Chapter 9
Global Tropical Cyclone Damages and Fatalities Under Climate Change: An Updated Assessment

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Abstract Although it is well known that climate change will alter future tropical cyclone characteristics, there have been relatively few studies that have measured global impacts. This paper utilizes new insights about the damage caused by tropical cyclones from Bakkensen and Mendelsohn (J Assoc Env Res Econ 3:555–587, 2016) to update the original methodology of Mendelsohn et al. (Nat Clim Change 2:205–209, 2012). We find that future cyclone losses are very sensitive to both adaptation and development. Future development (higher income) is predicted to sharply reduce future fatalities. However, damage may take two distinct paths. If countries follow the United States and adapt very little, damage is predicted to increase proportionally with income, rising 400% over the century. However, if development follows the remaining OECD countries, which have done a lot of adaptation, future cyclone damage will only increase slightly.

Keywords Tropical cyclone damage and fatalities · Adaptation

9.1 Motivation

Tropical cyclones (hurricanes, typhoons) cause significant damage to many coastal communities across the globe (Shultz et al. 2005; World Bank 2010; IPCC 2012) with average losses of $26 billion per year (Mendelsohn et al. 2012). It is well acknowledged that future cyclones will be affected by climate change (Emanuel 2005; Ranson et al. 2014). Although the number of hurricanes may not increase, it is expected that the intensity of the largest storms may well increase (Emanuel 2005;

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IPCC 2012; Ranson et al. 2014). This may have especially harmful consequences because damage increases nonlinearly with intensity (Hallegatte 2007; Pielke 2007; Narita et al. 2009; Nordhaus 2010; Bakkensen et al. 2018). The potential impacts of tropical cyclones can be a major factor in the social cost of carbon depending on how quickly tropical cyclone damage rises (Pearce 2003; Stern 2007; Tol 2008). Ranson et al. (2014) provides an excellent review of the current state of future tropical and extra-tropical cyclone damage estimates.

Many initial studies of tropical cyclone damage assumed that global cyclones would uniformly increase in intensity (Pielke 2007; Narita et al. 2009; Nordhaus 2010). However, climate change is likely to lead to much more complicated changes in future tropical cyclones (Emanuel et al. 2008; IPCC 2013; Walsh et al. 2016). There is some evidence that only larger storms will get stronger (Emanuel et al. 2008). There is also evidence that storm intensity may vary by ocean basin (Emanuel et al. 2008; IPCC 2012). One advantage of the Tropical Cyclone Integrated Assessment Model (TCIAM) is that the model captures alternative predictions of how cyclones might change in each basin (Mendelsohn et al. 2012). This model used simulated cyclone data to track cyclone intensity, position, and frequency in each basin in alternative climate scenarios so that it could predict how these changes might affect human communities.[1]

However, an important weakness of the TCIAM is that the damage function was heavily dependent on outcomes in the United States (Nordhaus 2010; Dinan 2017). At the time the model was built, the only available damage functions were based on American damage. New empirical research has broadened damage estimates to capture tropical cyclone impacts on not just the United States, but also other wealthy countries and the rest of the world (Bakkensen and Mendelsohn 2016). This paper explores how these new damage estimates alter the results of the original TCIAM.

The new damage research examines how tropical cyclone damage depends not only on storm intensity, but also on the income and the population density of the place that is struck by each storm (Bakkensen and Mendelsohn 2016). The results reveal that the damage caused by storms that hit the United States increase proportionally with income and increase very rapidly with intensity. The storms that hit other wealthy countries, in contrast, increase very slowly with income and are much less sensitive to intensity. Holding everything else constant, a storm that hits the United States causes ten times more damage than a storm that hits other wealthy countries. Looking across all countries, higher income monotonically decreases fatalities but has a hill-shaped effect on damage. As countries go from poor towards middle class, damage rises, but as they enter middle class, damage starts to fall (with the exception of the United States). Damage also depends on whether the region that is hit by the storm is urban or rural. Surprisingly, damage and fatalities do not rise

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[1] Hallegatte (2007) also utilizes simulation data to estimate future cyclone damages, thereby capturing sophisticated underlying distribution dynamics.

with population density because most urban centers do more to protect themselves. Additional literature on damage and fatality determinants identifies the importance of factors including institutions and economic growth (see reviews by Cavallo and Noy 2011; Kousky 2014). Similar to the climate change analyses, there are also many country-specific studies on damage and fatality determinants that we do not review here.

The chapter proceeds as follows: the theoretical foundations are explained in Sect. 9.2. Section 9.3 describes the empirical methodology followed by a list of data sources in Sect. 9.3.1. Section 9.4 presents and discusses the results, and Sect. 9.5 offers concluding remarks. The References and Appendix sections are presented at the end.

