical cyclones from which to examine whether current (2000) versus future (2100) storm patterns change. Normally, it would take three hundred years to observe this many tropical cyclones in nature.

The historic relationship between aggregate damages and the magnitude of each storm is estimated using data from storms that have hit the United States since 1960. Aggregate damages include the value of all lost structures and infrastructure. Damages do not include fatalities. Fatalities are estimated separately. Impacts in different years are updated to current dollars using the GDP deflator. 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 inferred from Census data for the five counties closest to the point of contact. A regression estimates the relationship between storm intensity and damages. We then use international data (EMDAT 2009) to estimate the relationship between storm damages and national income and population density (vulnerability). The limitation of the international data is that it has no information about the intensity of each storm.

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[2] 5000 tropical cyclones are seeded into the North Atlantic to get extra accuracy of the changes in this ocean.

The estimated regression coefficient on storm intensity from the US analysis and the estimated coefficients o income and population density from the international regression are then used to predict the damages that would be caused by each storm in the generated data set. The global data set of 17,000 storms for both current and future climate is a rich data set that describes the expected value and distribution of tropical cyclone damages. The comparison of the results across the four climate models also provides an additional sense of the uncertainty of the estimates with respect to climate. We use both a minimum pressure damage model and a maximum wind speed model to reflect some of the uncertainty in the damage function. In each case, the damages to each country are estimated and then aggregated.

The analysis first calculates the damages to each country from tropical cyclones with the current economic baseline and current climate. The damages are then predicted for the future using projected populations and economies in 2100. This analysis reveals how much baseline damages will increase because of higher incomes and populations given the current climate.

The second analysis estimates the impact of climate change on tropical cyclone damages. Climate change impacts are calculated as the tropical cyclone damages with a 2100 climate minus the tropical cyclone damages given the current climate, both estimated using future income and population.

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 a few 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 primarily on lost buildings and infrastructure. 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 tropical cyclones, it is critical to recognize that they are rare events. An important component of expected damages is the frequency or probability (π) the storm will occur in each place. In this case, we are interested in the probability that a tropical cyclone with particular characteristics (*X*) will strike a particular place. For example, the intensity of the storm can be measured either by its minimum barometric pressure (*MP*) or maximum wind speed (*WS*). Damages will 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 damages associated with any given tropical cyclone (*j*) also depend on the vulnerability (*Z*) of each place (*i*). For example, the damage function in each location (*i*) could depend on population density (*POP*) and income (*Y*):

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

Actual damages will also depend upon the adaptation (*A*) measures 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 any of these adaptation variables and so they cannot be included at this stage.

The expected value of tropical cyclone damages is:

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

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:

$$W = E[D(C1)] - E[D(C0)] \tag{4}$$

Note that this value is summed across all the storms. 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 tropical cyclone damages can be done for each country, for regions, or for the entire world. The calculation of the damages with and without climate change should be done holding the characteristics of each country constant. Otherwise, one will confuse changes caused by economic and population growth with changes caused by climate. Damages are estimated by country and then aggregated. The paper also reports regional results. Country specific results are available in Appendix A for each country and climate model.

Equation 4 calculates the expected welfare loss from climate change. The model also calculates the probability density function (pdf) of damages. The pdf describes the probability of different levels of damage per storm:

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

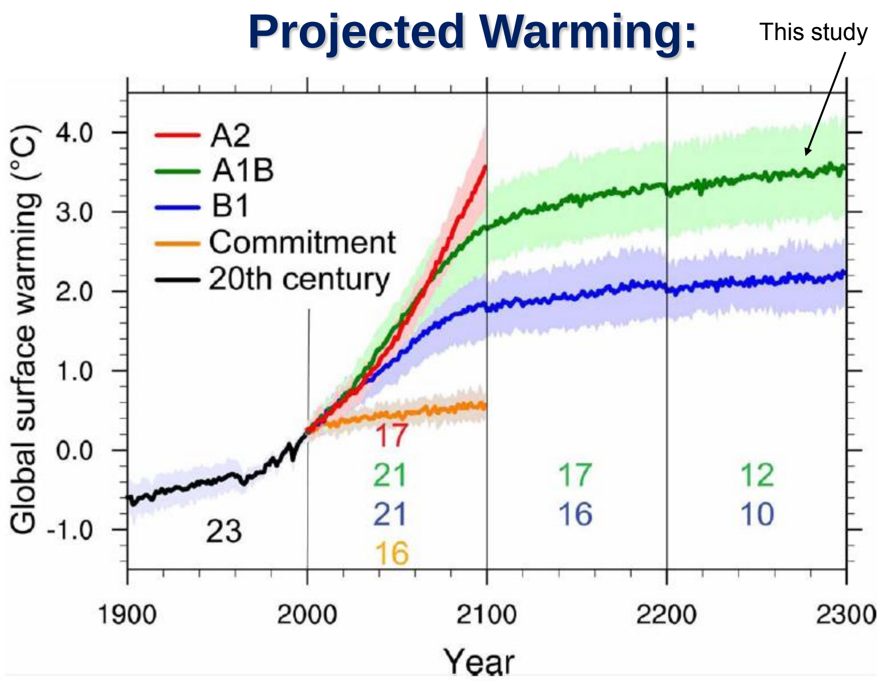
The frequency distribution allows policy makers to see what risks they face. The distribution indicates the level of damage and its chance of occurring. Similarly, a return period for damages is also calculated. This is a relationship between the average years between tropical cyclones that cause specific amounts of damage:

$$\mathrm{Re}turn = 1/\mathrm{Pr}ob(D) = g(D(X)) \tag{6}$$

III. Tropical Cyclone Integrated Assessment Model

The TCIAM has been constructed to project tropical cyclone risks given different climates. 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 tightened gradually over time so that greenhouse gas concentrations finally peak and stabilize at 720 ppm. Note that this is not a zero mitigation path (Business As Usual) which would lead to even higher emissions.

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). 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. By comparing current and future results within each model, we can isolate what each model is predicting will change. The climate scenario used in this analysis is shown in Figure 1. Note that a range of temperature changes are predicted for this emission scenario.



Using a tropical cyclone generator in each ocean basin, the climate data is used to project 17,000 tropical cyclone tracks (Emanuel et al. 2008). There are 3,000 tracks in four of the ocean basins and 5,000 tracks in the North Atlantic. Tropical cyclone tracks for both the current climate and future climate are predicted. Tracks are also estimated for each climate model. Altogether 8 sets of 17,000 tropical cyclones are generated. For each track, we follow where the tropical cyclone makes landfall. Tropical cyclones that land on continents are assumed to terminate there. Tropical cyclones that pass over islands are assumed to continue and can strike multiple locations. The minimum barometric pressure and the maximum wind speed at landfall of each storm are recorded. The models are also used to predict the expected frequency of tropical cyclones in each ocean basin.

A damage function is then used to predict the damage 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 (NOAA 2009). Several storm characteristics were tested including maximum wind speed and minimum barometric pressure. Vulnerability measures were used to control for population density and income at each impacted coastal area. These data were inferred for each year from decennial Census data by county (US Census of Population 1960, 1970, 1980, 1990, 2000).

A separate damage analysis was then conducted of tropical cyclones around the globe (EMDAT 2009). The international data set was used to estimate the coefficients for vulnerability (income and population density). The observations in this data set are damages and fatalities per country and event. These were matched with national income and population. All dollar values were adjusted for inflation to USD 2010.

Some storms were predicted to cause so much damage that damages exceeded the capital stock in the path of the storm. Storm damages were truncated at a maximum where all the capital ashore is destroyed. A value for US storms was calculated that assumed a highly destructive storm would destroy five coastal counties completely (Mendelsohn et al. 2010). The average damage for the US for these highly destructive storms was $172 billion per storm in 2100. This average national value was then transferred to other countries in proportion to their GDP in 2100. Countries with higher future GDP have higher maximum values.

The model calculated damages for each storm in the data set given its intensity and which country it landed in. The expected damages were calculated by summing the product of the probability of each storm times the damage it causes. Separate estimates were made by country. The damages were them summarized by continent. The probability distribution of global damages for storms was also calculated.

IV. Results

The climate changes in 2100 predicted by each climate model vary even though they share the same A1B emission scenario. 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 increase warm sea surface temperatures which in turn fuel the tropical cyclones. However, there are other changes in wind shear and wind direction that can reduce tropical cyclone intensity as well.

