

# The Impact of Climate Change on Global Tropical Storm Damages

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## Executive Summary

This project quantifies the global damages that climate change causes by altering future hurricanes. The project relies on an Integrated Assessment model of climate change and hurricanes. Greenhouse gas emissions are assumed to follow a path that would stabilize carbon dioxide concentrations at 720ppm (SRES emission trajectory A1B). Four climate models are used to predict the effect of climate change on hurricanes by 2100. For each model, a hurricane generator is used to create a set of 3000 hurricanes in each ocean basin under the current climate conditions and 3000 hurricanes in each ocean basin under future climate conditions. The wind speeds, barometric pressure, and landfall of each storm are then calculated.

The relationship between damages and the magnitude of the storm is estimated from aggregate damage data for hurricanes that have struck the United States in the last 50 years. The relationship between damages and vulnerability was calculated using international data over the same time period. Unfortunately, the international data did not record the intensity of each storm. Two measures of storm magnitude are explored: minimum barometric pressure and wind speed. The minimum pressure model does a better job of predicting storm damages than wind speed. However, both measures suggest a highly nonlinear relationship between storm magnitude and damages. A little more than a 1% reduction in barometric pressure or a 20% increase in wind speed doubles storm damage. Vulnerability also matters. Doubling income increases damages by about 40% and doubling population density actually reduces damages by 20%. These results reveal that the earlier literature on hurricane damages should not have assumed that damages are proportional to both population and income (that doubling income or population would double damages).

Damages for each storm are predicted given current climate and the current baseline. For each tropical storm that strikes land, damages are predicted using the barometric pressure of the storm (or wind speed) at landfall, income at landfall, and the population density at landfall. These damages are then aggregated across storms to estimate the expected value and distribution of damages for each country of the world

given current climate and current GDP. The model estimates that current tropical storm damages would be

We then project what baseline damages will be in 2100. We predict future income and population for each country. We use these future projected variables to predict a baseline level of damages for 2100 given the current climate. We then contrast these damages in the future with the damages that would result if climate changes. This leads to a new distribution of future damages from hurricanes.

We then compare the damages from hurricanes caused by current versus future climate assuming the future economic baseline. The difference between these two levels of damages is the climate change impact. If damages increase with the warmer climate, then climate change causes damages and if damages fall, then climate change causes benefits.

Estimates of hurricane damages are calibrated to current data. Current global damages from hurricanes average \$13 billion/yr (0.024 percent of GWP in 2008). With the growth in both population and income, future hurricanes are predicted to cause about \$30 billion/yr (0.0052 percent of GWP in 2100) in damages with the current climate. This is simply because more structures and people will be in harm's way.

As climate changes, the intensity of storms are expected to change, especially in the North Atlantic and also in the North West Pacific (Emanuel et al. 2008). This result is reproduced in this analysis. North Atlantic storms get more intense as measured by both minimum pressure and wind speed. There are smaller increases in the West Pacific. The changes in the other oceans are both small and inconsistent.

Climate change is predicted to increase the global damages from hurricanes in all 4 climate scenarios. On average, the global damages from hurricanes are expected to increase by \$10 billion per year, a 33 percent increase. The increase amounts to 0.0018 percent of GWP in 2100.

The changes are not uniform across the planet. The biggest and most consistent effects are in Asia (\$4.3 billion/yr) and North America (\$4.8 billion/yr). The remaining continents do not have consistent impacts across the four climate models. In some years, the damages increase and in other years, they fall. Only half of all nations are affected by tropical storms. All but 6 countries suffer effects that are smaller than 0.006 percent of

GDP. These 6 countries are all islands and all but the Philippines are in the Caribbean. The largest effect is in Cuba with damages of 0.025 percent of GDP.

The results reveal that hurricane damages have a very skewed distribution with a small number of hurricanes causing very large damages. The worst 10 percent of storms are expected to cause 90 percent of the damages given the current climate. The worst 1 percent of the storms cause 58 percent of total damages. With warming, this distribution gets even more skewed with the worst storms becoming even more harmful. The worst 10 percent of storms will cause 94 percent of damages and the worst 1 percent of storms will cause 64% of total damages with warming. Because the damages are concentrated in these large storms, adaptation planning should focus on these large and rare storms.

The skewed distribution of damages, unfortunately, makes it very difficult to predict trends in hurricane damages. A single very large storm can create a blip in damages that gives the appearance damages are increasing. However, the current climate is perfectly capable of generating large storms already. It will likely take many centuries of data to be certain that hurricane damages are changing from their current baseline.

Although this study is the most advanced analysis of hurricanes yet done, there remain many uncertainties. The emission pathway is uncertain, the climate response is uncertain, how hurricanes will change is uncertain, and what the damages will be is uncertain. Although the precise values reported here should not be taken literally, the overall scale of the damages is likely to be accurate. Damages are not likely to be ten times larger or ten times smaller.

## I. Introduction

Tropical storms (hurricanes, cyclones, 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 storms 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 tropical storm 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 hurricanes are rare events and so it is difficult to detect changes in underlying frequencies and severity (Landsea et al. 1999; 2006). There are approximately 50 hurricanes a year 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 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 the current damages from tropical storms in the US are \$2.2 billion/year (Nordhaus 2006). Estimates for the entire world are \$13 billion/yr (EMDAT 2009). Several authors have relied on the general result by Emanuel et al. (2005) that hurricane intensity (wind speed cubed) would increase by about 11% across the US with a 2°C warming. Nordhaus (2006), using a damage function based on aggregate damage data by storm, predicts hurricane damages would therefore double by 2100, an increase of 0.06% of GDP. Narita et al. (2008), using the FUND model, estimate that global hurricane damages would increase by 0.007% a year. Stern (2006), in contrast, predicts that damages might increase by an order of magnitude from their current level. But Stern's results are based on the assumption that damages would increase exponentially, an assumption that appears to be without empirical foundation (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 Integrated Assessment model of climate change. The model begins with the A1B SRES global emissions trajectory that stabilizes greenhouse gas concentrations at 720 ppm (IPCC 2000). This emissions path is inputted to four climate models which then predict four global climate scenarios for both the present and the future (2100). We use these climate scenarios to predict how hurricanes may change into the future (Emanuel et al. 2008). Given each climate scenario, hurricanes are seeded into each ocean basin. In both the current climate and the future climate, a total of 3000 hurricanes are generated per basin. This provides an extensive data set of hurricanes from which to examine whether current (2000) versus future (2100) patterns change.

We estimate a damage function with respect to the magnitude of the storm using historic data from storms that have hit the United States since 1950. 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. A regression is then used to predict the damages caused by each historic storm. We use international data (EMDAT 2009) from around the world to estimate the damage function with respect to income and population density (vulnerability). The limitation of the international data is that it has no information about the magnitude of each storm.

The estimated regression coefficients 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 hurricane damages. The comparison of the results across the four climate models also provides an additional sense of the uncertainty of the estimates. We also 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 compares the damages from tropical storms with the current economic baseline with damages caused with the future economic baseline. This analysis

shows the impact of higher incomes and populations in the future. The second analysis estimates the impact of tropical storms with the future climate minus the impact of tropical storms with the current climate in order to estimate the effect of climate change. Both of these estimates are made using the future economic baseline. The analysis then discusses how these impacts vary across the world and how damages are distributed across hurricanes.

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 as there are few 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 ( $\pi$ ) 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 ( $MP$ ) and maximum wind speed ( $WS$ ). Damages will also depend upon where the hurricane strikes ( $i$ ). Natural science can help predict the probability a hurricane ( $j$ ) with particular characteristics will strike each place ( $i$ ) given the climate ( $C$ ):

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

The actual damages associated with any given hurricane ( $j$ ) 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 ( $Y$ ):

$$D_i = D(X_i, Z_i) \quad (2)$$

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 hurricane damages is:

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

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:

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

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 hurricane damages can be done for each state and the whole country. The calculation of the damages with and without climate change should be done holding the characteristics of each region 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. However, country specific results are available in Appendix A.