9.2 Theoretical Foundation

The theoretical foundation is based on Mendelsohn et al. (2012). In this paper, the authors note that the economic damage from a tropical cyclone (D) is equal to the total of all property losses caused by the tropical cyclone. A parallel theory follows for fatalities as well. The expected value of damages from tropical cyclones can be calculated by:

$$E[D] = \sum_{j} \sum_{j} \pi\left(X_{ij}, C\right) D\left(X_{ij}, Z_i\right) \tag{9.1}$$

where $\pi(X_{ij}, C)$ is the probability that tropical cyclone j will make landfall at location i, given tropical cyclone characteristics X and climate conditions C. $D(X_{ij}, Z_i)$ represents the damages from tropical cyclone j at location i, given tropical cyclone characteristics X_{ij} and local socioeconomic conditions Z_i. Expected damages are a summation of the probability of a landfall at a given location multiplied by the damages from the tropical cyclones, summed across all locations and tropical cyclones. Atmospheric experts are key to estimating the probability function, while economists specialize in the damages portion (Mendelsohn et al. 2012).

The impact of socioeconomic change, or a change in human communities from current socioeconomic conditions, $Z_{0,}$ to new socioeconomic conditions, Z_1, while holding climate fixed at level C_0, on tropical cyclone damages can be calculated by:

$$SC = E[D(Z_1, X(C_0))] - E[D(Z_0, X(C_0))] \tag{9.2}$$

which is the difference between the expected damage of each society, holding all other factors constant.

The impact of climate change, or a change in atmospheric conditions from current climate, $C_{0,}$ to a new climate, C_1, on tropical cyclone damages can be calculated by:

$$CC = E[D(Z_1, X(C_1))] - E[D(Z_{1,} X(C_0))] \tag{9.3}$$

which is the difference between the expected damages of each climate holding all other factors constant, including socioeconomic conditions at their future level.

9.3 Methodology

We start with the insights about tropical cyclone damage and fatality functions gained from global data (Bakkensen and Mendelsohn 2016). We conduct a few additional analyses using ordinary least squares regressions of historical global hurricane and socioeconomic panel data. These new damage and fatality functions capture the heterogeneity of outcomes across levels of development. We estimate separate coefficients in the damage function for the United States, for the other wealthy countries of the Organization of Economic Cooperation and Development (OECD), and for Non-OECD countries (Bakkensen and Mendelsohn 2016).[2] The damage function has a log-log functional form to account for the count-data nature of the dependent variables. This functional form is easy to interpret and easy to incorporate into the integrated assessment model. The damage function of tropical cyclones is:

$$D_{ij} = \beta_0 + \beta_1 X_{ij} + \beta_2 Z_{ij} + \varepsilon_{ij} \tag{9.4}$$

where D_{ij} is the tropical cyclone damage from storm j in country i. X_{ij} represents the tropical cyclone intensity (either the minimum sea level barometric pressure (MSLP) or the maximum sustained wind speed upon landfall) as well as distance of closest approach of the cyclone (Mendelsohn et al. 2012; Bakkensen and Mendelsohn 2016).[3] Z_{ij} represents a vector of socioeconomic variables describing the conditions in location i where the cyclone j landed, and includes the average country-level population density and per capita income. We estimate this equation for a sample of all countries and for a sample of just the United States, all other rich countries

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[2] In our dataset, the following is the fraction of OECD country landfalls by member state: Australia (11.7%), Canada (2.26%), Japan (26.8%), South Korea (10.6%), New Zealand (1.13%) and the United States (45.7%). France, Germany, Ireland, and the United Kingdom together receive 1.9% of OECD cyclone landfalls.

[3] If a tropical cyclone does not make landfall in a country and damages were observed in the historical evidence, characteristics were used from the storm when it was at its closest point to the given country.

(members of the Organization for Economic Cooperation and Development (OECD) excluding the United States), and a sample of other countries (Non-OECD).

Following Bakkensen and Mendelsohn (2016), we estimate the following log-log tropical cyclone fatality function:

$$F_{ij} = \alpha_0 + \alpha_1 X_{ij} + \alpha_2 Z_{ij} + u_{ij} \tag{9.5}$$

where F_{ij} is a record of tropical cyclone fatalities from storm j in country i. Similar to the damage function, we include cyclone intensity characteristics (MSLP or wind speed) and distance of closest approach of the cyclone, as well as socioeconomic characteristics (population density and per capita income). We estimate this regression on all countries. We also estimate the regression for all OECD countries (including the US) and for Non-OECD countries. We combine the United States and other OECD countries in the fatality regression because there is no difference in fatality regression for the United States and other OECD countries. A fatality function using a negative binomial estimator was found to have qualitatively similar results as the log-log functional form employed here (Bakkensen and Mendelsohn 2016).