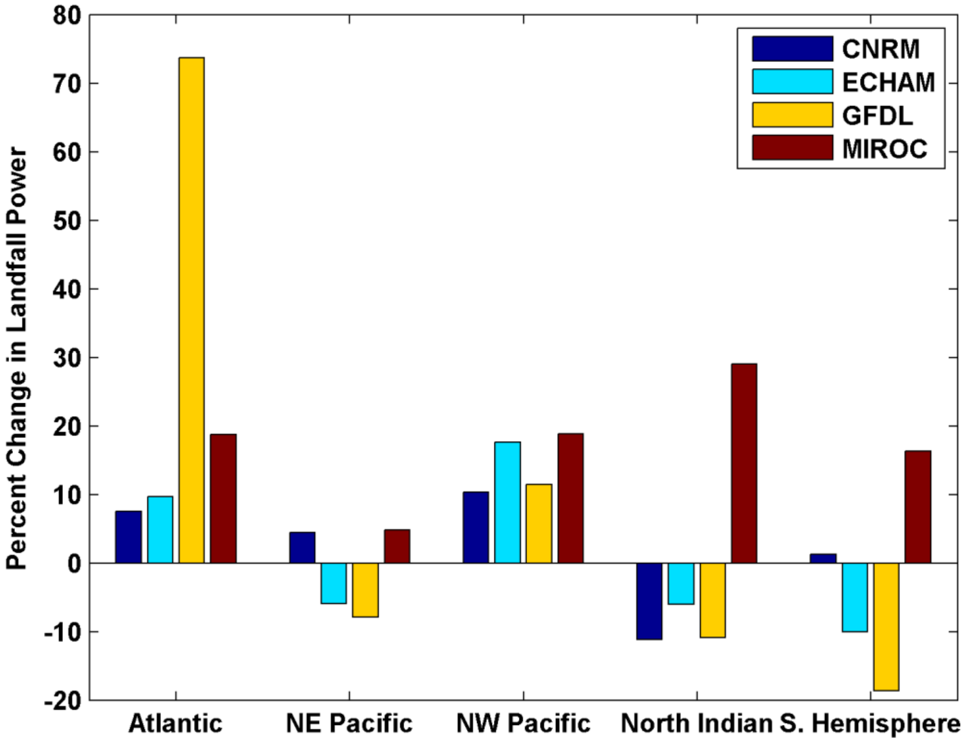
The 17,000 storms in each scenario have different properties. Table 1 presents the average minimum pressure and wind speed of all the global storms at landfall. It is clear from Table 1 that average wind speed has increased and average minimum pressure has fallen in the future climate relative to the current climate in every scenario except GFDL.

Table 1: Average Global Minimum Pressure and Wind Speed at Landfall by Scenario

Climate Model	Climate	Minimum Pressure	% Change Pressure	Wind Speed	% Change Wind Speed
CNRM	Current	990.0		52.5	
	Future	990.0	-0.005%	52.8	0.406%
ECHAM	Current	989.1		53.8	
	Future	988.2	-0.097%	55.2	2.576%
GFDL	Current	988.0		55.1	
	Future	989.5	0.151%	51.2	-7.032%
MIROC	Current	989.2		53.6	
	Future	988.1	-0.110%	55.0	2.664%

However, the average global changes hide important changes. First, climate change does not alter the bulk of storms. Only more powerful storms appear to be affected by climate change. Second, the effects are not similar across each ocean basin. Figure 2 shows the changes in intensity by ocean basin between the tropical cyclones in the future (2100) climate versus tropical storms in the current climate. Intensity consistently climbs in two of the ocean basins: the North Atlantic and the North Western Pacific across all four models. These predicted changes in tropical cyclone intensity will especially influence damages in North America and Asia respectively. Changes in the other ocean basins are not consistent across the climate models with some predictions of an increase in intensity and other predictions of a fall in intensity.

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



Note: Intensity is the cube of maximum wind speed. The change in intensity is the difference between the intensity with the future climate minus the intensity with the current climate.

Table 2 shows the relationship between aggregate US damages and storm intensity. The regression shows that damages are a highly nonlinear function of minimum pressure, intensity. Damages increase inversely with the 86th power of minimum pressure. A similar regression using wind speed reveals that damages increase with the fifth power of wind speed. In contrast, damages are assumed to be a function of the cube of wind speed in the traditional tropical cyclone literature (Emanuel 2005). Nordhaus (2010) finds that damages increase with the ninth power of wind speed. We rely on the minimum pressure measure of storm damage because it is more significant than wind speed and does a much better job of explaining aggregate damages. The 95% confidence interval for the minimum pressure damage coefficient lies between -69 and -103. In contrast, the vulnerability damage coefficients in Table 2 are not significant.

Table 2: Regression of US Tropical Cyclone Impacts on Intensity and Vulnerability

Model	Constant	Log (Minimum Pressure)	Log (Income)	Log (Population Density	Adj Rsq/ F Stat
Damage	607.5 (10.39)	-86.3 (9.96)	0.370 (0.45)	0.488 (1.53)	0.501 35.76
Fatality	247.5 (4.10)	-33.3 (3.69)	-2.36 (1.74)	1.28 (2.78)	0.208 4.42

Note: There were 111 observations in the damage regression and 40 observations in the fatality regression. The t statistics are in parenthesis. The functional form of the regression is log log. Source: NOAA(2009).

Table 2 also shows the impact of tropical cyclones on US fatalities. Only 40 of the 111 storms to strike the US caused any deaths. The results are consequently less accurate than the damage results. Nonetheless, there are some interesting findings. More powerful storms cause more deaths, although the elasticity of intensity is not as large as in the damage regression. The 95% confidence interval for the minimum pressure fatality coefficient lies between -15 and -51. Higher incomes lead to lower deaths but the coefficient is not significant at the 5% level (the t-statistic is less than 2). More dense US populations had higher fatalities. Cities in the US were more vulnerable to fatalities than more rural locations.

In order to understand the role of vulnerability, we turn to international data. The international regressions measure the relationship between damage and fatalities and population and income (using international data EMDAT 2009). Storm intensity is not recorded in the international data so it is an omitted variable. Table 3 reveals that damages increase with income but fall with population density. These coefficients are significantly different from zero. Perhaps more important, they are significantly different from unitary (1). The elasticities of income and population are less than 1, contrary to assumptions in the literature Pielke and Landsea 1998, (Pielke et al. 2008, and Nordhaus 2010). It is likely that people privately adapt to reduce damages as their incomes rise and as they urbanize. The damages consequently do not rise proportionally with income or population in a specific location. Note that the coefficients on income and population density are far more significant in Table 3 than in Table 2. This is probably because there is a lot more variation in the international sample compared to the sample of counties in the US.

Table 3: International Regressions of Global Tropical Cyclone Damages and Fatalities

Impact	Constant	Log(Income)	Log(Population Density)	Adj Rsq/ F Stat	N
Damages	15.17 (22.77)	0.415 (6.44)	-0.21 (3.04)	0.066 29.6	807
Fatalities	6.25 (18.20)	-0.477 (14.01)	0.07 (1.86)	0.158 103.2	1089

Source: EMDAT 2009. The t statistics are in parenthesis. The functional form of the regression is log log.

The results in Table 3 also reveal that fatalities fall with income. The elasticity implies that a doubling of income reduces fatalities by 50%. Fatalities increase with population density but only slightly. A doubling of population density increases fatalities by only 7%. However, both the income and population density coefficient are significantly different from 1. That is, the 95 percent confidence interval for the income fatality coefficient lies between -.48 and -.47 and the confidence interval for the population density coefficient lies between -.01 and 0.22. The data suggest wealthier people protect themselves from tropical cyclones and that the risk per person falls as populations become more urbanized. Note that there are more storms that cause fatalities in the international data set than cause damages. This is because the international data set has a minimum damage requirement before storm damages are reported. It is not likely that this will bias the results because the bulk of damages done by tropical storms are caused by the most powerful storms.

