Tropical and extratropical cyclone damages under climate change

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Abstract This paper provides the first quantitative synthesis of the rapidly growing literature on future tropical and extratropical cyclone damages under climate change. We estimate a probability distribution for the predicted impact of changes in global surface air temperatures on future storm damages, using an ensemble of 478 estimates of the temperature-damage relationship from nineteen studies. Our analysis produces three main empirical results. First, we find strong but not conclusive support for the hypothesis that climate change will cause damages from tropical cyclones and wind storms to increase, with most models predicting higher future storm damages due to climate change. Second, there is substantial variation in projected changes in losses across regions. Potential changes in damages are greatest in the North Atlantic basin, where the multi-model average predicts that a 2.5 °C increase in global surface air temperature would cause hurricane damages to increase by 63 %. The ensemble predictions for Western North Pacific tropical cyclones and European wind storms (extratropical cyclones) are +28 % and +23 %, respectively. Finally, our analysis shows that existing models of storm damages under climate change generate a wide range of predictions, ranging from moderate decreases to very large increases in losses.

1 Introduction

In recent years, an unusually devastating series of super-storms have made landfall along the world's coastlines. The damages caused by tropical cyclones such as Hurricane Katrina,

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Hurricane Sandy, and Typhoon Haiyan have been far outside the bounds of historical experience (Rosenthal et al. 2012). Some researchers have suggested that part of this upward trend in the destructiveness of large storm systems may be due to anthropogenic climate change (Emanuel 2005; Kunkel et al. 2013). However, attributing observed changes in losses to climate change is difficult, given the concurrent trend of increasing coastal development, the highly stochastic nature of storm damages, and natural multi-decadal variability in storm patterns (Pielke 2007; Emanuel 2011). Thus, efforts to understand the effects of climate change on storm damages have relied primarily on prospective modelling (e.g., Bender et al. 2010; Choi and Fisher 2003; Mendelsohn et al. 2012; Schwierz et al. 2010).

In this paper, we provide the first quantitative synthesis of the growing literature on future tropical and extratropical cyclone damages under climate change. Our analysis is based on 478 distinct projections of future economic losses under a variety of climate change scenarios, taken from nineteen different studies. Thirteen of the studies model future losses from tropical cyclones, and eight model future losses from European wind storms (a type of extratropical cyclone that is also sometimes called a "winter storm"). We limit our focus to studies that predict changes in economic losses (as opposed to other endpoints) due to climate change, and we do not consider mortality impacts. We use this set of data points to estimate a probability distribution for the predicted impact of changes in global surface air temperatures on future storm damages.

A key challenge for our analysis is that the modelling literature on storm damages has not yet coalesced around a shared framework for describing scenarios, assumptions, and results. Thus, we take several steps to standardize projections of future losses under climate change. First, we remove the effects of population and economic growth. We do this by calculating the percent change in losses for each prediction relative to an otherwise-identical "no-climate change" prediction from the same study. Second, to facilitate comparison of estimates based on different climate change scenarios, we convert the scenario associated with each loss projection into an equivalent change in global mean surface air temperatures. This allows us to calculate a normalized temperature-damage treatment effect based on each estimate. Each of these treatment effects expresses the percent change in storm losses that is predicted to occur per degree Celsius of surface air temperature warming, with all other economic and population characteristics held constant, and with no adaptation. The end result is a set of 178 estimates of the temperature-damage relationship for tropical cyclones, and 300 for wind storms. Based on this ensemble of 478 treatment effects, we estimate probability distributions for the predicted impact of surface air temperatures on future storm damages, taking into account the possibility that temperature and losses may have a nonlinear relationship.