The underlying emission scenario in all model runs is the IPCC AR4 A1B emissions scenario (IPCC 2007) stabilizing carbon dioxide equivalent atmospheric concentrations at 720 ppm by the year 2100 (Emanuel et al. 2008).[4] The emissions scenario is then translated to changes in global climate through four general circulation models: CNRM (Gueremy et al. 2005), ECHAM (Cubasch et al. 1997), GFDL (Manabe et al. 1991), and MIROC (Hasumi and Emori 2004).[5] By exploring alternative climate models, the TCIAM provides the reader with a sense of the uncertainty coming from the climate forecasts.

Simulated storms are randomly seeded across the globe and then allowed to develop and move by the cyclone simulator. Each track contains the simulated cyclone location and characteristics at 6-h intervals for the lifetime of the storm. A total of 5000 tracks are simulated for the Atlantic basin and 3000 for each of the Western and Eastern Pacific, Indian Ocean, and Southern Hemisphere basins, for each of four climate models, for both current (1980–2000) and future (2080–2100)

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[4] This emission scenario is similar to RCP 6.0 in IPCC (2013).

[5] The baseline simulated tracks reflect climate from 1980 to 2000. Using a more severe climate change assumption (IPCC AR5 RCP8.5), Emanuel (2013) finds only minor increases in cyclone power from 1995 to 2015, thus these tracks are still arguably a relevant baseline for the climate from 2000 to 2020. Climate signals can take up to a few decades to impact cyclones given the complex responses across ocean and atmosphere dynamics. In addition, by employing these simulation tracks, we can directly compare across the Mendelsohn et al. (2012) earlier results and the present results. All differences between these two papers are driven by assumptions of the damage caused by each simulation track since the tracks have not changed.

climate, resulting in a total of 136,000 storms. The TCIAM then calculates when a simulated cyclone track intersects with land. The intensity of the storm and the location of landfall is then recorded for that storm. Socioeconomic characteristics of that location are matched with the storm.

Cyclone outcomes in each basin are predicted for both the current climate and future climates for all storms. Note that many storms do not make landfall and therefore cause no damage. The predictions of cyclones in the current climate are similar to observed outcomes in all but the GFDL climate model (Emanuel et al. 2008).

We then calculate the consequence of socioeconomic change (population and income) on future baseline cyclone damage and fatality, holding climate constant at its current level. We then examine how changes in cyclones caused by climate change alter future cyclone damage and fatalities. That is, we compare the future outcome with the current climate with the future outcome with the new climate, all at the future baseline income and population. The impact of climate change is the difference between the expected outcome from the future climate and the current climate, given future baseline socioeconomic projections.

9.3.1 Data

The analysis utilizes data from multiple sources. The first part of the analysis relies on country-level historical tropical cyclone damage and fatality data, as well as affiliated historical country population and income data. Data on tropical cyclone damages and fatalities are from Bakkensen and Mendelsohn (2016) and the sources, processing, and considerations of measurement error are more fully explained and explored in the previous paper. Altogether, more than 1400 landfalls are included from 1960 to 2010 and account for approximately $0.75 trillion in damages and 400,000 fatalities. Note that this represents the full history of storms for which damage or fatalities are publicly recorded and can be linked with cyclone and local socioeconomic data. Damage and fatality reports are obtained from EM-DAT, the International Disaster Database managed by the Center for Research on the Epidemiology of Disasters, as well as Nordhaus (2010) for the United States. The EM-DAT database includes information on over 17,000 natural and technological disasters, and is sponsored in part by the United Nations and United States Agency for International Development. Data on historical country population and income data are gathered from the Penn World Table v7.1, the USDA ERS International Macroeconomic Data, the CIA World Factbook, and Columbia University's CIESIN's Gridded Population of the World v3. Further, we collect local data at the county-level for six large countries across the globe, including Australia, China, India, Japan, Philippines, and United States. In addition, we collect data at the state level for Mexico. Future Gross Domestic Product (GDP) by country are projected from current (real observed) levels assuming a 2% constant growth rate for highly developed countries, 2.7% for transitioning countries, and 3.3% for developing countries (Mendelsohn et al. 2012). Projections of population are compiled by the United Nations (2018). GDP per capita are estimated by the ratio of future GDP to future population. We assume land area is constant over time to estimate population density.

Historical tropical cyclone data are collected from several sources including the National Oceanic and Atmospheric Administration's International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010), the U.S. Navy's Joint Typhoon Warning Center's Tropical Cyclone Reports, and Nordhaus (2010). These sources include variables such as location, wind speed, and minimum barometric pressure at 6-h intervals for each hurricane since the mid-1800s (NOAA 2010). Affiliated tropical cyclone characteristics from these sources were matched by hand with the country level damages data and affiliated socioeconomic data to complete the historical data set (Bakkensen and Mendelsohn 2016). Simulated storm tracks are detailed in Sect. 9.3.