We rely on the US regressions for the storm intensity coefficients. We rely on the international coefficients for the income and population density coefficients. We then calibrate the damage function for each country so that current baseline and current climate lead to observed national damages:

$$D = A_D * MP^{-86} Y^{0.06} Pop^{-0.2} \qquad (7)$$

$$F = A_F * MP^{-33} Y^{-0.5} Pop^{0.07} \qquad (8)$$

In order to test whether other variables may also influence the damage function, a set of damage regressions were explored using the international data set. Democratic elections, the literacy of men and women, infant mortality rates, HIV rates, the Gini coefficient, and the percent of people living in poverty were all tested and found to be insignificant. As shown in Table 4, the percent urban is quite significant. As with population density, the percent urban suggests that damages fall rapidly as density rises.

Table 4 Alternative Damage Regression

Variable	Coefficient (t statistic)
Constant	13.76 (3.73)
Log (Population Density)	-0.17 (1.76)
Log (Income)	0.95 (7.43)
Log (urban)	-2.99 (7.22)
Log(Gini index)	-1.25 (1.71)

The damage function is then used to estimate the impacts of each tropical storm generated by each climate model. The climate models are also used to predict the intensity and frequency of each storm in each ocean basin. By construction, the global expected damages given current climate and current baseline conditions are $26 billion per year (0.043 percent of GWP).

In order to project how damages might increase with economic growth, both population and income are projected to 2100. The population in each country is assumed to follow projections made by demographers (United Nations 2004). GDP is assumed to grow at a 2 percent rate in developed countries, 2.7 percent in developing countries, and 3.3 percent in emerging countries[3]. Dividing GDP by population yields a future prediction of income per capita for each country in 2100. Using the future baseline leads to higher expected damages even with the current climate. With future baseline conditions in 2100 and the minimum pressure model, the global expected damage with current climate will grow to $55 billion per year (0.01 percent of GWP). Damages will grow more slowly than GDP because the coefficients on income and population in the damage function are less than 1.

It is important to understand that tropical cyclone damages are not uniformly distributed across the planet even without climate change. Figure 3 displays the distribution of current and future damages from tropical cyclones without climate change. The bulk of current tropical cyclone damages occur in North America (59 percent) and Asia (29 percent). With economic growth, the predicted distribution would shift by 2100 so that North America would have 48 percent and Asia 38 percent of global damages. Damages are likely to be concentrated in these two continents partially because they have a lot in harm's way and partially because this is where tropical cyclones are most frequent and intense.

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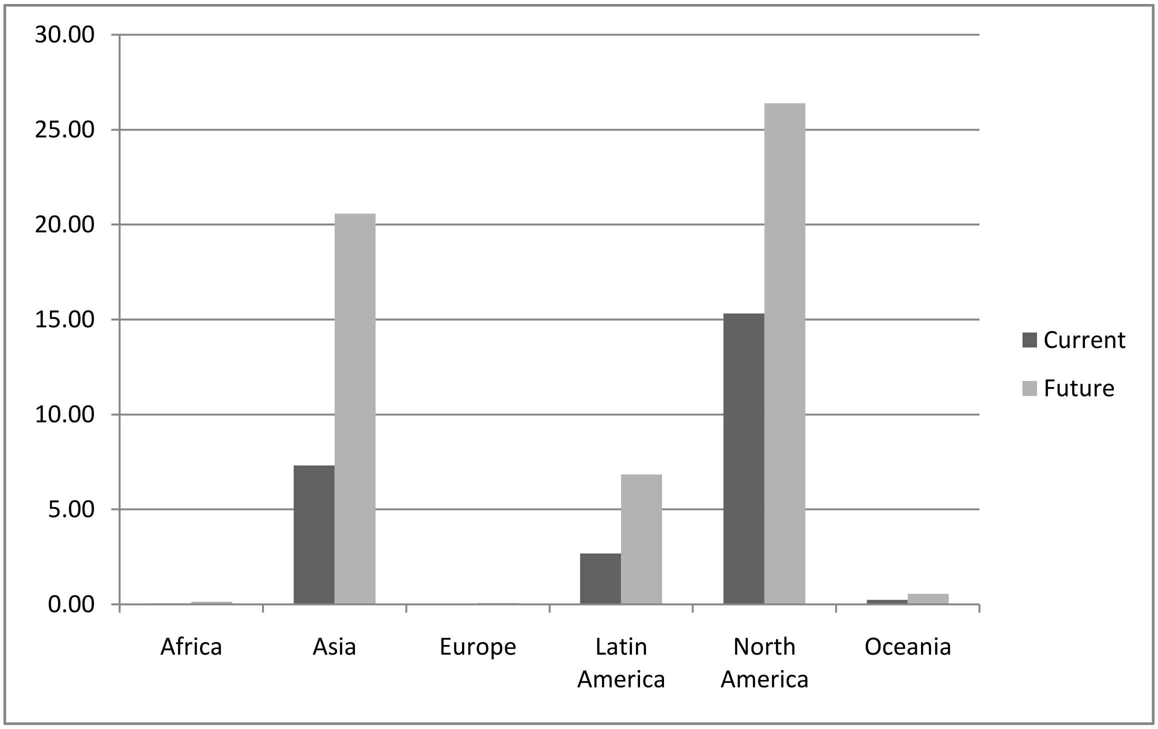
[3] Emerging countries include Argentina, Brazil, Chile, China, Columbia, Czech Republic, Egypt, Hungary, India. Indonesia, Mexico, Morocco, Peru, Philippines, Poland, South Africa, and Turkey.

Figure 3: Current and Future Baseline Tropical Cyclone Damages



Damages in billions USD with current climate.

In order to calculate the impact of climate change, the damages from tropical cyclones are calculated for the future baseline with and without climate change. The additional impact of climate change is the difference in damages with the 2100 climate versus the current climate. Both measures of damages are calculated using the future baseline so that changes in baseline conditions are not being confused with change in climate. Note that by evaluating the impact of climate change using the future baseline, the impacts are larger than they would have been with the current baseline.

The results, shown in Table 4, reveal that climate change by 2100 is expected to cause tropical cyclone damages to increase $54 billion/yr (a 100% increase above the baseline). This additional damage is equal to 0.01 percent of GWP. Looking across the different climate models, the additional damages from climate change are between $28 and $68 billion/yr. The results are consistent with most of the findings in the literature that climate change might double tropical cyclone damages.

Table 4: Increased Tropical Cyclone Damages from Climate Change

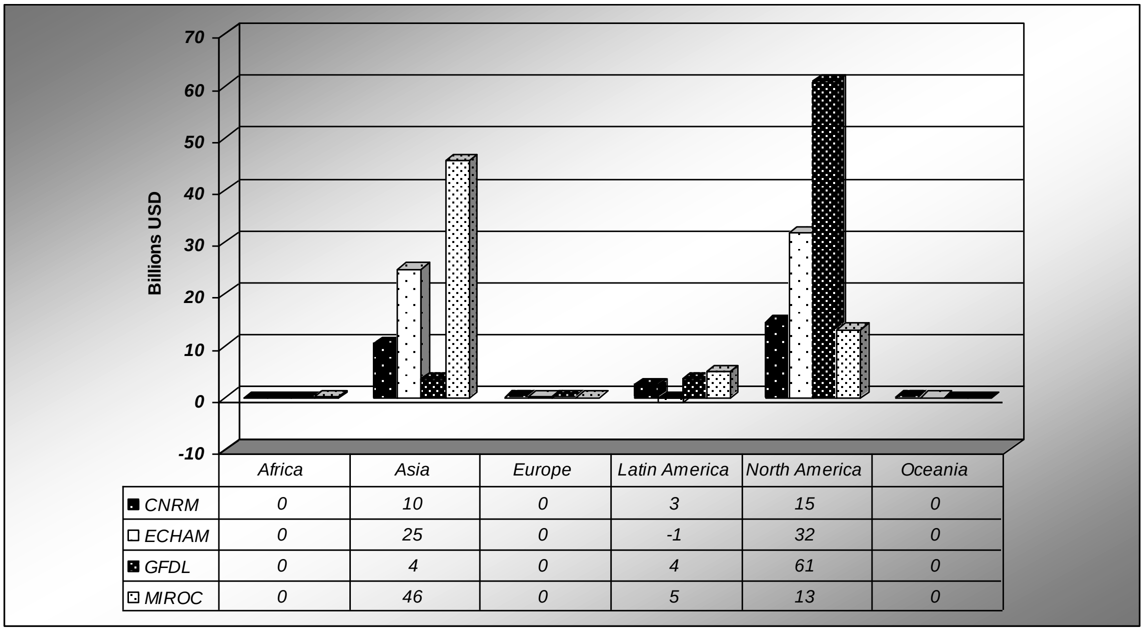
Damage Model	CNRM	ECHAM	GFDL	MIROC
Damage	28	55	68	64

Note: Damages are in billions of USD/yr based on A1B emission scenario and 2100 baseline.