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

$$\text{Pr ob}(D) = f(D(X)) \quad (5)$$

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, we calculate a return rate of damages. This is a relationship between the average years between hurricanes that cause specific amounts of damages:

$$\text{Return} = 1/\text{Pr ob}(D) = g(D(X)) \quad (6)$$

### III. Integrated Assessment Model

The integrated assessment model has been constructed to project hurricane 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 over time so that greenhouse gas concentrations finally peak and stabilize at 720 ppm. This path mirrors what economists believe to be the optimal balance between abatement costs and climate damages (Nordhaus 2008b).

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.

Using a hurricane generator in each ocean basin, the climate data is used to project 17,000 hurricane tracks (Emanuel et al. 2008). There are 3,000 tracks in four of the ocean basins and 5,000 tracks in the North Atlantic. Hurricane tracks for both the

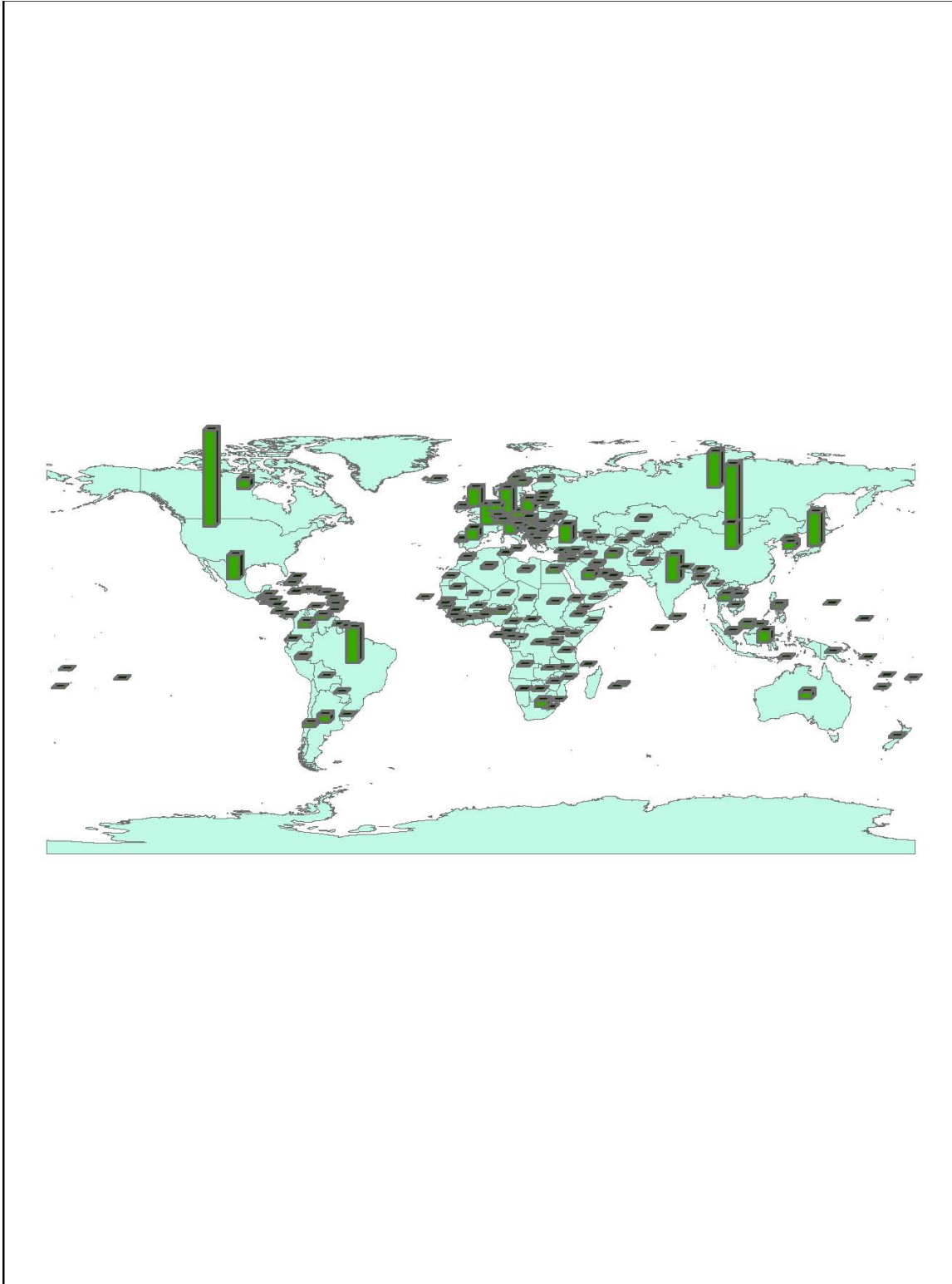
current climate and future climate are predicted. Tracks are also estimated for each climate model. Altogether 8 sets of 17,000 hurricanes are generated. For each track, we follow where the hurricane makes landfall. Hurricanes that land on continents are assumed to terminate there. Hurricanes that pass 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 hurricanes in each ocean basin.

A damage function is then used to predict the damages that each storm will cause. The coefficient for storm magnitude was estimated using aggregate damages per storm and storm characteristics at landfall from US storms since 1950 (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 1950, 1960, 1970, 1980, 1990, 2000). Fatalities were explored but were found to be randomly distributed across US storms.

A separate analysis was then conducted of major storms striking the globe (EMDAT 2009). The limitation of this second data set is that there was no information about the magnitude of the storm. The international data set was used to estimate the coefficients for vulnerability (income and population density).

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. 2009). 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. A map of these maximum damages in the future baseline for 2100 is shown in Figure 1. Countries with higher future GDP have higher maximum values.

Figure 1: Maximum damage from future hurricanes in billions



Note: The United States value is \$172 billion (Mendelsohn et al 2009).

The model calculated damages for each storm in the data set given its intensity and where it landed. The expected damages were calculated by summing the product of the probability of each storm times the damage it causes. Separate estimates were made for each region as well as the country. 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 hurricanes. However, there are other changes in wind shear and wind direction that can reduce hurricane 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. However, the change is quite small. Average wind speed has changed from -7 to +3 percent across the climate models. Average minimum pressure has changed from -0.11 to +0.15 percent. Given the high variance in the underlying distribution, it could take hundreds of years of empirical evidence to reveal these mean differences.

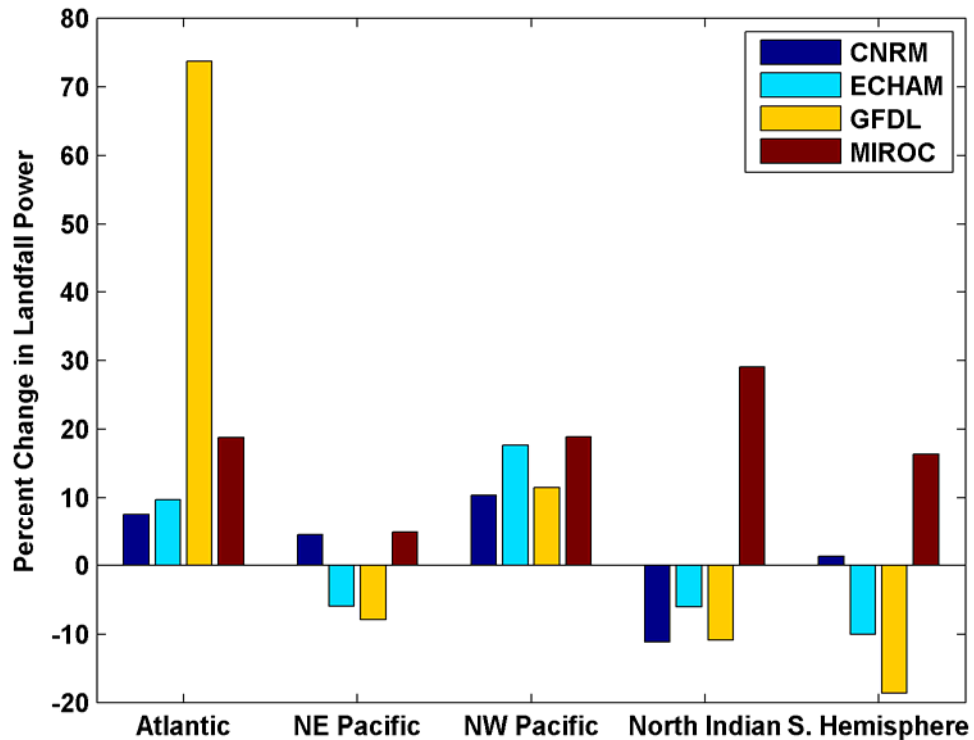
Perhaps more important than average global changes, it is important to see how climate change affects the intensity of tropical storms in each ocean basin. Figure 2 shows the changes in intensity by ocean basin between the tropical storms in the future (2100) climate versus tropical storms in the current climate. Intensity consistently climbs consistently in two of the ocean basins: the North Atlantic and the North Western Pacific across all four models. Changes in the other oceans basins are not consistent across the climate models with some predictions of an increase in intensity and other predictions of a fall in intensity. There are two especially large signals. The GFDL model predicts a very large increase in intensity in the North Atlantic and the MIROC model predicts a

large combination of increases in the North Pacific and Indian Ocean. These two predictions will especially influence damages in North America and Asia respectively.