By necessity, our methodology for standardizing and combining results involves simplification of the complex relationship between climate change, atmospheric processes, storm formation, and resulting coastal damages. Tropical cyclone development and power dissipation is a nonlinear, dynamic process that depends on whether sea surface temperatures (SST) exceed 26.5 °C, as well as on SST gradients, vertical wind shear, atmospheric stability, and other factors (Dare and McBride 2011; Bender et al. 2010; Knutson et al. 2010). Anthropogenic climate change is likely to cause increases in SST, but is not expected to cause continuously increasing SST gradients, resulting in ambiguous predicted net effects on tropical cyclone power dissipation (IPCC, 2012). Furthermore, for extratropical cyclones, a major factor driving storm development is atmospheric instability (baroclinicity), which could depend on regional variation in the future pole-to-equator temperature gradient (IPCC, 2012; Ulbrich et al. 2009). For these reasons, representing storm damages as a normalized function of a single variable—global atmospheric temperature—is an oversimplification, but one that presents the best feasible approach for synthesizing results from many different studies, given the current state of the literature.

The existing research closest to ours in concept is Bouwer (2013), who uses a graphical approach to summarize the results from nine studies that project losses from tropical cyclones in the year 2040. Other closely related research includes Kousky (2012) and IPCC (2012). However, none of these papers attempt to combine results from different studies in a probabilistic framework. Thus, our paper provides the first quantitative multi-model synthesis of the predicted effect of climate change on tropical and extratropical cyclone damages. The paper's goal is to provide researchers and policymakers with the best estimates currently possible about the range of storm losses likely to be experienced in the future.

The remainder of the paper is organized as follows. Section 2 describes the studies chosen for inclusion in our analysis. Section 3 describes our methodological approach. Section 4 presents the main results and uses them to characterize the distribution of predicted future storm losses. Section 5 discusses the broader context for our findings, and Section 6 concludes.

2 Literature and dataset

The scientific and economic literature on climate change and storm damages is broad and varied. To keep our analysis manageable, we have chosen to restrict the scope in several ways. First, we focus only on studies of tropical cyclones (in any basin) and wind storms (in Europe). Second, we limit our analysis to studies that project either future losses or current-day losses under counter-factual climatic conditions. This results in the exclusion of studies that solely estimate historical losses. Third, we limit our analysis to studies that estimate either monetary damages (e.g., insured losses, total direct losses) or unmonetized "loss potential". We exclude studies of impacts on mortality, as well as scientific literature that focuses on changes in storm patterns but not economic damages. Fourth, we exclude studies that do not provide control predictions against which to calculate the change in loss attributable solely to climate change. Finally, we exclude observations from three studies that include adjustments for future adaptation.

We have conducted an extensive search that initially identified more than 800 studies. Of these, nineteen papers meet all of our inclusion criteria.[1] Table 1 lists these studies and provides summary information about each. The table shows that the studies cover a diverse set of storm types, geographies, and climate change scenarios. The table also shows that most studies have been published in the last 7 years, and that none were published before 2000. To address the possibility of publication bias, we include both peer-reviewed and non-peer-reviewed studies in our sample.[2]

Table 2 presents detailed summary statistics about our dataset of studies. The table shows that most studies report a large number of predictions of future losses: on average, 14 estimates per study for tropical cyclones, and 38 estimates per study for wind storms. While some studies do estimate losses under several different climate change scenarios, the large number of estimates per study is primarily due to predicting losses for multiple geographies using multiple methodologies. We interpret the concept of methodology broadly to include choices

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[1] We do exclude one potentially relevant study, Dorland et al. (1999), which predicts future wind storm damages in the Netherlands. This study is considerably older than any other study in our dataset, and predicts climate change damages that are many standard deviations higher than any other wind storm study (+600 % change in damages by 2065). Furthermore, the authors themselves are critical of their empirical estimates, based on their small sample size: "The database to estimate a storm damage function is rather poor. We only have the four observations on total damage to houses and business" (p.527). On the basis of this concern, we exclude this study from our analysis.

[2] To test for publication bias, we run a version of our analysis that excludes the five non-peer-reviewed studies. The results (shown in the Appendix) are very similar to the results based on the full sample.