However, what is unique to this paper is that it also predicts the distribution of damages across the world. Figure 4 displays the additional damages caused by climate change in each continent. The results from the tropical cyclone modeling (see Figure 2) suggests that the North Atlantic and the Western Pacific oceans are the primary oceans that will respond to warming, Consequently, Asia and North America are the two continents that are predicted to be consistently affected by more severe tropical cyclones. This is evident in Figure 4. North American and Asia would suffer the highest additional damages from climate change: $30 billion and $21 billion respectively. The additional damages from global warming in the rest of the world are likely to be small and inconsistent. In some regions and models, the damages from tropical storms are expected to fall with warming. Note that the predicted regional damages vary a great deal across the climate models. For example, GFDL predicts especially large impacts in the Western Hemisphere, MIROC predicts especially large damages in Asia, and ECHAM predicts large damages in Asia and North America.

Figure 5 displays the additional tropical cyclone damages caused by climate change 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 was 0.01 percent. North America (0.03 percent of GDP) and Asia (0.01 percent of GDP) would have the largest average impacts per unit of GDP. The tropical cyclone damages per unit of GDP caused by climate change is expected to be low in the remaining continents.

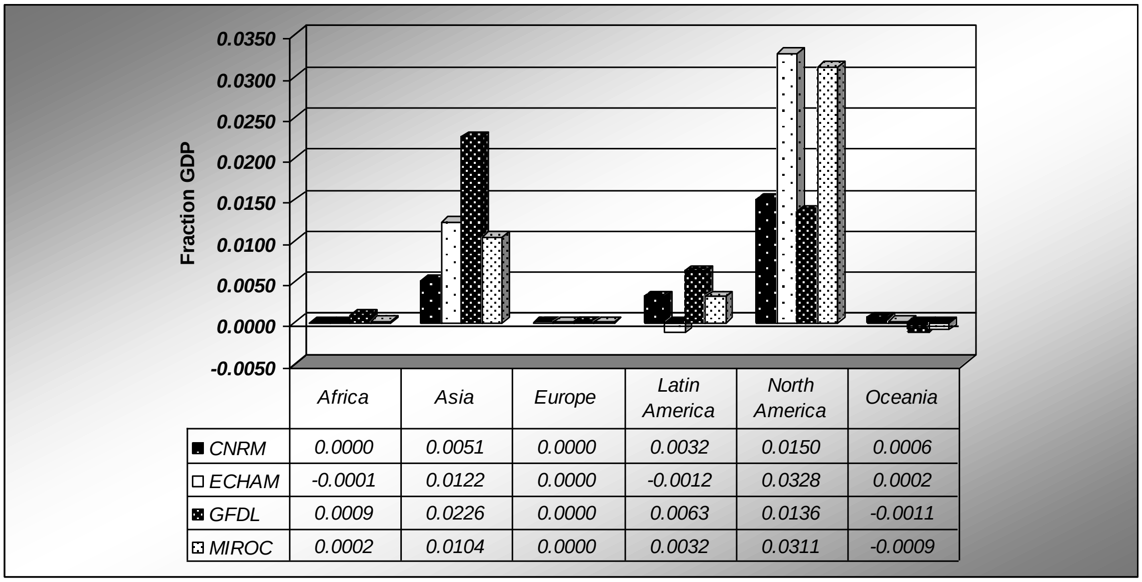
Figure 4: Additional Tropical Cyclone Damages Caused by Climate Change by Region by 2100



	Africa	Asia	Europe	Latin America	North America	Oceania
■ CNRM	0	10	0	3	15	0
□ ECHAM	0	25	0	-1	32	0
▩ GFDL	0	4	0	4	61	0
⊡ MIROC	0	46	0	5	13	0

Note: Additional annual damages in billions of dollars calculated using minimum pressure damage model with 2100 baseline.

Figure 5: Tropical Cyclone Damages as a Fraction of GDP



	Africa	Asia	Europe	Latin America	North America	Oceania
■ CNRM	0.0000	0.0051	0.0000	0.0032	0.0150	0.0006
□ ECHAM	-0.0001	0.0122	0.0000	-0.0012	0.0328	0.0002
▩ GFDL	0.0009	0.0226	0.0000	0.0063	0.0136	-0.0011
⊡ MIROC	0.0002	0.0104	0.0000	0.0032	0.0311	-0.0009

Note: Additional damages caused by climate change calculated using minimum pressure damage model with 2100 future baseline.

The continental averages, however, hide disproportionate effects in individual countries. The expected additional damages from climate change to all affected countries for each climate model are shown in Appendix A. The countries with the likely largest tropical cyclone impacts from climate change are the United States ($30 billion), Japan ($9 billion), and China ($8 billion). The climate change damages to these three countries account for 88 percent of the global damages. However, other countries could suffer climate change impacts which are a relatively large fraction of their GDP. The 9 countries listed in Table 5 may endure additional tropical cyclone damages greater 0.2 percent of their GDP. All but one of these countries is an island in the Caribbean. The largest impact is to St Kitts-Nevis with additional damages possibly equal to 1.4 percent of their GDP.

Table 5: Additional Damage From Climate Change to Most Heavily Impacted Nations

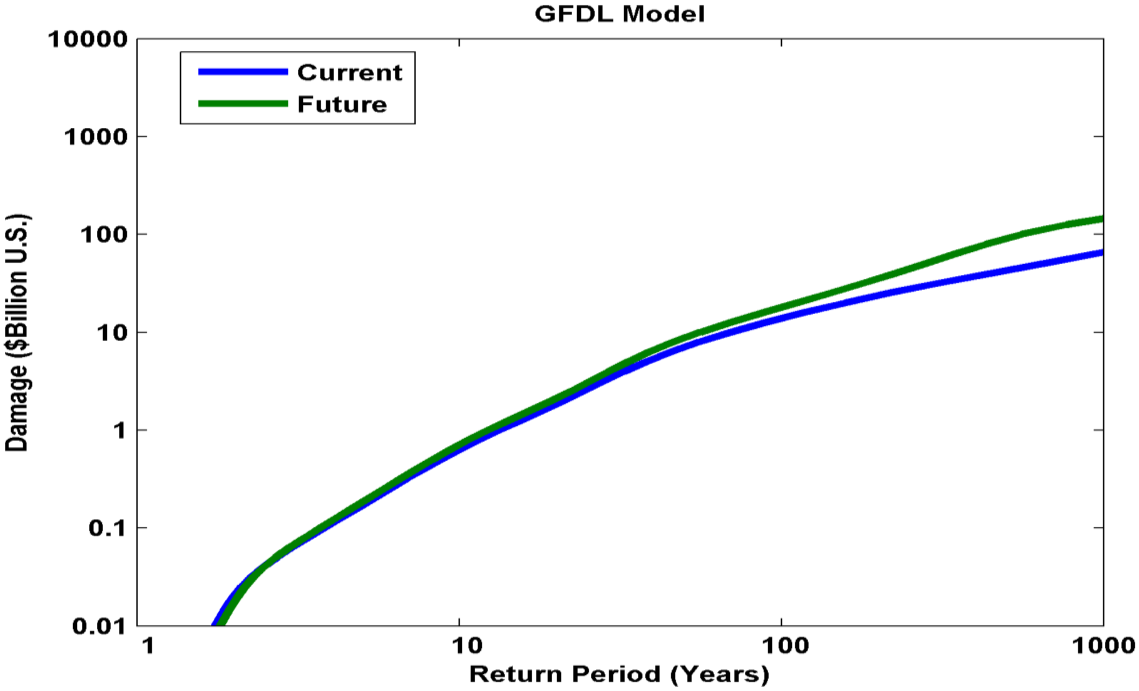
Country	Average Damage	Percent of GDP
Antigua-Barbados	69	0.5%
Cayman	75	0.5%
Dominica	22	0.5%
Grenada	24	0.3%
Honduras	553	0.3%
Montserrat	3	0.2%
St. Kitts-Nevis	91	1.4%
Turks-Caicos	17	0.4%
US Virgin Islands	184	1.0%

Source: Additional tropical cyclone damages in millions of USD/yr calculated using the minimum pressure model and the future baseline in 2100.