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%              |

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.

Damage functions are estimated from US hurricane data collected by the National Hurricane Center (NOAA 2009) in order to measure the effect of the magnitude of each storm. The Hurricane Center reports that 111 hurricanes have struck the United States between 1960 and 2008 (49 years). This historic data implies that the Atlantic coast of the United States is hit by 2.2 storms per year. The data include information on the magnitude, location, and damages from these storms. The storm data were matched with vulnerability measures at the point of impact. The vulnerability measures include population density and income (US Census of Population). These values were interpolated between decennial Census measures from 1960 through 2000. All values are in 2008 USD. Elevation was also tried but dropped because it was insignificant.

The results of the regression of log damages on the log of the independent variables are shown in Table 2. The regressions reveal that the magnitude of the storm is

highly significant. Whether measured by maximum wind speed or minimum pressure at landfall, damages are a highly nonlinear function of magnitude. Damages increase inversely with the 86<sup>th</sup> power of minimum pressure and directly 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 hurricane literature (Emanuel 2005) with the exception of Nordhaus (2006) who finds similar results with respect to wind speed. Comparing the results of the minimum pressure and wind speed regressions reveals that minimum pressure is a better explanatory variable for hurricane damages. This could be due to measurement error in wind speed. To test this, we also explore a two stage regression. In the first stage, we regress wind speed on minimum pressure. In the second stage, we regress damages on predicted wind speed and other variables. The significance of the results improves. The coefficient on predicted wind speed increases to the sixth power.

Table 2: Regressions of US Hurricane Damages on Magnitude and Vulnerability

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

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

Regressions were also estimated using international data (EMDAT 2009) in order to determine how damages change with population and income. Table 3 reveals that damages increase with income and population density. The results suggest that damages increase slightly with income but fall with population density. Lives lost fall dramatically with income and are not related to population density at all. The elasticities of these variables are significantly less than 1 (contrary to assumptions in the literature Pielke and Landsea 1998 and Pielke et al. 2008).

Table 3: Regressions of Global Hurricanes on Damages and Lives Lost

| Impact     | Constant         | Log(Income)       | Log(Population Density) | Adj Rsq/<br>F Stat | N    |
|------------|------------------|-------------------|-------------------------|--------------------|------|
| Damages    | 15.17<br>(22.77) | 0.415<br>(6.44)   | -0.21<br>(3.04)         | 0.066<br>29.61     | 807  |
| Lives Lost | 6.25<br>(18.20)  | -0.477<br>(14.01) | 0.07<br>(1.86)          | 0.158<br>103.18    | 1089 |

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

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%. The data suggest wealthier people protect themselves from hurricanes and that the risk per person falls as populations become more urbanized.

The final damage function has the following form:

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

$$D = A * WS^5 Y^{.06} Pop^{-0.2} \quad (8)$$

$$F = A * Y^{-0.5} Pop^{0.07} \quad (9)$$

Because we could not estimate a significant relationship between fatalities and magnitude using US data, it was not possible to estimate a climate change impact on fatalities.

Although one could have assumed that fatalities simply changed in proportion to hurricane frequency, climate change does not have consistent impacts on tropical storm frequency. Further, most of the fatalities from tropical storms occur in poorer countries where magnitude may have an impact on the number of fatalities. This is clearly a topic that deserves further research.

The damage functions are then used to estimate the damages for each tropical storm generated by each climate model. The climate models are also used to predict the frequencies of storms in each ocean basin. The global expected damages given current

climate and current baseline conditions are reported in Table 3. Expected damages range from \$12.8 to \$14.5 billion per year. The reported historic values in EMDAT are \$13.9 billion per year. Current damages from tropical storms are equal to 0.024 percent of GDP.

Table 3: Current and Future Global Damages from Tropical Storms With No Climate Change

|                  | CNRM   | ECHAM  | GFDL   | MIROC  |
|------------------|--------|--------|--------|--------|
| Current Baseline | 13,886 | 14,462 | 14,459 | 12,772 |
| Future Baseline  | 30,343 | 31,885 | 31,736 | 27,608 |

Note: Expected Damages in millions of USD.

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 growth rate in developed countries, 2.7 percent in developing countries, and 3.3 percent in emerging countries. Dividing GDP by population yields a future prediction of income per capita for each country in 2100. Using the future baseline leads to higher expected damages even with the current climate. As shown in Table 3, future damages increase 2.2 fold in each scenario. Future damages, however, fall relative to GDP because GDP is expected to increase almost 10 fold. Without any climate change, tropical storm damages as a fraction of GWP are equal to 0.024 percent in 2000 but are projected to be equal to 0.0052 percent of GWP in 2100.

In order to calculate the impact of climate change, the damages from tropical storms are calculated for the future baseline with and without climate change. The future impact of climate change is the difference in damages with a warmed climate and the future baseline minus the current climate and the future baseline. Climate change is measured holding the baseline constant. The results, shown in Table 4, reveal that climate change is expected to cause hurricane damages to increase between \$5 billion to \$14 billion per year by 2100. The average of these damages across the four models is \$10 billion/yr which is equal to 0.0024% of future GWP. The damages as a fraction of GDP

are one third of the 0.007% prediction of Narita et al (2008) because of the empirical evidence that tropical storm damages increase less than proportionally with income and population. The impacts from ECHAM and MIROC are higher because they both predict a greater reduction in minimum pressure.