9.4 Results

9.4.1 Historical Global Damage and Fatality Functions

In this section, we present and discuss our historical damage and fatality functions. Note that these regressions mirror the work of Bakkensen and Mendelsohn (2016) in their Sect. 3.5 (including Table 7) for damages and their Appendix Section F (including Table 16) for fatalities. However, in this analysis, we present all three specifications (all countries, OECD versus Non-OECD, and USA versus Non-USA OECD versus Non-OECD) in this section and in the Appendix.

Table 9.1 presents our historical global damage functions partitioned between United States, OECD, and Non-OECD countries for both minimum sea level pressure in columns 1 through 3, respectively, and maximum wind speed in columns 4 through 6, respectively. Appendix Table 9.7 presents the results for all countries and the OECD versus Non-OECD specifications for both minimum pressure and wind speed. Due to the log-log functional form, the estimated coefficients are elasticities (the percent change in damage or fatalities for a percent change in the explanatory variable). Looking first at the socioeconomic coefficients, we find the United States to be significantly different than the rest of the world. Specifically, we find the estimated income coefficient of 1.15 in the pressure specification and 1.64 in the wind specification, indicating that damages scale at least proportionately with economic growth. The Non-OECD countries have a lower income elasticity of

Table 9.1 Historical damage functions

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln damages	Ln damages	Ln damages	Ln damages	Ln damages	Ln damages
	MSLP	MSLP	MSLP	Wind	Wind	Wind
	USA	OECD (non-USA)	Non-OECD	USA	OECD (non-USA)	Non-OECD
Ln income per capita	1.148**	−0.624	0.285***	1.636***	−0.459	0.229**
	(0.577)	(0.472)	(0.0976)	(0.607)	(0.579)	(0.0991)
Ln population density	−0.300*	0.298***	0.0980	−0.342**	0.309**	0.0677
	(0.162)	(0.0821)	(0.0783)	(0.169)	(0.137)	(0.0776)
Ln MSLP	−84.75***	−34.35***	−23.70***			
	(9.254)	(12.45)	(3.631)			
Ln wind				5.069***	2.005**	1.425***
				(0.616)	(1.005)	(0.235)
Ln distance	−0.135	−0.690***	−0.351***	−0.0339	−0.680***	−0.322***
	(0.271)	(0.123)	(0.0406)	(0.247)	(0.132)	(0.0406)
Constant	592.1***	260.0***	177.9***	−17.07**	13.88**	9.737***
	(63.37)	(86.73)	(25.03)	(7.245)	(6.806)	(1.227)
Observations	108	95	653	110	81	652
R-squared	0.498	0.334	0.171	0.446	0.315	0.155

Standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Note that these regression results are identical to the specification in estimation Eq. 9.4 but are formatted as separate regressions here for ease of presentation and comparison

between 0.23 and 0.29. The income elasticity for the other OECD countries is less than one, but not significantly different from zero, implying that damage does not increase as their incomes rise. This is a striking difference compared to the United States. It is also important to note that damages do not scale proportionately with population density, meaning damages are not much larger, and in some cases lower, in highly urban areas.[6] This could be reflective of better building codes, or higher resilience in cities relative to more sparsely populated rural regions.

Turning to the cyclone characteristic coefficients, we again find the United States to be a large outlier in terms of damage, with damage scaling to the –84th power of pressure and the 5th power of wind speed. This is much larger than the intensity coefficients for other OECD and Non-OECD countries. For example, damage increases with the square of wind speed in other OECD countries and 1.4 times

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[6] This finding is empirically tested and discussed in Bakkensen and Mendelsohn (2016). In their analysis, they estimate damage and fatality functions using country-level data and, in a separate regression, county-level data for six large countries (plus Mexico at the state level). The results are qualitatively similar across the two geographic scales yet have important nuance to the interpretation. The country-level analysis examines the differences driven by more densely populated versus less densely populated countries. The county-level analysis explores the differences between urban and rural locations hit by storms.