Although expected damages provide a good sense of long term damages, they hide the skewed nature of tropical cyclone damages. Many storms cause relatively little damages. However, a few storms cause very large impacts. Figure 6 displays the relationship between damages and return rates for the GFDL model. The return rate is 1/frequency and it explains how many years pass on average before one is expected to see another storm of this magnitude. The figure reveals that, in the current climate, most tropical storms cause relatively small damages but a few cause very large damages.

Figure 6 also reveals that climate change is not expected to change the entire distribution of storms. The pattern of small and frequent storms is expected to remain the same as it is with the current climate. Climate change is primarily expected to affect only the largest most powerful storms. The analysis suggests that the return rate of the most powerful storms is shorter- they will become more frequent. Or to put the same result another way, these rare storms will become even more powerful with climate change. Return rate figures for the other climate models are not shown but they are similar. For example, the current and future return period functions are more similar for the CNRM climate model, suggesting there is only a small effect from climate change. The remaining models predict much larger shifts with the future climate.

Figure 6: Return Period for Current and Future Climate (GFDL)



Note: Estimates calculated using 2100 baseline, minimum pressure, and GFDL climate model. Axes are in logs for ease of presentation.

It is important to stress that a surprisingly large fraction of the expected value of tropical storms is caused by the most harmful storms. Table 6 presents the expected fraction of total damages caused by the top 10 percent and top 1 percent worst storms. Storms are ranked by the damage they cause. Even with the current climate, the top 10 percent worst storms cause 90 percent of the total damages from tropical storms. The top 1 percent worst storms cause 58 percent of all the damages. With the future climate, those percentages would likely climb. The top 10 percent worst storms are predicted to cause 93 percent of the damages and the top 1 percent of storms are predicted to cause 64 percent of all damages from tropical storms.

Table 6: Fraction of Total Damages Caused by Most Harmful Storms

Model	Climate	Top 10 Percent Worst Storms	Top 1 Percent Worst Storms
CNRM	Present	90.9%	63.7%
CNRM	Future	93.6%	70.4%
ECHAM	Present	87.2%	53.4%
ECHAM	Future	92.7%	62.3%
GFDL	Present	88.9%	48.9%
GFDL	Future	92.1%	59.3%
MIROC	Present	92.6%	63.9%
MIROC	Future	94.3%	65.5%

Note: Assumes baseline in 2100 and minimum pressure damage model.

Many of the most powerful storms would destroy everything in their path. We assume that these storms destroy all the capital within five coastal counties. Table 7 presents the predicted percent of storms that cause total destruction in each simulation. All the simulations assume the future baseline and use the minimum pressure damage model. These powerful storms are present in both the current and future climates. The only climate model where the number of truncations is significantly different between the current climate and the future climate is the MIROC model.

Table 7: The Percent of Complete-Destruction Tropical cyclones

Climate Model	Current Climate	Future Climate
CNRM	1.3%	1.6%
ECHAM	6.1%	6.0%
GFDL	4.5%	4.4%
MIROC	4.7%	6.3%

There are several sources of uncertainty in the modeling. In order to get a better sense of the relative importance of different assumptions, we undertake a sensitivity analysis. The report has already shown the relevance of different climate scenarios by showing the results from 4 different climate models. In this sensitivity analysis, we examine several other assumptions. A higher population leads to slightly lower damages because of the negative elasticity with respect to population density. Higher GDP leads to higher income which increases baseline damages about 9% and climate change damages about 7 percent. However, the results are quite sensitive to changes in the damage function. A unitary population elasticity of damages increases baseline damages by 25 percent and climate change damages by 23 percent. A unitary income elasticity increases baseline damages by over 250% and climate change damage by 230%. The empirical finding that the elasticity of population and income is less than one is very important. The fact that many earlier analyses simply assumed these elasticities were unitary would have caused these studies to overestimate damages.

Table 8: Sensitivity Analysis of Global Damages

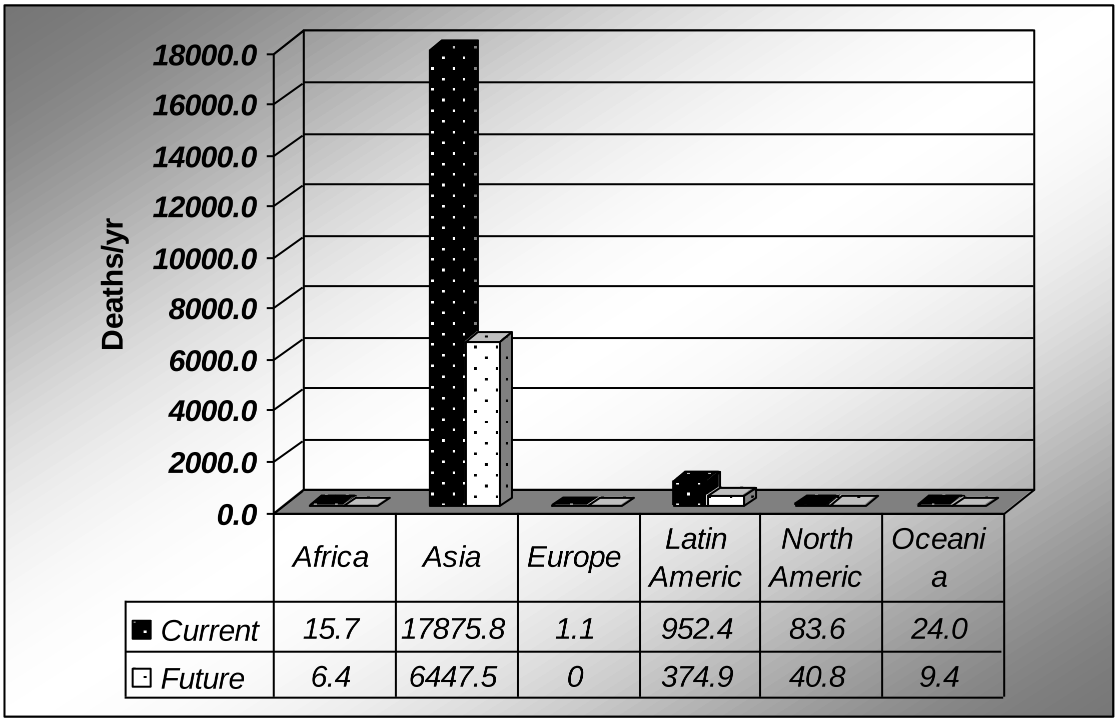
Scenario	Future Baseline	Climate Change
Baseline	$54.9	$53.7
Population=10 billion	$54.3	$52.4
GDP=+20%	$59.6	$57.2
Population elasticity=1	$68.4	$65.8
Income elasticity=1	$194.7	$178.2

Note: Damages are measured in billions of USD/year. Baseline assumes population is 9 billion, GWP is $565 trillion, the population elasticity is -0.2, and the income elasticity is 0.4.

The model was also used to calculate the fatalities associated with tropical cyclones. Currently, there are 19,000 fatalities/yr from tropical cyclones. As incomes rise, however, that number is expected to fall. The model predicts that the annual global number of fatalities will fall to 7,000 by 2100 just from economic development (rising income and population density).

Fatalities would not be spread equally across the globe. Figure 7 presents the projected current and future fatalities from tropical cyclones in each continent. The results make clear that almost all deaths from tropical cyclones would occur in Asia (94 percent). In fact, two countries would be responsible for 83 percent of all deaths from tropical cyclones: Bangladesh and Myanmar. Because Myanmar and Bangladesh are responsible for such a large fraction of total deaths, they tend to dictate what happens to the world total.

Figure 7: Projected Baseline Fatalities



	Africa	Asia	Europe	Latin Americ	North Americ	Oceania
■ Current	15.7	17875.8	1.1	952.4	83.6	24.0
☐ Future	6.4	6447.5	0	374.9	40.8	9.4

In order to calculate the additional impact of climate change on fatalities, we calculate the difference between the tropical cyclone deaths in a future world with the climate in 2100 minus the tropical cyclone deaths in a future world with the current climate. The analysis using minimum pressure reveals that climate change would cause 670 fewer deaths than the current climate. This value could vary from an increase of 1300 additional deaths to a reduction of 3300 deaths depending on the climate model. What happens globally is largely dictated by what happens in Myanmar and Bangladesh. For example, in the MIROC model, storms become more intense on the Indian Ocean and fatalities in Bangladesh and Myanmar increase by 1028 and global fatalities increase by 1303. However, in the GFDL scenario, the intensity of storms in the Indian Ocean falls, fatalities in Bangladesh and Myanmar fall by 3240, and global fatalities fall by 3266.