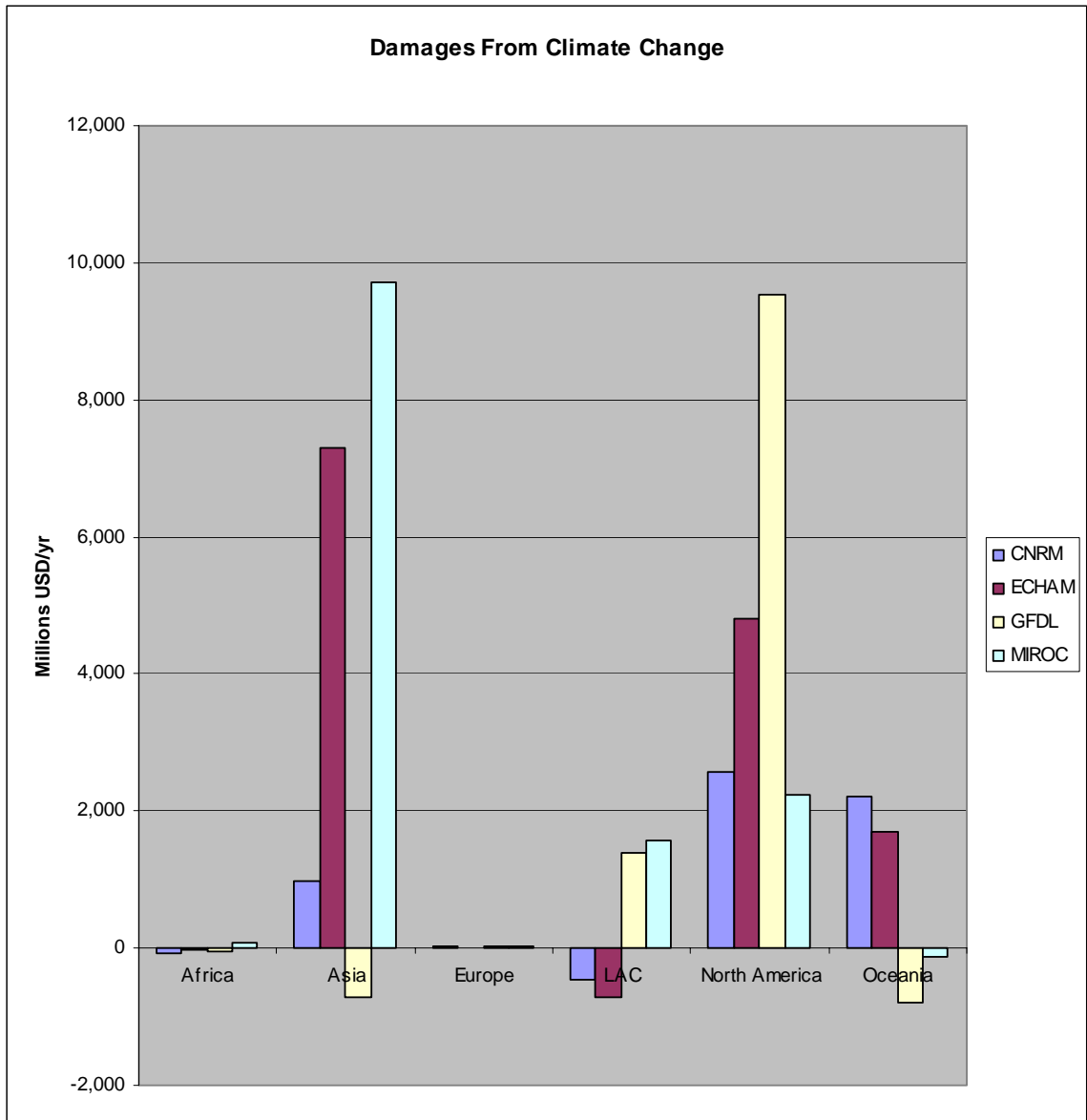
Table 4: Global Hurricane Damages Caused By Climate Change in 2100

| Damage Model     | CNRM  | ECHAM  | GFDL  | MIROC  |
|------------------|-------|--------|-------|--------|
| Minimum Pressure | 5,271 | 13,070 | 9,402 | 13,529 |
| Wind Speed Fifth | 239   | 2,462  | 6,195 | 5,611  |

Note: Values are in millions of USD/yr based on A1B emission scenario (720 ppm by 2100) and future baseline.

The distribution of damages is not even across the world. Figure 2 displays the damages caused by climate change in each continent. The results from the hurricane modeling (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 damaged by warming across all four climate models in Figure 3. These two continents are also predicted to suffer the highest average damages: \$4.5 billion in North America and \$4.4 billion in Asia. The damages from global warming in the rest of the world are small and inconsistent. In some regions and models, the damages from tropical storms are expected to be less with warming than without. 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 3: Hurricane Damages by Region by 2100

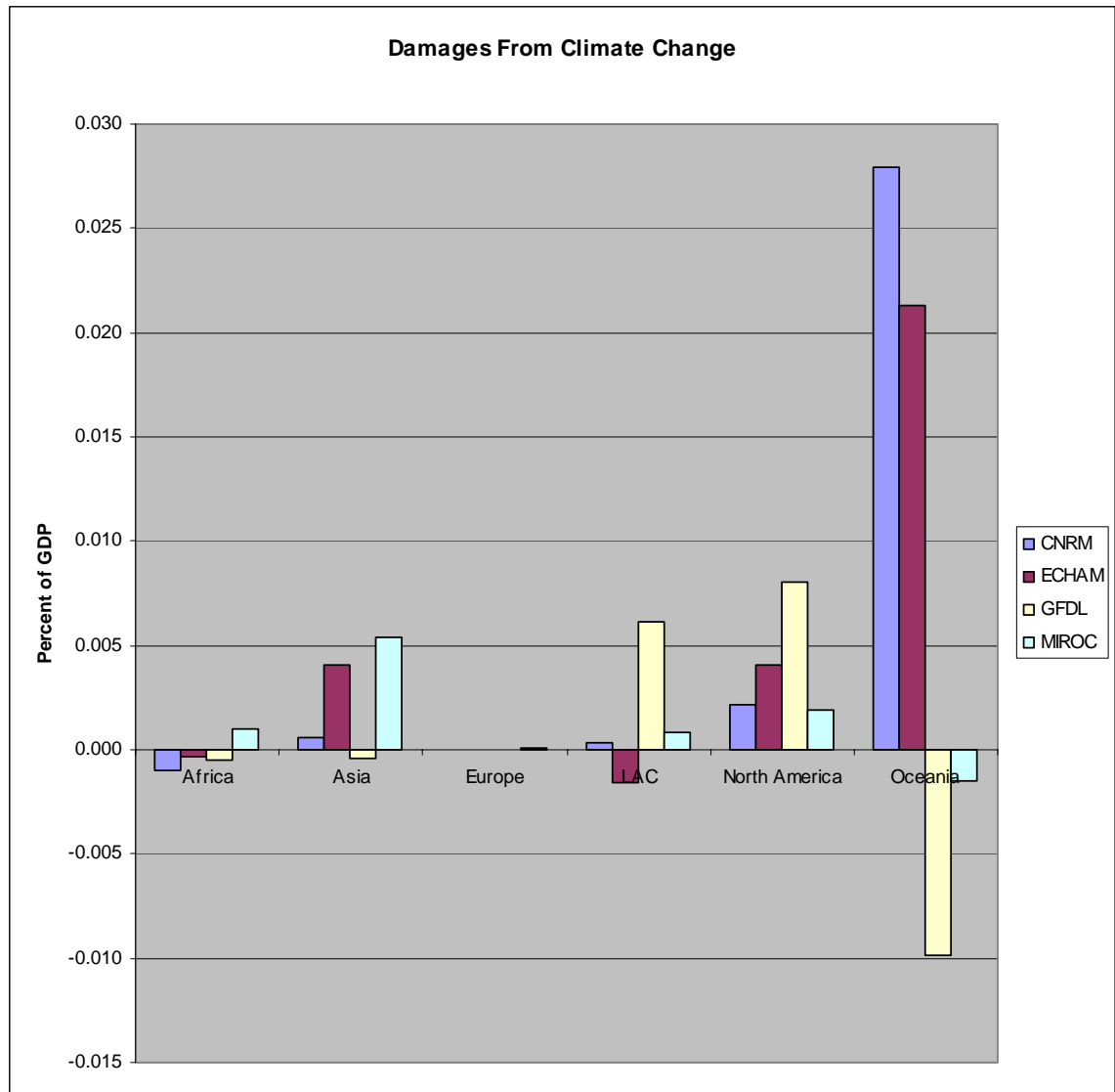


Note: Calculated using minimum pressure damage model with future baseline.

Figure 4 displays hurricane damages from 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. From a continental perspective, the extra damages caused by climate change are less than 0.03 percent of GDP by 2100 in all continents and climate scenarios. The effect is quite small averaged across these large areas. Oceania has the largest average impacts (0.009 percent of GDP), although the effects are not

consistent across climate models. North America (0.004 percent of GDP) and Asia (0.002 percent of GDP) have the most consistent effects. Latin America also has large average but inconsistent damages (0.002 percent of GDP).