Table 1 Studies included in the analysis

Citation[a]	Storm type[b]	Geographic areas	Time period	Climate scenarios
ABI (2005)	TC, WS	U.S., Japan, Europe	2080–2099	A1FI, A2, B1, B2
ABI (2009)	TC	China, U.K.	2040,2075	A1FI, A1B, B2
Bender et al. (2010)*	TC	U.S.	2081–2100	A1B
Choi and Fisher (2003)*	TC	U.S.	NA	+100 % CO_2
Donat et al. (2011)*	WS	Europe	2021–2100	A1B
ECAWG (2009)	TC, WS	Florida, U.K.	2030	A2
Emanuel (2011)*	TC	U.S.	2000–2100	A1B
Hallegatte (2007)*	TC	U.S.	2000–2099	+2 °C SST
Leckebusch et al. (2007)*	WS	U.K, Germany	2060–2100	A2, IS92A
Mendelsohn et al. (2011)	TC	U.S.	2100	A1B
Mendelsohn et al. (2012)*	TC	World	2100	A1B
Narita et al. (2009)*	TC	World	2100	EMF 14
Narita et al. (2010)*	WS	World	2100	EMF 14
Nordhaus (2010)*	TC	U.S.	NA	+100 % CO_2
Pinto et al. (2007)*	WS	Europe	2060–2100	A1B, A2
Pinto et al. (2010)*	WS	Germany	2060–2100	A1B, A2
Ranger and Niehorster (2011)	TC	Florida	2018–2092	A1B
Schmidt et al. (2009)*	TC	U.S.	2015,2050	A1
Schwierz et al. (2010)*	WS	Europe	2071–2100	A2

[a] Peer-reviewed studies are marked with an asterisk. [b] The abbreviation *TC* represents tropical cyclones; *WS* represents wind storms

of economic and scientific parameters, use of particular general circulation models, assumptions about socioeconomic growth, and use of particular historical damage datasets. For example, if a study reports sensitivity analysis results based on three different parameter values for the elasticity of damages with respect to wind speed, we treat these predictions as coming from three different methodologies.

Table 2 also describes the set of variables extracted from each study. The primary outcome variable is the predicted change in storm losses. The main socioeconomic variables we track are population growth and economic growth (we use these variables to identify matched "no-climate change" predictions for each observation). We also extract geography variables and map them to one of four aggregate regions. For wind storms (extratropical cyclones), the only aggregate region included in our analysis is Europe. For tropical cyclones, the three regions we use are: the North Atlantic basin, the Western North Pacific basin, and an "other/multiple basins" category. This last category includes all other areas of the world, including the Indian Ocean, the Eastern North Pacific, and Europe, as well as global-scale estimates and estimates covering multiple basins. Due to sample size limitations, we are unable to disaggregate this category further.

As Table 2 illustrates, the studies in our dataset define climate change scenarios in a variety of ways, including as CO_2 concentrations, IPCC SRES scenarios, and changes in temperature. To make results comparable across studies, we convert each climate change scenario into an equivalent change in global mean surface air temperature. When a prediction represents a range of years, we define the prediction year using the range midpoint. In roughly half of the projections, temperature change was either provided explicitly or was based on current

Table 2 Summary statistics

Variable	Tropical cyclones	Wind storms
Mean and standard deviation of:		
Percent change in losses relative to control scenario	74.8 (98.6)	11.7 (22.8)
Temperature change (°C)	2.8 (1.1)	1.9 (0.7)
Percent of predictions with counterfactual values of:		
Population growth	38.8	0.0
Economic growth	41.0	0.3
Number of tropical cyclone predictions, by region:		
North Atlantic	107	–
Western North Pacific	29	–
Other/Multiple	42	–
Number of wind storm predictions, by region:		
Europe	–	300
Number of predictions, by scenario definition:		
Temperature	111	1
CO_2	18	1
IPCC SRES or other standardized scenario	49	298
Number of studies	13	8
Number of predictions	178	300
Predictions per study	14	38

The table shows characteristics of the predictions from studies included in the analysis. It excludes the control (no-climate change) predictions used as baselines

conditions (i.e., a change of zero degrees). Most of the remaining projections did not report temperature change but did specify a well-defined climate scenario (e.g., A1FI, A1B) and year. In these cases, we used external projections of temperature change in each scenario (IPCC, 2007; Mitchell and Gregory 1992) to estimate an approximate temperature change. Finally, a few projections provided only a change in CO_2 concentration (and possibly a year). For these studies, we calculated the temperature change by assuming that a CO_2 concentration of 1000 ppm would result in a 4.5 ° C change in temperature, and that a CO_2 concentration of 370 ppm would result in a .35 ° C change in temperature, roughly following IPCC (2007). We then interpolated linearly between these points to calculate the temperature change corresponding to the CO_2 concentration specified in the study. We acknowledge that these conversions are approximate.[3]

3 Methodology

Our analysis consists of two parts. First, we standardize each estimate of future storm losses under climate change, to generate a set of normalized treatment effects expressed as a percent change in economic losses per degree Celsius of warming. Second, we characterize the distribution of these temperature-damage relationships.