V. Conclusion

This study relies on a Tropical Cyclone Integrated Assessment Model to predict the damages that climate change may cause to tropical cyclones. The A1B emission scenario is combined with four climate models. A tropical cyclone generator is then used to create 3000 tropical cyclones in each of five ocean basins for both the current climate and the future climate. The path and magnitude of each of these storms is followed for each scenario. The results of this analysis suggest that climate change will cause tropical cyclone intensity to increase in both the North Atlantic and North West Pacific ocean basins. The reliance on modeling individual storms in this study leads to far more accurate measures than using blanket assumptions about increased intensity. The analysis is the first to be able to detect different outcomes in different locations.

The study also estimates a new damage function for tropical cyclones. Data from the United States is used to estimate the relationship between damage per storm and storm intensity. The analysis suggests that minimum pressure provides a more accurate measure of storm intensity than maximum wind speed. The results of this analysis suggest that damages are highly sensitive to storm intensity. Damages are expected to double with a 1.2 percent decrease in minimum pressure.

International data is then used to estimate the relationship between national damages and income and population density. The results of this analysis suggest that damages increase with income but fall slightly with population density. A doubling of income increases damages by 40 percent. Doubling population density reduces damages by 20 percent. The results using the international data indicate that the vulnerability of countries does not vary in proportion to income and population as previously thought. The income and population elasticity of damages is less than unitary. As incomes rise in the future, damages from tropical cyclones will increase, but not as fast as previously thought. Future income and population is predicted to increase tropical cyclone damages from $26 billion to $55.5 billion USD/yr with the current climate. Future damages will double even without climate change. 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 of GWP in 2100.

The impact of climate change is estimated using the future baseline income and population. The impact of climate change is equal to the future tropical cyclone damage with a warmer climate minus the future tropical cyclone damage with the current climate. Using the minimum pressure damage model, the estimated impact of climate change on tropical storm damages ranges from $28 to $68 billion USD/yr (0.005 to 0.012 percent of GWP) by 2100. This represents an increase of between 50 percent and 122 percent over future baseline levels. Climate change is expected to double the damages from tropical cyclones by 2100 by $54 billion USD/yr. The findings confirm the results of earlier tropical cyclone studies that relied on cruder methods.

The damages would 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 are likely to have the largest and most consistent impacts. The average additional impact in Asia is predicted to be $21 billion of damages and the average additional impact in North America is predictedt to be $30 billion of damage. The average impact on the rest of the world is predicted to be just $3 billion because the remaining continents see both harmful and beneficial impacts depending on the climate model. A beneficial impact is simply a reduction in existing tropical cyclone damages. Even controlling for GDP, North America and eastern Asia are predicted to bear the highest damages per unit of GDP. However, the most vulnerable countries are predicted to be relatively small islands especially in the Caribbean.

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. The 1 percent worst storms in the world account for 58 percent of the damages. With warming, these powerful storms get even more harmful. In a warmer climate, the 10 percent worst storms are predicted to account for 93 percent of the total damages and the 1 percent worst storms are predicted to account for 64 percent of the total damages. Because these large storms explain so much of the story and are very rare, it is very difficult to rely on observations of tropical storms over time to detect a trend. The large storms are so rare so that it may take several centuries of observations to see whether there is a change in their frequency.

The analysis also examines the impact of tropical cyclones on fatalities. The analysis finds that almost all deaths from tropical cyclones occur in just two countries: Myanmar and especially Bangladesh. The impact of climate change on tropical cyclone deaths depends on what happens in these two nations. Since the model predicts that tropical cyclones in the Indian Ocean might get more intense but more likely will get less intense, deaths in these two countries are expected to fall. Consequently, global deaths are expected to fall.

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 any government 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 different projections by the four climate models used in this analysis. Exactly how tropical cyclones will react to climate change is also uncertain as it depends upon many factors that are difficult to predict. Finally, the magnitude of the damages that future tropical storms will cause is uncertain. The damages with respect to storm intensity appear to be very sensitive to minimum pressure. The damages are also very dependent on the elasticity of population and especially income. However, the vulnerability parameters are quite different depending upon whether one uses US or international data. There is a clear need for better international data that includes the intensity of storms as well as their location. How damages might change if there is both a change in tropical cyclones and sea level rise has barely been analyzed. Nicholls et al. 2008 suggest an additive effect between sea level damages and storm damages. But the interaction between these two effects may be more than additive. This is clearly a topic that deserves further research.

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 in harm’s way. For example, subsidizing flood insurance and capping the cost of catastrophic insurance makes it cheaper to live in risky locations. Even providing federal disaster relief reduces the overall cost of choosing a risky location to develop. 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 because most of the damage is caused by rare but very powerful storms with 5 meter storm surges. Walls would have to be very strong and high to prevent inundation but they would only be needed in very rare circumstances (for example to protect against a one in a thousand year storm). The best adaptation strategy for such a rare event is not clear.

References

Cubasch, U, R. Voss, G. Hegerl, J. Waskiewitz, and T. Crowley. 1997. Simulation of the Influence of Solar Radiation Variations on the Global Climate with an Ocean-Atmosphere General Circulation Model" *Climate Dynamics* **13**: 757-767.

Emanuel, K. 2005. "Increasing destructiveness of tropical cyclones over the past 30 years," *Nature,* 436: 686 – 688.

Emanuel, K., R. Sundararajan, and J. Williams, 2008. "Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations" *Bull. Amer. Meteor. Soc,* **89**: 347-367.

EM-DAT. 2009 "The OFDA/CRED International Disaster Database" www.emdat.be Universite Catholique de Louvain, Brussels, Belgium

Gueremy, J.F., M. Deque, A Braun, J.P. Evre. 2005. "Actual and potential skill of seasonal predictions using the CNRM contribution to DEMETER: coupled versus uncoupled model" *Tellus* 57: 308–319

Hallegate, S. 2007. "The use of synthetic hurricane tracks in risk analysis and climate change damage assessment", *Journal of Applied Meteorology and Climatology,* 46: 1956–1966.

Hasumi, H. and S. Emori. 2004. *K-1 Coupled GCM (MIROC) Description,* Center for Climate System Research, University of Tokyo, Tokyo.

IPCC (Intergovernmental Panel on Climate Change). 2000. *Special Report on Emissions Scenarios,* Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate Change 2001: Impacts, Adaptation and Vulnerability,* Cambridge University Press, Cambridge UK.

IPCC (Intergovernmental Panel on Climate Change). 2007a. *The Physical Science Basis,* Cambridge University Press, Cambridge UK.

IPCC (Intergovernmental Panel on Climate Change). 2007b. *Impacts, Adaptation and Vulnerability,* Cambridge University Press, Cambridge UK.

Landsea, C. W., B. A. Harper, K. Hoarau, and J. A. Knaff. 2006. "Can We Detect Trends in Extreme Tropical Cyclones?" *Science* 313: 452 – 454.

Manabe, S., J. Stouffer, M.J. Spelman, and K. Bryan. 1991. “Transient Responses of a Coupled Ocean-Atmosphere Model to Gradual changes of Atmospheric CO2. Part I: mean annual response” *Journal of Climate* **4**: 785-818.

Mendelsohn, R. K. Emanuel, and S. Chonabayashi. 2010. “The Impact of Climate Change on Tropical Cyclone Damages in the United States” World Bank Policy Working Paper, Washington DC.

Narita, D., Tol, R., Anthoff, D. 2009. “Damage Costs of Climate Change through Intensification of Tropcial Cyclone Activities: An Application of FUND” *Climate Research* **39**: 87-97.

Nicholls, R.J. , S. Hanson, C. Herweijer, N. Patmore , S. Hallegatte, J. Corfee-Morlot, J. Château, R. Muir-Wood. 2008. “Ranking Port Cities With High Exposure and Vulnerability to Climate Change” OECD Environment Working Paper No 1, Paris, France.