Figure 4: Hurricane Damages as a Fraction of GDP

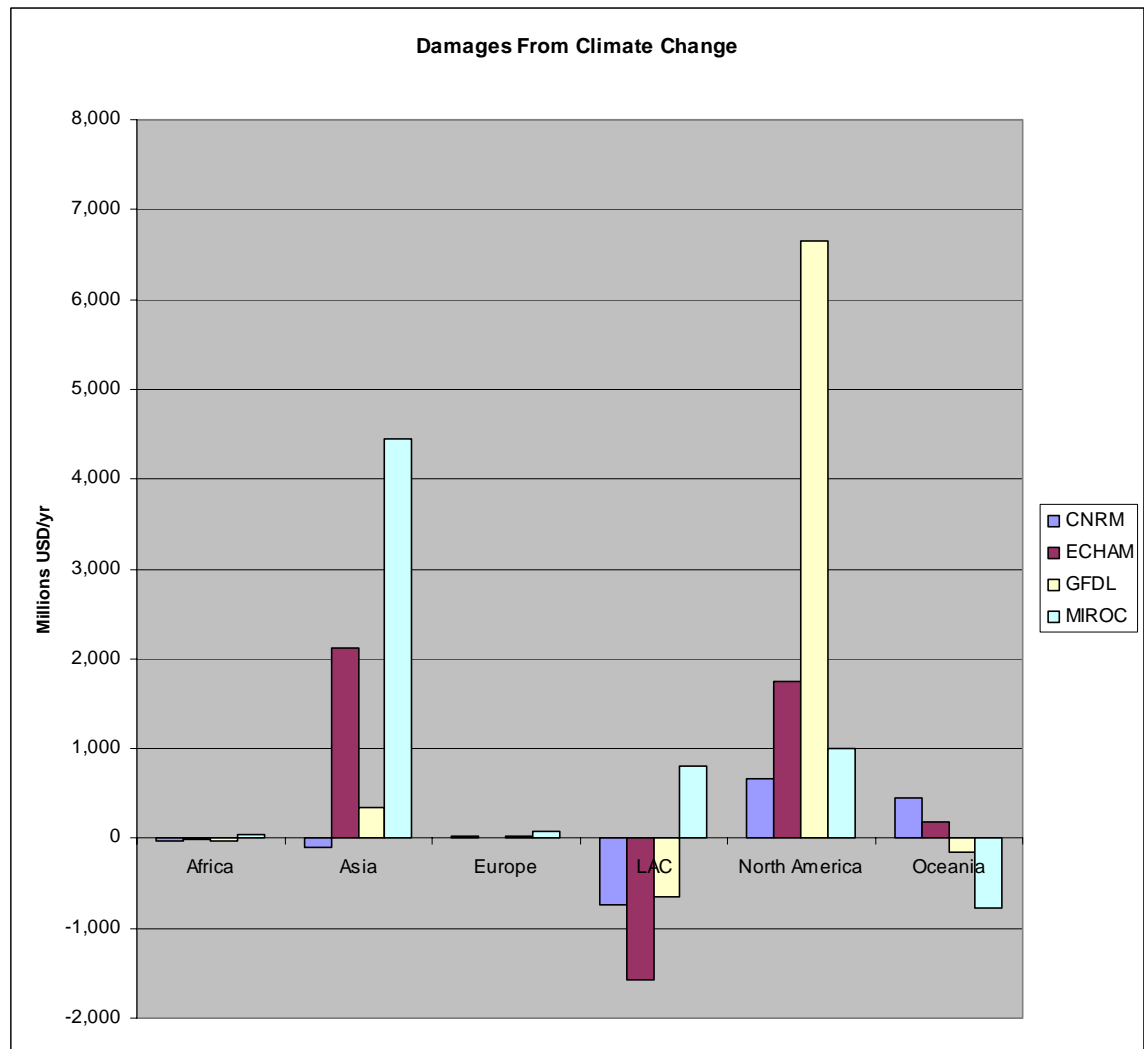


Note: Calculated using minimum pressure damage model with future baseline.

In addition to the minimum pressure damage model, we also calculated damages using the wind speed damage model. Figure 5 illustrates that the regional impacts from climate change are similar using the wind speed model to the results of the minimum

pressure model (Figure 3). However, there are some differences between the two figures. Overall damages are smaller using wind speeds compared to minimum pressure because the wind speed damage function is not as responsive to magnitude. In particular, except for the reduction in damages in Oceania under MIROC, every other predicted impact shrinks with the wind speed model. The effects by continent are also less consistent across the four climate models with wind speed. No continent except North America is consistently harmed or helped by climate change across all four models with the wind speed model.

Figure 5: Impact of Climate Change on Tropical Storm Damage Using Wind Speeds

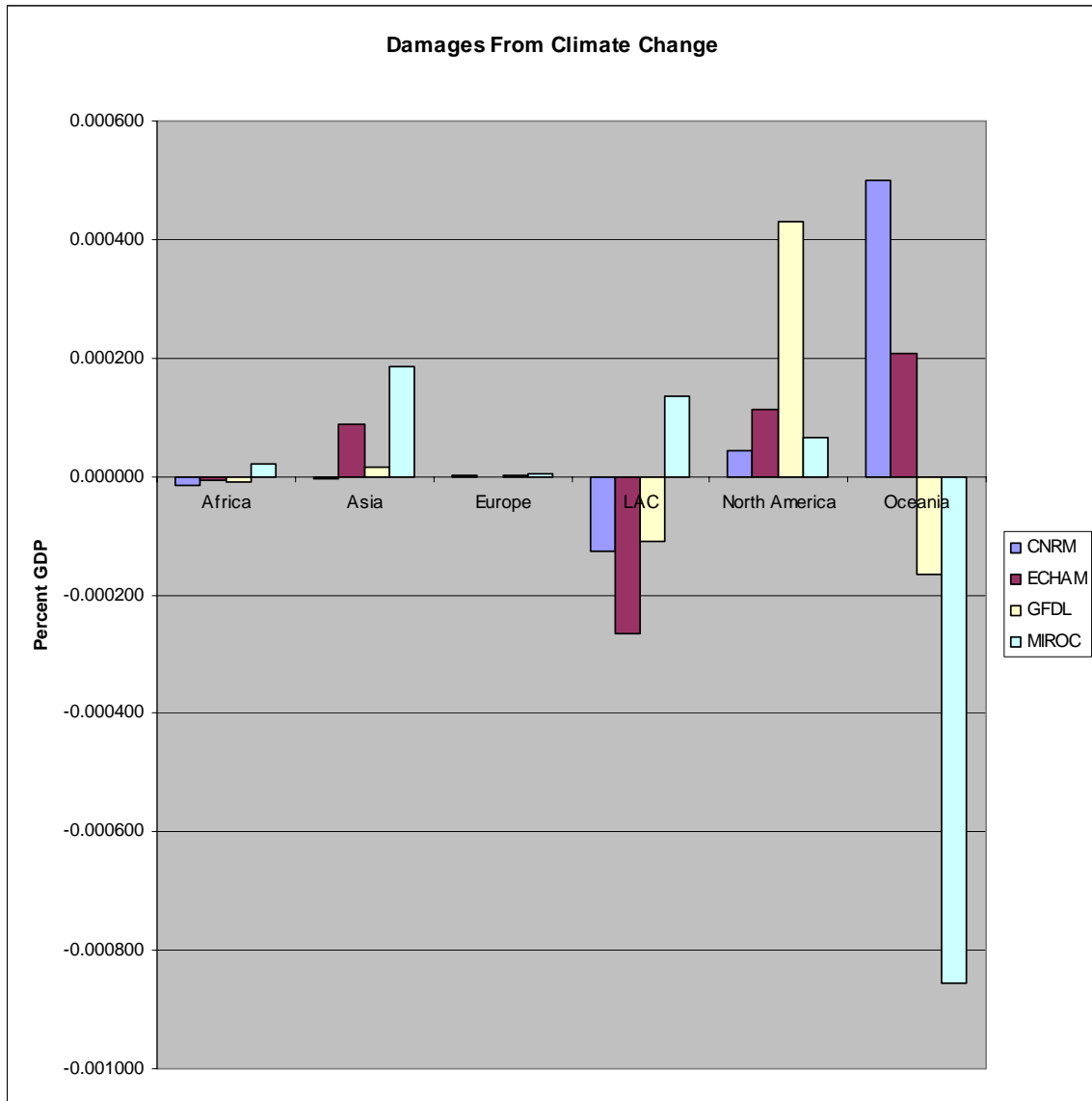


Note: Values calculated for 2100 using future baseline using the wind speed damage model.