Table 9.2 Historical fatality functions

	(1)	(2)	(3)	(4)
	Ln fatalities	Ln fatalities	Ln fatalities	Ln fatalities
	MSLP	MSLP	Wind	Wind
	OECD	Non-OECD	OECD	Non-OECD
Ln income per capita	−1.223***	−0.758***	−1.257***	−0.743***
	(0.184)	(0.0564)	(0.191)	(0.0580)
Ln population density	0.247***	0.159***	0.246***	0.107**
	(0.0465)	(0.0418)	(0.0546)	(0.0427)
Ln MSLP	−9.356**	−9.047***		
	(4.599)	(2.235)		
Ln wind			0.628**	0.511***
			(0.312)	(0.136)
Ln distance	−0.155***	−0.187***	−0.156***	−0.187***
	(0.0454)	(0.0240)	(0.0455)	(0.0248)
	78.15**	70.90***	11.59***	6.746***
	(31.87)	(15.40)	(2.393)	(0.730)
	172	848	166	842
	0.327	0.247	0.333	0.232

Standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Note that these regression results are identical to the specification in estimation Eq. 9.5 but are formatted as separate regressions here for ease of presentation and comparison

wind speed in Non-OECD countries. Most of the literature assumes damage increases with the cube of wind speed. Finally, as expected, we find that the closer a cyclone comes to land, the larger the damages, all else equal. Using an F-Test comparing the joint equivalency of all estimated coefficients across the models, we can reject that the USA is the same as OECD and Non-OECD countries at the 0.001% level. We find the OECD to be different from Non-OECD countries at the 2.5% level. Thus, we find systematic differences in cross-country determinants of cyclones damage.

Table 9.2 presents the results from our global fatality functions partitioned by OECD and Non-OECD countries, with minimum sea level pressure in columns 1 and 2, and maximum wind speed in columns 3 and 4. We find the United States and the OECD fatality coefficients are not statistically different, so we combine the two samples in the fatality function (Bakkensen and Mendelsohn 2016). The socio-economic coefficients of fatalities resemble the previous literature (e.g., Kahn 2005; Bakkensen and Mendelsohn 2016). Higher income lowers fatalities especially in more developed countries. Wealthier countries place a high value on human life and do a lot to reduce fatalities (Fankhauser and McDermott 2014).[7] While we find fatalities to increase with population density, fatalities do not scale proportionately with increases in population density. Cities are able to protect human life more

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[7] We leave empirical exploration of the efficiency versus demand hypothesis for future work.

Table 9.3 Current and future cyclone damage from socioeconomic change by 2100 ($ billions)

		3 regions model		All countries model	
	Current	Future baseline damages	% increase	Future baseline damages	% increase
USA	15.3	46.2	201.7%	30.4	99.0%
(Non-USA) OECD	3.6	0.8	−78.8%	10.0	176.4%
Non-OECD	6.7	12.9	92.2%	18.2	171.4%
Total	**25.6**	**59.8**	**133.6%**	**58.6**	**128.8%**

Column 1 presents summary statistics for current average annual damages (in $ Billions) across the three (USA, Non-USA OECD, and Non-OECD) regions. The second column presents the future baseline damage assuming current climate and future projections of socioeconomic factors. Column 3 states the percent increase between columns 1 and 2. This is our preferred specification. Columns 4 and 5 mirror the results of columns 2 and 3 except using the all countries regression model to value the simulated cyclone landfalls

effectively than rural areas (Bakkensen and Mendelsohn 2016).[8] Turning to cyclone characteristics, we find fatalities increase with the –9th power of pressure and the 0.5th or 0.6th power of wind speed. We do not find statistically significant differences in the coefficient of intensity across OECD and Non-OECD countries. However, there is a significant difference in the coefficients of the socioeconomic coefficients between the OECD and Non-OECD regressions at the 0.001% level.

9.4.2 Socioeconomic Change Impact on Tropical Cyclone Damages and Fatalities

Tropical cyclones currently lead to about $26 billion in damages, on average, across the globe each year (Mendelsohn et al. 2012). However, the damage varies a great deal across space with the United States, accounting for approximately 60% of global annual damages despite only receiving an average of two landfalls per year (NHC 2010). The other OECD countries suffer 14% of damage and the 86 Non-OECD countries and territories account for $6.7 billion (26%) of global damage.

We first assess the impact of future socioeconomic change on projected cyclone damage and fatalities, assuming that the world's climate remains unchanged. The future will be a much richer and more populated world. In Table 9.3, we calculate how much tropical cyclone damage would change simply because of these future socioeconomic changes given the minimum pressure damage model in Tables 9.1 and 9.2. We compare the results using a single damage function for the whole globe and a separate damage function for the United States, Non-US OECD countries, and

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[8] Bakkensen and Mendelsohn (2016) find evidence in heterogeneity of damages across urban versus rural locations. We leave exploration of the specific relationship for future work.

Non-OECD countries. The results of the two models lead to a very similar aggregate prediction of global damage in 2100 of almost $60 billion per year. However, the distribution of damage changes a lot. The single damage function for the world projects the future damage in the United States would increase by almost 100%, and the damage in the rest of the world would rise by 175%. With the three-region model, the United States future damage rises 200% to $46 billion/year. The other OECD country damage falls to 20% of its former level while Non-OECD damage doubles. China, India, and the Philippines' future losses will be approximately 125% more than today.