NOAA. 2009., “Tropical Cyclone Reports” National Oceanic Atmospheric Administration, National Tropical cyclone Center. `http://www.nhc.noaa.gov/pastall.shtml#tcr`

Nordhaus, W. 2008b. *A Question of Balance: Weighing the Options on Global Warming Policies*, Yale University Press, New Haven, CT

Nordhaus, W. 2010. “The Economics of Hurricanes and Implications of Global Warming” *Climate Change Economics* **1**: 1-24.

Pielke, R. A. Jr. 2005. “Are There Trends in Tropical cyclone Destruction?” *Nature* 438: E11

Pielke, R.A. Jr. 2007b. “Future economic damage from tropical cyclones: sensitivities to societal and climate changes” *Philosophical Transactions Royal Society* **365:** 1-13.

Pielke, R. A. Jr. and C. W. Landsea. 1998. “Normalized Tropical Cyclone Damages in the United States: 1925-1995,” *Weather and Forecasting* 13: 621-631

Pielke, R. A. Jr. J. Gratz, C. W. Landsea, D. Collins; M. A. Saunders; and R. Musulin. 2008. “Normalized Tropical Cyclone Damage in the United States: 1900–2005.” *Natural Hazards Review*, 9: 1-29.

Swiss Re, 2006. *The effect of climate change: storm damage in Europe on the rise,* Focus report.

United Nations. 2004. *World Population in 2300* Department of Economic and Social Affairs. New York.

Appendix A: Damages in 2100 by Country (million USD/yr)

	Baseline	Climate Change	Climate Change	Climate Change	Climate Change
Country	Future	CNRM	ECHAM	GFDL	MIROC
Afghanistan	0.0	0.0	0.0	0.0	0.0
Albania	0.0	0.0	0.0	0.0	0.0
Algeria	0.0	0.0	0.0	0.0	0.0
American Samoa	15.7	-1.3	-4.6	+9.9	-6.4
Andorra	0.0	0.0	0.0	0.0	0.0
Angola	0.0	0.0	0.0	0.0	0.0
Anguilla	0.0	0.0	0.0	0.0	0.0
Antigua & Barbuda	62.0	+75.4	+4.7	+82.5	+112.1
Argentina	0.0	0.0	0.0	0.0	0.0
Armenia	0.0	0.0	0.0	0.0	0.0
Aruba	6.6	+2.5	-4.9	+5.7	+2.2
Australia	233.9	+39.6	+41.6	0.0	-3.8
Austria	0.0	0.0	0.0	0.0	0.0
Azerbaijan	0.0	0.0	0.0	0.0	0.0
Bahrain	0.0	0.0	-18.7	0.0	-18.5
Bangladesh	446.1	+277.0	-253.6	-396.8	+300.9
Barbados	0.8	+0.4	-0.2	+0.2	+0.8
Belarus	0.0	0.0	0.0	0.0	0.0
Belgium	0.0	0.0	-2.0	0.0	0.0
Belize	63.8	-28.7	-12.5	+27.7	+78.1
Benin	0.0	0.0	0.0	0.0	0.0
Bermuda	25.1	-9.7	0.0	+2.7	+0.9
Bhutan	0.0	0.0	0.0	0.0	0.0
Bolivia	0.0	0.0	0.0	0.0	0.0
Bosnia & Herzegovina	0.0	0.0	0.0	0.0	0.0
Botswana	0.0	0.0	0.0	0.0	0.0
Brazil	0.0	0.0	0.0	0.0	0.0
British Virgin Is.	1.2	+1.6	-0.1	+1.9	+1.6
Brunei	13.6	-3.7	+1.2	+14.8	0.0
Bulgaria	0.0	0.0	0.0	0.0	0.0
Burkina Faso	0.0	0.0	0.0	0.0	0.0
Burundi	0.0	0.0	0.0	0.0	0.0
Cambodia	0.0	0.0	0.0	0.0	0.0
Cameroon	0.0	0.0	0.0	0.0	0.0
Canada	22.6	+1.5	+6.3	+29.7	+6.7
Cape Verde	0.0	0.0	0.0	0.0	0.0
Cayman Is.	282.7	-46.0	-78.0	+127.2	+294.8
Central African Republic	0.0	0.0	0.0	0.0	0.0
Chad	0.0	0.0	0.0	0.0	0.0
Chile	0.0	+28.8	0.0	-429.5	+3.4
China	7166.1	+2075.9	+16054.2	+50.7	+13644.0
Colombia	0.1	+0.2	0.0	+0.1	0.0
Comoros	0.4	0.0	0.0	0.0	0.0
Congo	0.0	0.0	0.0	0.0	0.0
Congo, DRC	0.0	0.0	0.0	0.0	0.0
Cook Is.	5.1	+0.4	-3.4	-1.9	-1.7
Costa Rica	39.7	+20.5	+5.7	+9.8	+5.6
Cote d'Ivoire	0.0	0.0	0.0	0.0	0.0

Croatia	0.0	0.0	0.0	0.0	0.0
Cuba	1532.8	+46.7	-491.2	+1072.8	+330.5
Cyprus	0.0	0.0	0.0	0.0	0.0
Czech Republic	0.0	0.0	0.0	0.0	0.0
Denmark	0.0	0.0	0.0	0.0	0.0
Djibouti	0.6	0.0	+0.1	-0.1	+0.1
Dominica	26.5	+36.2	-5.6	+18.0	+41.2
Dominican Republic	337.6	+17.3	-37.1	+438.4	+641.5
Ecuador	0.0	0.0	0.0	0.0	0.0
Egypt	0.0	0.0	0.0	0.0	0.0
El Salvador	78.1	-29.8	-11.9	-23.1	+557.6
Equatorial Guinea	0.0	0.0	0.0	0.0	0.0
Eritrea	0.0	0.0	0.0	0.0	0.0
Estonia	0.0	0.0	0.0	0.0	0.0
Ethiopia	0.0	0.0	0.0	0.0	0.0
Faroe Is.	0.0	+0.1	+13.2	0.0	-27.9
Fiji	69.3	+3.2	+4.5	-19.9	-38.5
Finland	0.0	0.0	0.0	0.0	0.0
France	0.0	+0.1	0.0	+0.4	0.0
French Guiana	0.0	0.0	0.0	0.0	0.0
French Polynesia	1.5	+0.7	-0.1	-6.0	-0.4
Gabon	0.0	0.0	0.0	0.0	0.0
Gaza Strip	0.0	0.0	0.0	0.0	0.0
Georgia	0.0	0.0	0.0	0.0	0.0
Germany	0.0	0.0	0.0	0.0	0.0
Ghana	0.0	0.0	0.0	0.0	0.0
Gibraltar	0.0	0.0	0.0	0.0	0.1
Greece	0.0	0.0	0.0	0.0	0.0
Greenland	1.9	+0.4	+0.9	+1.4	0.0
Grenada	94.6	+39.2	-54.2	+34.9	+76.2
Guadeloupe	37.6	+84.3	-2.2	+30.7	+30.9
Guam	79.7	+26.7	+19.0	-37.6	+7.0
Guatemala	148.7	+24.9	-77.8	-51.6	-4.6
Guernsey	0.0	0.0	0.0	0.0	0.0
Guinea	0.0	0.0	0.0	0.0	0.0
Guinea-Bissau	0.0	0.0	0.0	0.0	0.0
Guyana	0.0	0.0	0.0	0.0	0.3
Haiti	41.3	-4.6	-15.5	+42.7	+66.1
Honduras	405.2	+1076.0	+37.5	+623.9	+473.3
Hungary	0.0	0.0	0.0	0.0	0.0
Iceland	0.0	0.0	-0.1	+1.0	+0.1
India	986.4	-402.6	-190.5	-955.7	+1119.2
Indonesia	609.7	+6839.3	+793.4	-166.2	-174.3
Iran	456.5	+1016.6	+2285.9	-382.9	+571.5
Iraq	0.0	0.0	0.0	0.0	0.0
Ireland	0.1	+0.4	+0.2	+3.8	+0.1
Isle of Man	0.0	+0.1	0.0	+0.4	+0.2
Israel	0.0	0.0	0.0	0.0	0.0
Italy	0.0	0.0	0.0	0.0	0.0
Jamaica	151.2	+143.1	-54.7	+187.4	+284.2
Japan	6736.0	-453.1	+4464.9	+4945.9	+26020.4
Jersey	0.0	0.0	0.0	0.0	0.0
Jordan	0.0	0.0	0.0	0.0	0.0