Figure 6 displays the climate damages as a fraction of GDP. Because Figure 6 and Figure 4 are based on the exact same set of hurricanes and future GDP levels, they predict similar impact patterns across the climate models and regions. However, the smaller response function of the wind speed damage function leads to smaller damages and therefore the predicted impacts as a fraction of GDP are smaller with the wind speed model. One interesting exception in Figure 6 is that the MIROC climate model now predicts a very large benefit for Oceania of 0.009%.

The continental averages, however, hide disproportionate effects in individual countries. Impacts to all affected countries are shown in Appendix A. The five countries with the largest average impacts from climate change are the United States (\$4.8 billion), China (\$2.8 billion), Japan (\$1.0 billion), Australia (\$0.8 billion), and the Philippines (\$0.6 billion). The damages from these five countries account for 97 percent of the global damages. Half of all countries in the world have no effects at all because they are not vulnerable to hurricanes. Of the 84 countries that are impacted by hurricanes, the impacts are less than 0.01 percent of GDP in all but 4 countries (see Table 5). These 4 countries include Australia, Cuba, Philippines, and Vanuatu. The largest impact is to Cuba with a loss of 0.028 percent of GDP/yr.

Figure 6: Climate Impacts as a Fraction of GDP Using the Wind Speed Model



Note: Values calculated for 2100 using future baseline using wind speed damage model.

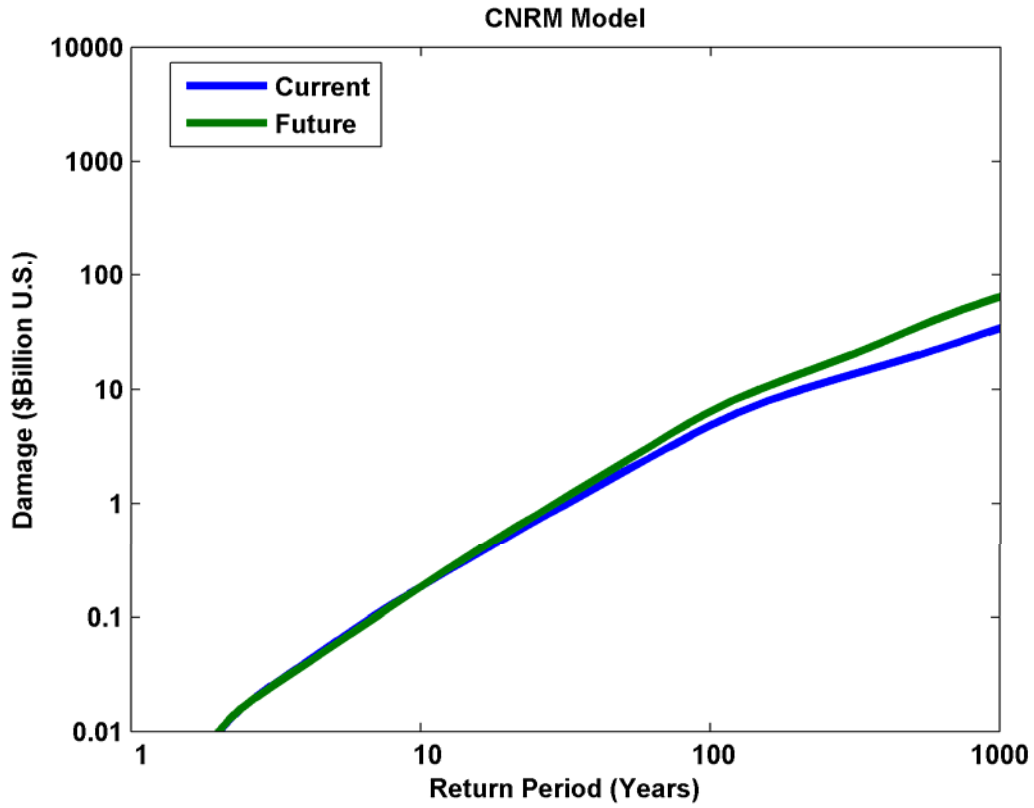
Table 5: Damages as a Fraction of GDP in The Most Heavily Impacted Nations

| Country     | Average<br>Damage (billion<br>USD/yr) | Percent of GDP |
|-------------|---------------------------------------|----------------|
| Australia   | 761.1                                 | 0.012%         |
| Cuba        | 176.32                                | 0.028%         |
| Philippines | 622.2                                 | 0.019%         |
| Vanuatu     | 1.11                                  | 0.017%         |

Source: Values in millions of USD/yr. Calculated using the minimum pressure model and the future baseline in 2100.

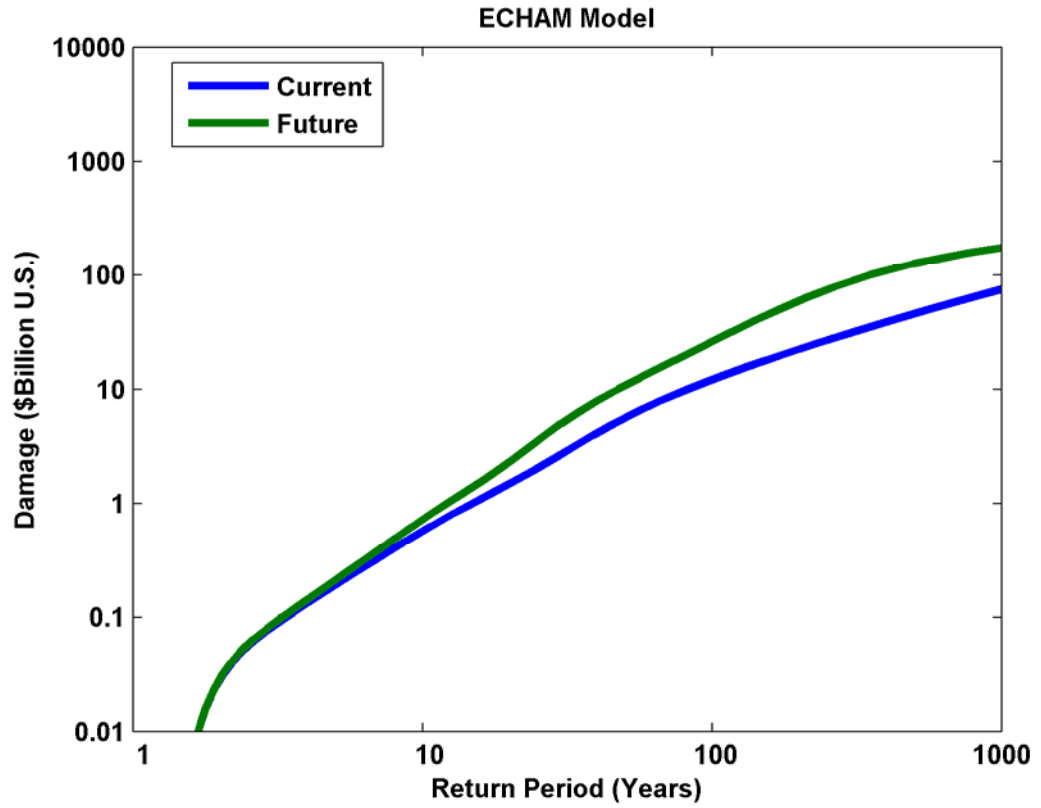
Although expected damages provide a good sense of long term damages, they hide the skewed nature of hurricane damages. Many storms cause relatively little damages. However, a few storms cause very large impacts. Figures 7 through 10 display the relationship between damages and return rates. The return rate is 1/frequency and it explains how many years pass on average before one is expected to see another storm of this magnitude. These figures illustrate that the primary influence of climate change is upon the most powerful storms. The return rate for the most powerful storms is shorter. Of course, the four graphs are not identical. The current and future curves are more similar for the CNRM climate model, suggesting there is only a small climate change. The remaining models predict much larger shifts with the future climate.