This analysis does not account for the cost of adaptive measures that many countries might take to reduce storm damage and is not meant to be a welfare analysis. Nonetheless, the results highlight the potential for countries to significantly decrease their losses as they develop. One interesting question for Non-OECD countries is whether to follow the no adaptation path of the United States or the adaptation path of other OECD countries as they develop.

Sensitivity analysis is critical in validating climate-economy models (Burke et al. 2015; Milner and McDermott 2016). Thus, we re-run our model using different valuation assumptions. Using wind instead of minimum sea level pressure, the story is qualitatively similar, with damages increasing in the "all countries model" by approximately 80% for the United States and between 140% and 150% for the rest of the world. Turning to the all countries model, the wind model estimates similar results for OECD and Non-OECD countries when compared with the pressure results, with losses decreasing for the former by approximately 70% and increasing for the latter by the same magnitude. However, given the larger income elasticity for the United States in the wind model relative to the pressure model, the wind model estimates future damage due to socioeconomic change alone of more than $153 billion/year, a 900% increase from the current levels. All these estimates assume that damage will be truncated at complete destruction of the capital stock, which we operationalize as $1 trillion for a single landfall.[9] Relaxing this truncation assumption only impacts estimates for the United States. In the three countries pressure model, losses would increase by about 400%, instead of the estimated 200% in Table 9.3. We also compare these results with the sensitivity analysis originally performed by Mendelsohn et al. (2012). In their analysis, they find future damage is most sensitive to assumptions of the estimated income elasticity, and less so to the population density elasticity. We find this in our results as well for the all countries versus three regions model, the latter of which leads to the largest spread in future damage projections. The model sensitivity is larger than the sensitivity to projections of future income and population. Additional sensitivity results are presented below for climate change.

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[9] The truncation assumption is an estimate of the maximum damage a single future cyclone could destroy. We calculate it as six time the losses of the most damaging cyclone to date (Hurricane Katrina at approximately $165 billion in losses, NCEI 2018).

Table 9.4 Current and future cyclone fatalities under socioeconomic change

		2 regions model		All countries model	
	Current	Future baseline fatalities	% increase	Future baseline fatalities	% increase
OECD	155	11	−92.83%	46	−70.37%
Non-OECD	8033	2116	−73.66%	2583	−67.85%
Total	**8187**	**2127**	**−74.02%**	**2628**	**−67.90%**

Column 1 presents summary statistics for current average annual fatalities across the three (USA, Non-USA OECD, and Non-OECD) regions. The second column presents the future baseline fatalities assuming current climate and future projections of socioeconomic factors. Column 3 states the percent increase between columns 1 and 2. This is our preferred specification. Columns 4 and 5 mirror the results of columns 2 and 3 except using the all countries regression model to value the simulated cyclone landfalls

Table 9.4 presents the results for the impact of socioeconomic change on future cyclone fatalities. Here, our preferred model combines the United States and other OECD countries. We compare this model with a model that combines all countries. The "all countries model" projects a 68% decrease in overall fatalities and not much difference between regions. The two regions model predicts a larger effect with OECD fatalities falling from 155 to approximately 11 per year, and Non-OECD countries fatalities falling from 8000 to 2000 per year.[10, 11] The qualitative fatality results are similar whether one uses wind or minimum pressure.

9.4.3 Climate Change Impact on Global Tropical Cyclone Damages and Fatalities

We now evaluate the effect of climate change given these future baseline impacts from population and economic development. We again compare the "all countries model" with the more spatially explicit damage and fatality functions. Changes in losses are now due solely to changes in cyclone characteristics, including the frequency of hits and especially intensity. The cyclone intensity coefficient coupled with changes in cyclone intensity estimates from the four general circulation models are the key determinants in these projections.

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[10] Note that we include Bangladesh and Myanmar, two high fatality outlier countries, in the current annual fatality statistic.

[11] We note that we use the same underlying income and population projections across both the damage and fatality estimates. Thus, the difference is driven by the estimated income and population density elasticities across the damage versus fatality functions across the outcomes. For the United States, damages increase sharply because they scale proportionately with GDP growth whereas fatalities decrease with development.

Table 9.5 Future cyclone damage with climate change (USD billions/year)

	Future baseline	CNRM	ECHAM	GFDL	MIROC	Average
All countries model						
USA	30.4	37.5	34.3	52.6	28.7	38.3
(Non-USA) OECD	10.0	10.7	11.3	8.8	9.3	10.0
Non-OECD	18.2	19.6	18.4	22.2	18.6	19.7
Total	**58.6**	**67.7**	**64.1**	**83.6**	**56.6**	**68.0**
3 regions model						
USA	46.2	79.3	86.4	97.5	41.6	76.2
(Non-USA) OECD	0.8	0.8	0.9	0.8	0.7	0.8
Non-OECD	12.9	13.3	12.9	14.2	13.2	13.4
Total	**59.8**	**93.3**	**100.2**	**112.5**	**55.5**	**90.4**