Kazakhstan	0.0	0.0	0.0	0.0	0.0
Kenya	25.3	+19.4	+12.4	+0.4	-0.3
Kiribati	0.0	0.0	0.0	0.0	0.0
Kuwait	0.0	0.0	0.0	0.0	+10.6
Kyrgyzstan	0.0	0.0	0.0	0.0	0.0
Laos	31.9	-1.2	+7.7	+1.3	-6.9
Latvia	0.0	0.0	0.0	0.0	0.0
Lebanon	0.0	0.0	0.0	0.0	0.0
Lesotho	0.0	0.0	0.0	0.0	0.0
Liberia	0.0	0.0	0.0	0.0	0.0
Libya	0.0	0.0	0.0	0.0	0.0
Liechtenstein	0.0	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0	0.0
Macedonia	0.0	0.0	0.0	0.0	0.0
Madagascar	38.4	-15.4	-8.7	-12.1	+85.5
Malawi	0.0	+0.1	-0.3	-0.2	+0.4
Malaysia	6.5	-2.9	+0.9	-0.4	-3.7
Maldives	1.5	-1.4	-1.1	-0.9	-0.6
Mali	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0
Marshall Is.	0.1	0.0	0.0	-0.2	0.1
Martinique	49.7	-10.4	+0.7	+23.0	+94.0
Mauritania	0.0	0.0	0.0	0.0	0.0
Mauritius	28.0	-1.2	-13.0	+41.3	+68.9
Mayotte	13.0	+7.3	+2.1	-3.4	+7.6
Mexico	2288.2	-306.9	-128.4	-24.9	+545.8
Micronesia	0.1	0.0	0.0	0.0	0.0
Moldova	0.0	0.0	0.0	0.0	0.0
Monaco	0.0	0.0	0.0	0.0	0.0
Mongolia	0.0	0.0	0.0	0.0	0.0
Montenegro	0.0	0.0	0.0	0.0	0.0
Montserrat	2.5	+5.5	0.0	+1.8	+3.5
Morocco	0.0	0.0	0.0	0.0	0.0
Mozambique	3.6	-2.0	0.0	-0.8	+4.7
Myanmar	424.4	-195.1	-159.2	-349.0	+7.6
Namibia	0.0	0.0	0.0	0.0	0.0
Nauru	0.0	0.0	0.0	0.0	0.0
Nepal	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	0.0	0.0	0.0	0.0
Netherlands Antilles	143.9	-9.3	-106.6	+107.7	+44.8
New Caledonia	4.3	+1.0	-0.6	-1.2	-1.2
New Zealand	52.7	-27.4	-26.5	-183.7	-36.9
Nicaragua	93.9	+15.9	+35.1	+21.1	+88.9
Niger	0.0	0.0	0.0	0.0	0.0
Nigeria	0.0	0.0	0.0	0.0	0.0
North Korea	922.8	-107.7	+59.8	-30.1	+1423.2
Northern Mariana Is.	17.6	+3.6	+3.8	-4.6	+1.8
Norway	0.0	0.0	0.0	0.0	0.8
Oman	243.9	+647.6	+251.8	-96.5	+292.1
Pakistan	117.1	+115.4	+210.9	-104.1	+517.3
Palau	0.1	0.0	0.0	-0.2	0.0
Panama	0.0	0.0	0.0	0.0	0.0

Papua New Guinea	0.2	+0.3	0.0	0.0	-0.1
Paraguay	0.0	0.0	0.0	0.0	0.0
Peru	0.0	0.0	0.0	0.0	+3.8
Philippines	431.1	+443.3	+184.5	+182.6	+35.5
Poland	0.0	0.0	0.0	0.0	0.0
Portugal	1.1	-1.1	-0.2	+1.0	1.5
Puerto Rico	385.2	+851.3	+55.4	+667.0	+890.3
Qatar	0.0	+0.2	-62.4	0.0	+6.6
Reunion	4.8	-1.7	+3.8	-3.0	+17.3
Romania	0.0	0.0	0.0	0.0	0.0
Russia	15.1	+3.4	-1.8	+8.1	+5.8
Rwanda	0.0	0.0	0.0	0.0	0.0
Samoa	60.9	-1.3	-22.1	+18.0	-0.5
San Marino	0.0	0.0	0.0	0.0	0.0
Sao Tome & Principe	0.0	0.0	0.0	0.0	0.0
Saudi Arabia	0.0	+0.1	+0.1	0.0	-115.3
Senegal	0.0	0.0	0.0	0.0	0.0
Serbia	0.0	0.0	0.0	0.0	0.0
Seychelles	1.3	-0.1	0.0	-0.1	+0.6
Sierra Leone	0.0	0.0	0.0	0.0	0.0
Singapore	0.0	0.0	0.0	0.0	0.0
Slovakia	0.0	0.0	0.0	0.0	0.0
Slovenia	0.0	0.0	0.0	0.0	0.0
Solomon Is.	0.3	+0.1	+0.1	-0.1	-0.1
Somalia	1.9	0.0	+0.1	-0.3	+0.2
South Africa	0.0	0.0	-10.0	-39.8	+4.1
South Korea	1272.1	+206.1	+639.4	+964.8	+2051.2
Spain	7.3	+0.7	+19.1	+12.4	-1.6
Sri Lanka	48.3	-34.5	-4.8	-43.5	+10.4
St. Helena	0.0	0.0	0.0	0.0	0.0
St. Kitts & Nevis	77.3	+116.3	+7.8	+117.2	+123.0
St. Lucia	5.3	+1.8	-1.8	+0.9	+6.8
St. Pierre & Miquelon	1.3	+0.5	+0.4	+1.3	0.0
St. Vincent & the Grenadines	2.1	+0.5	-1.0	+0.4	+2.2
Sudan	0.0	0.0	0.0	0.0	0.0
Suriname	0.0	0.0	0.0	0.0	0.0
Swaziland	0.0	0.0	0.0	0.0	0.0
Sweden	0.0	0.0	0.0	0.0	0.0
Switzerland	0.0	0.0	0.0	0.0	0.0
Syria	0.0	0.0	0.0	0.0	0.0
Tajikistan	0.0	0.0	0.0	0.0	0.0
Tanzania	15.0	-8.2	-1.3	-0.2	+4.6
Thailand	66.2	-27.2	-14.6	-12.8	+26.7
The Bahamas	261.8	+32.8	-19.5	+230.3	-12.9
The Gambia	0.0	0.0	0.0	0.0	0.0
Timor-Leste	0.0	0.0	0.0	0.0	0.0
Togo	0.0	0.0	0.0	0.0	0.0
Tonga	7.0	-1.3	-2.1	-0.4	-3.3
Trinidad & Tobago	0.1	0.0	-0.1	+0.1	+0.1
Tunisia	0.0	0.0	0.0	0.0	0.0
Turkey	0.0	0.0	0.0	0.0	0.0
Turkmenistan	0.0	0.0	0.0	0.0	0.0
Turks & Caicos Is.	47.3	+21.1	-8.7	+39.0	+16.6

Tuvalu	0.0	0.0	0.0	0.0	0.0
Uganda	0.0	0.0	0.0	0.0	0.0
Ukraine	0.0	0.0	0.0	0.0	0.0
United Arab Emirates	193.5	-116.4	+554.7	-133.9	-68.8
United Kingdom	34.7	+1.0	+34.0	+1.8	+58.9
United States	26337.6	+14526.1	+31650.2	+60896.9	+13087.0
Uruguay	0.0	0.0	0.0	0.0	0.0
Uzbekistan	0.0	0.0	0.0	0.0	0.0
Vanuatu	0.6	+0.2	+0.2	-0.1	-0.2
Venezuela	0.6	-0.4	-0.5	+0.2	+1.1
Vietnam	379.3	+59.2	-100.3	+179.6	-12.8
Virgin Is.	176.8	+332.3	-7.5	+186.7	+225.8
Wallis & Futuna	5.2	+2.1	+1.7	-3.3	+3.1
Western Sahara	0.0	0.0	0.0	0.0	0.0
Yemen	31.5	+63.5	+30.9	-24.0	+58.5
Zambia	0.0	0.0	0.0	0.0	0.0
Zimbabwe	0.1	0.0	-0.1	0.0	+0.1

Note: Average of results from 4 climate models using future baseline for 2100 and minimum pressure model. Damages in million of USD/year.