Figure 7: Return Rate by Damage For CNRM Climate Model



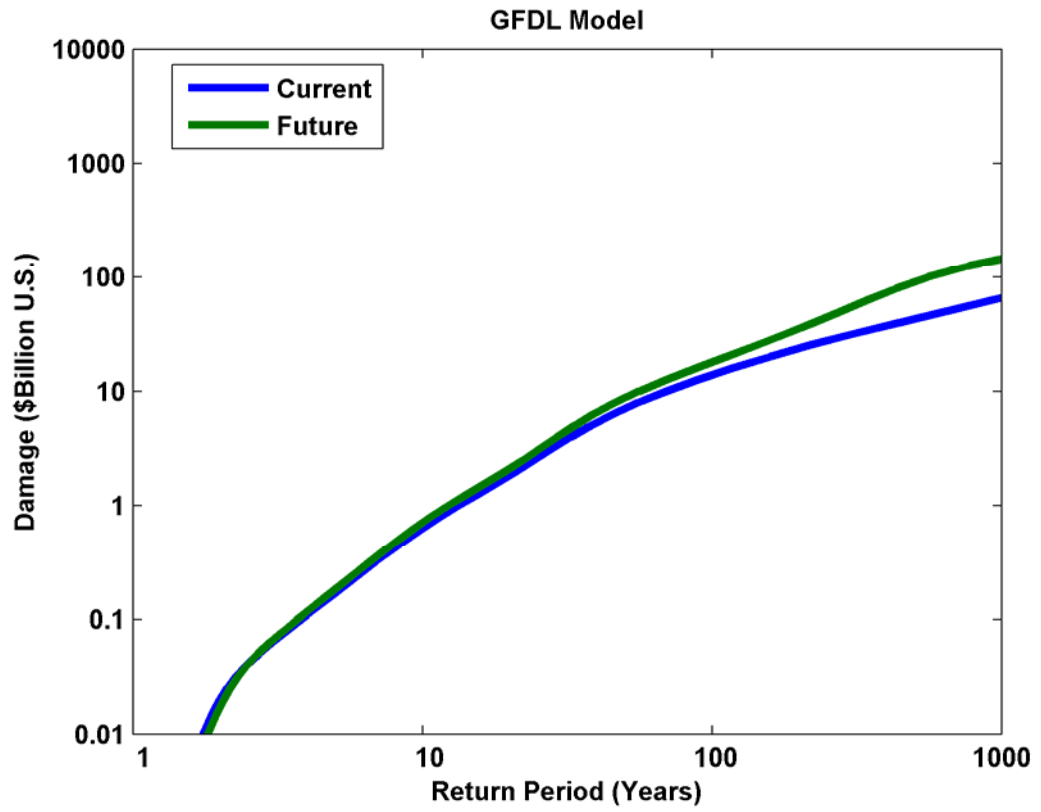
Note: Damages calculated in 2100 with future baseline and minimum pressure damage model.

Figure 8: Return Rate by Damage For CNRM Climate Model



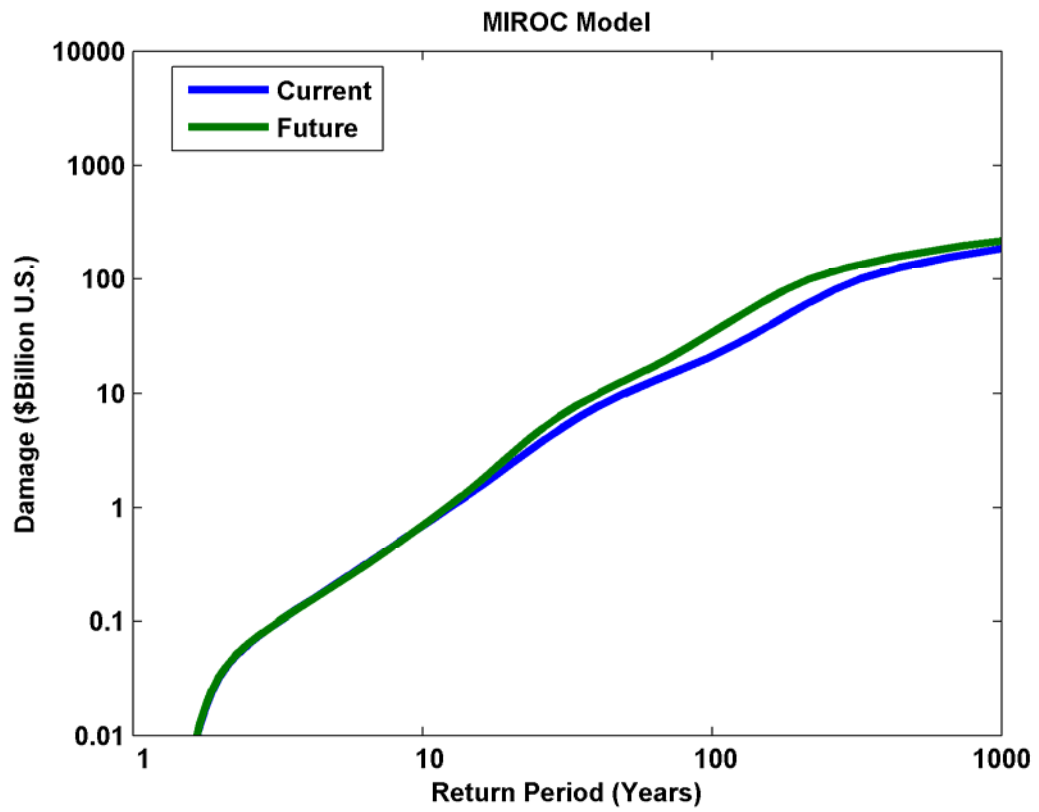
Note: Damages calculated in 2100 with future baseline and minimum pressure damage model.

Figure 9: Return Rate by Damage for the GFDL Model



Note: Damages calculated in 2100 with future baseline and minimum pressure damage model.

Figure 10: Return Rate by Damage for the MIROC Model



Note: Damages calculated in 2100 with future baseline and minimum pressure damage model.

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 fraction of damages caused by the top 10% and top 1% worst storms. Even with the current climate, the top 10% worst storms cause 90% of the total damages from tropical storms. The top 1% worst storms cause 58% of all the damages. With the future climate, those percentages will climb. The top 10% worst storms will cause 93% of the damages and the top 1% of storms will cause 64% of all the damages from tropical storms.

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

| Model | Time    | Top 10% Worst Storms | Top 1% 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 future baseline and minimum pressure damage model.

Many of the most powerful storms destroy everything in their path. We assume that these storms destroy all the capital within five coastal counties. Table 7 presents the 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 Hurricanes

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

Note: Analysis based on future baseline and minimum pressure damage model.

## V. Conclusion

This study relies on an integrated assessment model to predict the damages that climate change may cause on hurricanes. The A1B emission scenario is combined with four climate models. A hurricane generator is then used to create 3000 hurricanes in each ocean basin 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 hurricane intensity to increase in both the North Atlantic and North West Pacific ocean basins.

The study then estimates a damage function associated with tropical storms. Data from the United States is used to estimate the relationship between damage and storm magnitude. The results of this analysis suggest that damages are highly sensitive to storm magnitude. Damages double with a reduction of slightly more than 1% of minimum pressure or an increase in wind speed of 20%. International data is then used to estimate the relationship between 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%. Doubling population density reduces damages by 10%. This result is in sharp contrast to the assumptions in the literature that damages are directly proportional to income and population. Higher income people apparently take measures to reduce their vulnerability. Urban populations are less sensitive than rural populations to tropical storms.

The analysis then forecasts how damages will change because of changes in income and population. Projected population and income changes are combined with the coefficients from the international regressions to estimate how damages will change. The analysis predicts that tropical storm damages will increase by 2.2 times from an average of 14 billion to 30 billion USD/yr. However, damages as a fraction of GDP are expected to fall from their current rate of 0.024 percent in 2000 to 0.0052 percent of GDP in 2100.