Column 1 presents summary statistics for the future average annual baseline damages – assuming future socioeconomic conditions but current climate conditions – across the three (USA, Non-USA OECD, and Non-OECD) regions. The next four columns present average annual future damages assuming future socioeconomic and climate conditions. The final column presents the average across the four models. All values are in real 2008 Billions of USD

The hurricane model across the four climate scenarios predicts that cyclone intensity increases in three models in the North Atlantic Ocean and across all four models in the Northeast Pacific Ocean (Mendelsohn et al. 2012). Changes in the other basins were less systematic. A comprehensive analysis of the impact of climate change on cyclone behavior is provided by Emanuel (2013).

Table 9.5 presents the tropical cyclone damage estimates from climate change. In the all countries model, climate change increases damage by about 25% in the United States. Climate change causes no consistent impact on other OECD countries and only an 8% increase in damage in Non-OECD countries. The three region model suggests that United States tropical cyclone damage would increase by 67% to $76 billion/year. The rest of the world would see an average increase of between 2% and 4%. Damage in Australia would increase by about 6% and damage in Japan would fall by about 13%. China, India, and the Philippines are estimated to see a reduction in damage of between 10% and 15% from the future baseline level. The results suggest it is the United States who is the most vulnerable to tropical cyclones and the most vulnerable to changes in tropical cyclones from climate change. In our sensitivity analysis, the wind model predicts future United States damages could increase by $50 billion/year due to climate change, topping more than $205 billion/year, compared to just $1.1 and $11.5 billion/year in other OECD and Non-OECD countries, respectively.

Lastly, we consider future fatalities under climate change in Table 9.6. Due to a weak intensification signal coupled with smaller (closer to zero) intensity elasticities, we find that climate change will have a very small effect on future fatalities. Specifically, future fatalities will only increase by about 3% for OECD countries

Table 9.6 Future cyclone fatalities under climate change

	Future baseline	CNRM	ECHAM	GFDL	MIROC	Average
All countries model						
OECD	46	47	47	50	46	47
NonOECD	2583	2633	2816	2904	2903	2814
Total	**2628**	**2681**	**2863**	**2954**	**2948**	**2862**
2 regions model						
OECD	11	11	11	12	11	11
NonOECD	2116	2158	2377	2534	2451	2380
Total	**2127**	**2169**	**2388**	**2546**	**2462**	**2391**

Column 1 presents summary statistics for the future average annual baseline fatalities – assuming future socioeconomic conditions but current climate conditions – across the three (USA, Non-USA OECD, and Non-OECD) regions. The next four columns present average annual future damages assuming future socioeconomic and climate conditions. The final column presents the average across the four models

and 12.5% for Non-OECD countries. The all countries model predicts climate change will cause the same percentage changes in fatalities as the two regions model. The absolute numbers differ because the baseline fatalities are different. The fatality estimates are similar across the wind model as well.

9.5 Conclusion

We provide updated estimates of the costs of climate and socioeconomic change on tropical cyclone losses, utilizing the methodology of Mendelsohn et al. (2012) and new insights surrounding cyclone damage and fatality functions (Bakkensen and Mendelsohn 2016). Future development is predicted to reduce overall fatalities from 8000 to 2100 per year. Climate change is predicted to increase these future deaths on average by 260 per year, entirely in Non-OECD countries.

Climate change will have a larger impact on damage. Allowing the damage function to vary across the United States, other OECD countries, and non-OECD countries, overall damage will increase from a future baseline of $60 billion/year to $90 billion/year, an increase of 50%. The striking result in both current tropical cyclone damage and future damage is the outsized role of damage in the United States. The United States is currently responsible for 60% of global damage, and that percentage could increase to 84% by 2100. The data suggests that the United States is doing very little to adapt to tropical cyclones compared to other countries in the world. If these trends continue, future tropical cyclone damage will reach $76 billion/year in the United States alone.

We note some important limitations of this analysis. Similar to previous work, we do not include rainfall or storm surge in our analysis, although both are likely to be important (Bakkensen et al. 2017; Seo and Bakkensen 2016). There are important uncertainties in these projections. We do not model alternative paths of economic growth. Faster growth will lead to more emissions but also higher income. The future level of mitigation is uncertain. The analysis examines a modest mitigation path, but the world may do no mitigation at all or engage in more rigorous efforts. By comparing the results of four climate models, the paper reveals there is uncertainty in climate projections. The paper utilized only a single model of tropical cyclones. This is also an important source of uncertainty. The damage and fatality functions are uncertain, as is evident from the uncertainty surrounding the coefficients. Finally, adaptation may change over time. To the extent that countries may adapt differently in the future, future losses could be quite different. Of particular policy relevance for developing countries, the three regions model highlights that their development trajectory will have critical implications for future losses. If developing countries follow the model of the United States, tropical cyclone damage will accelerate rapidly with development. However, if developing countries follow the model of the rest of the OECD, they will see only modest increases in tropical cyclone damage. Perhaps most urgent is that the United States revisit their own strategy for adapting to tropical cyclones and invest in a more rigorous coastal protection program.