The impact of climate change is estimated using the future baseline income and population. The damages from tropical storms in the future climate is subtracted from the damages from tropical storms in the current climate, both estimated with the future baseline. Using the minimum pressure damage model, the estimated impact of climate change on tropical storm damages ranges from \$5 to \$14 billion USD/yr depending on the climate scenario. This represents an increase of between 17 percent to 49 percent over background levels. The damages as a fraction of GWP in 2100 range from 0.001 to 0.002 percent. Damages are slightly smaller using the wind speed model.

The damages are not evenly spread across the planet. Because hurricanes in the North Atlantic and North West Pacific Oceans increase in intensity with warming, North America and Asia have the largest and most consistent impacts. The average impact in Asia is an additional damage of \$4.5 billion of damages and the average impact in North America is an additional damage of \$4.4 billion. The average impact on the entire world is \$9.2 billion so that the remaining average impacts in the rest of the world are quite small. The remaining continents see both harmful and beneficial impacts depending on the model. A beneficial impact is simply a reduction in existing hurricane damages.

The results reveal that the damages from hurricanes are quite skewed. Even with the current climate, the 10 percent worst storms 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 account for 93 percent of the total damages and the 1 percent worst storms account for 64 percent of the total damages. Because these large storms explain so much of the story, it is very difficult to rely on observations of tropical storms over time to detect a trend. The large storms are rare so that it may take several centuries of observations to see whether the changes predicted in this paper actually have occurred.

There are many uncertainties associated with the forecasts made in this study. The emission path of greenhouse gases is highly uncertain because it depends upon the long term growth of the economy, the long term relationship between GDP and energy, and any government 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 in the four climate models used in this analysis. Exactly how hurricanes 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 economic measures of damages are poor and the international data does not even record the magnitude of the storms causing damage. Hurricanes clearly cause loss of life but the link between this and the magnitude of storms cannot be measured with available data. Finally, how damages might change if there is both a change in hurricanes and sea level rise has not yet been analyzed. Without adaptive measures, hurricanes will surely cause more damage. How society will adapt in the future is not yet clear.

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Appendix A: Average Impact by Country

| <b>Continent</b> | <b>Country</b>       | <b>Climate Impact</b> | <b>% GDP</b> |
|------------------|----------------------|-----------------------|--------------|
| Africa           | Comoros              | -0.28                 | -0.00456     |
| Africa           | Djibouti             | 0.01                  | 0.00010      |
| Africa           | Kenya                | 2.27                  | 0.00057      |
| Africa           | Madagascar           | -16.93                | -0.01627     |
| Africa           | Mauritius            | 1.38                  | 0.00138      |
| Africa           | Morocco              | 0.00                  | 0.00000      |
| Africa           | Mozambique           | 0.29                  | 0.00026      |
| Africa           | Seychelles           | 0.25                  | 0.00330      |
| Africa           | South Africa         | -0.62                 | -0.00001     |
| Africa           | Tanzania             | -3.12                 | -0.00131     |
| Asia             | Bangladesh           | -15.46                | -0.00169     |
| Asia             | Brunei Darussalam    | 0.57                  | 0.00043      |
| Asia             | Cambodia             | -4.34                 | -0.00391     |
| Asia             | China                | 2,792.99              | 0.00365      |
| Asia             | India                | -267.59               | -0.00111     |
| Asia             | Indonesia            | 323.17                | 0.00317      |
| Asia             | Iran                 | -5.51                 | -0.00012     |
| Asia             | Iraq                 | 0.00                  | 0.00000      |
| Asia             | Japan                | 973.58                | 0.00321      |
| Asia             | Kuwait               | 0.00                  | 0.00000      |
| Asia             | Malaysia             | -62.89                | -0.00163     |
| Asia             | Maldives             | 0.01                  | 0.00005      |
| Asia             | Myanmar              | -29.46                | -0.00934     |
| Asia             | Oman                 | 20.10                 | 0.00485      |
| Asia             | Pakistan             | -3.69                 | -0.00019     |
| Asia             | Philippines          | 622.16                | 0.01880      |
| Asia             | Saudi Arabia         | 0.02                  | 0.00000      |
| Asia             | South Korea          | 18.52                 | 0.00032      |
| Asia             | Sri Lanka            | -8.92                 | -0.00189     |
| Asia             | Thailand             | -44.71                | -0.00087     |
| Asia             | United Arab Emirates | -3.09                 | -0.00016     |
| Asia             | Vietnam              | 17.93                 | 0.00170      |
| Asia             | Yemen                | 2.73                  | 0.00089      |
| Europe           | Belgium              | 0.00                  | 0.00000      |
| Europe           | France               | 0.03                  | 0.00000      |
| Europe           | Iceland              | 0.06                  | 0.00006      |
| Europe           | Ireland              | 1.10                  | 0.00006      |
| Europe           | Norway               | 0.00                  | 0.00000      |
| Europe           | Portugal             | 0.16                  | 0.00001      |
| Europe           | Russia               | 16.84                 | 0.00005      |
| Europe           | Spain                | 0.32                  | 0.00000      |
| Europe           | United Kingdom       | 0.76                  | 0.00000      |
| LAC              | Antigua & Barbuda    | 0.78                  | 0.00722      |
| LAC              | Barbados             | 0.12                  | 0.00032      |
| LAC              | Belize               | 0.19                  | 0.00121      |

|               |                          |          |          |
|---------------|--------------------------|----------|----------|
| LAC           | Chile                    | -9.86    | -0.00029 |
| LAC           | Colombia                 | 0.51     | 0.00001  |
| LAC           | Costa Rica               | 0.89     | 0.00026  |
| LAC           | Cuba                     | 176.26   | 0.02753  |
| LAC           | Dominica                 | 0.52     | 0.01463  |
| LAC           | Dominican Republic       | 36.75    | 0.00692  |
| LAC           | El Salvador              | -1.00    | -0.00039 |
| LAC           | Grenada                  | -0.07    | -0.00126 |
| LAC           | Guatemala                | -5.16    | -0.00114 |
| LAC           | Guyana                   | 0.00     | 0.00000  |
| LAC           | Haiti                    | 3.85     | 0.00477  |
| LAC           | Honduras                 | 3.05     | 0.00186  |
| LAC           | Jamaica                  | 11.57    | 0.00662  |
| LAC           | Nicaragua                | 3.13     | 0.00410  |
| LAC           | Panama                   | 0.28     | 0.00010  |
| LAC           | Peru                     | 0.00     | 0.00000  |
| LAC           | Puerto Rico              | 41.23    | 0.00390  |
| LAC           | St. Kitts & Nevis        | 0.27     | 0.00535  |
| LAC           | St. Lucia                | 0.36     | 0.00303  |
| LAC           | St. Vincent & Grenadines | 0.10     | 0.00151  |
| LAC           | Trinidad & Tobago        | 2.12     | 0.00077  |
| LAC           | Venezuela                | 5.40     | 0.00015  |
| North America | Mexico                   | 175.43   | 0.00081  |
| North America | Bermuda                  | 0.28     | 0.00050  |
| North America | Canada                   | 23.78    | 0.00027  |
| North America | United States            | 4,766.02 | 0.00543  |
| Oceania       | Australia                | 761.12   | 0.01212  |
| Oceania       | Fiji                     | -1.94    | -0.00474 |
| Oceania       | French Polynesia         | -0.23    | -0.00053 |
| Oceania       | Marshall Is.             | 0.06     | 0.00361  |
| Oceania       | Micronesia               | 0.07     | 0.00250  |
| Oceania       | New Caledonia            | 0.88     | 0.00229  |
| Oceania       | New Zealand              | -7.09    | -0.00088 |
| Oceania       | Palau                    | -0.19    | -0.01087 |
| Oceania       | Papua New Guinea         | -1.85    | -0.00196 |
| Oceania       | Samoa                    | -0.42    | -0.00689 |
| Oceania       | Solomon Is.              | 1.00     | 0.00016  |
| Oceania       | Tonga                    | -0.05    | -0.00174 |
| Oceania       | Vanuatu                  | 1.11     | 0.01673  |

Note: Average of results from 4 climate models using future baseline and minimum pressure model.