Appendix

Additional Historical Damage and Fatality Functions

In this section, we present additional historical damage and fatality functions. Namely, in Table 9.7, we present the all countries functions as well as damage functions partitioned based on OECD (including the United States) versus Non-OECD countries. While the estimated coefficients are qualitatively similar (in terms of coefficient sign) across the regressions, important differences are present, especially with respect to the magnitude of the cyclone elasticity coefficients. However, given Table 9.1, combining US and Non-US OECD countries hides the underlying heterogeneity in coefficient magnitudes. Thus, Table 9.1 is a preferred partitioning. Also see Bakkensen and Mendelsohn (2016) for a much more detailed analysis of damage and fatality functions.

Lastly, Table 9.8 presents additional historical fatality functions, namely the all countries model and partitioning between US, Non-US OECD, and Non-OECD countries. We find the estimated coefficient on US income and pressure to be imprecisely estimated, perhaps partly due to the small sample size. Thus, we prefer the partitioning in Table 9.2 in the main paper.

Table 9.7 Additional historical damage functions

	(1)	(2)	(3)	(4)	(5)	(6)
	Ln damages	Ln damages	Ln damages	Ln damages	Ln damages	Ln damages
	MSLP	Wind	MSLP	MSLP	Wind	Wind
	All	All	OECD	Non- OECD	OECD	Non-OECD
Ln income per capita	0.447***	0.394***	0.249	0.285***	0.279	0.229**
	(0.0737)	(0.0760)	(0.372)	(0.0976)	(0.417)	(0.0991)
Ln population density	0.0688	0.0112	0.187**	0.0980	0.0613	0.0677
	(0.0539)	(0.0627)	(0.0791)	(0.0783)	(0.110)	(0.0776)
Ln MSLP	−29.48***		−59.94***	−23.70***		
	(3.318)		(7.689)	(3.631)		
Ln wind		1.808***			4.148***	1.425***
		(0.219)			(0.553)	(0.235)
Ln distance	−0.396***	−0.363***	−0.569***	−0.351***	−0.466***	−0.322***
	(0.0373)	(0.0377)	(0.116)	(0.0406)	(0.117)	(0.0406)
Constant	216.7***	7.198***	428.0***	177.9***	−1.247	9.737***
	(22.83)	(1.136)	(52.91)	(25.03)	(5.141)	(1.227)
Observations	856	843	203	653	191	652
R-squared	0.223	0.206	0.295	0.171	0.292	0.155

Standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Table 9.8 Additional historical fatality functions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Ln fatalities	Ln fatalities	Ln fatalities	Ln fatalities	Ln fatalities	Ln fatalities	Ln fatalities	Ln fatalities
	MSLP	Wind	MSLP	MSLP	MSLP	Wind	Wind	Wind
	All	All	USA	OECD (Non-USA)	Non-OECD	USA	OECD (Non-USA)	Non-OECD
Ln income per capita	−0.616***	−0.615***	−0.538	−1.701***	−0.758***	−0.609	−1.715***	−0.743***
	(0.0439)	(0.0454)	(0.456)	(0.215)	(0.0564)	(0.466)	(0.212)	(0.0580)
Ln population density	0.165***	0.134***	0.242*	0.273***	0.159***	0.285**	0.273***	0.107**
	(0.0336)	(0.0359)	(0.129)	(0.0469)	(0.0418)	(0.133)	(0.0576)	(0.0427)
Ln MSLP	−9.707***		−23.28***	−3.003	−9.047***			
	(2.050)		(7.146)	(5.719)	(2.235)			
Ln wind		0.562***				1.574***	−0.0774	0.511***
		(0.127)				(0.532)	(0.358)	(0.136)
Ln distance	−0.189***	−0.186***	−0.246**	−0.142***	−0.187***	−0.235**	−0.144***	−0.187***
	(0.0216)	(0.0223)	(0.105)	(0.0465)	(0.0240)	(0.103)	(0.0458)	(0.0248)
Constant	74.34***	5.446***	167.2***	38.91	70.90***	1.007	18.75***	6.746***
	(14.14)	(0.642)	(48.89)	(39.91)	(15.40)	(5.672)	(2.569)	(0.730)
Observations	1020	1008	56	116	848	58	108	842
R-squared	0.229	0.216	0.320	0.466	0.247	0.317	0.485	0.232

Standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

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