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[3] To assess whether estimating temperatures introduces any inaccuracies into our analysis, the appendix presents a sensitivity analysis with results for the subsample of observations for which temperature was given in the study.

3.1 Normalized relationship between temperature and losses

The studies in our dataset use a wide variety of approaches to estimate damages. These range from spatially-explicit simulations of future storm tracks to reduced-form calculations based on the historical temperature-storm damage relationship.

In order to combine these heterogeneous studies in a statistical analysis, we use the information contained in each prediction from each study to calculate the implied treatment effect of changes in temperature on losses from storms. This process has two steps.

First, we remove the effects of population and economic growth. We do this separately for each estimate of future losses under climate change by identifying a "no climate change" control estimate from the same study that (i) predicts losses for the same geography and time period, (ii) makes identical assumptions about population and economic growth, and (iii) uses the same modelling methodology. The only way in which the control observation differs is that it must predict losses under current climatic conditions. Then, by normalizing each estimate of losses under climate change relative to its corresponding control observation, we are able to calculate the percent change in losses attributable to climate change, holding all other variables constant.[4] For example, if a particular estimate predicts average U.S. hurricane losses in the year 2099 under the IPCC's A1B scenario with two percent population growth, then we would normalize that observation relative to a control observation from the same study that predicts average U.S. hurricane losses in the year 2099 under two percent population growth but with no climate change (and otherwise using the same methodology). So, if total losses in the A1B scenario were l_1 and losses in the no-climate-change scenario were l_0, then the percent change in losses for this estimate would be:

$$L \equiv \left(\frac{l_1 - l_0}{l_0} \right) \tag{1}$$

Second, we calculate a normalized temperature-damage treatment effect based on each loss estimate. Each of these treatment effects expresses the percentage change in storm losses per degree Celsius of surface air warming, with all other economic and population characteristics held constant, and with no adaptation. For each estimate i from study s of the total percentage change in future losses L_{si}, we calculate the corresponding percent change in loss per degree α_{si} using the following compounding formula:

$$\alpha_{si} \equiv (1 + L_{si})^{\left(\frac{1}{\Delta T_{si}} \right)} - 1 \tag{2}$$

where ΔT_{si} is the change in surface air temperature relative to the baseline year specified in the study. To capture the range of variation in climate change scenarios, methodological assumptions, and geography, we allow the treatment effect α_{si} to take a different value for each unique loss estimate.

Note that although we present all treatment effects as percent changes in loss per degree Celsius of warming, this normalization is intended only to aid in comparing different estimates, and does not imply that the relationship between losses and temperature should have an exponential functional form. In our analysis below in Table 3 and Fig. 3, we explicitly allow for the possibility that normalized loss per degree of warming may depend in a nonlinear, unrestricted way on the magnitude of the change in temperature.

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[4] In cases when an estimate of future damages under climate change has no corresponding control observation, we drop that estimate.

3.2 Distribution of temperature-damage predictions

The calculations in the previous section yield a set of 178 estimates of the temperature-damage treatment effect for tropical cyclones, and 300 estimates of the temperature-damage treatment effect for wind storms. This ensemble of 478 standardized predictions is the basis for the second stage in our analysis.

To characterize the range of variability in these temperature-loss relationships, we model them as a log-normal distribution. Because the effect of climate change on losses could vary across basins and types of storms (Knutson et al. 2010; Ulbrich et al. 2009), we estimate separate distributions for tropical cyclones in the North Atlantic, Western North Pacific, and other/multiple basins, and for wind storms in Europe. Additionally, to allow for the possibility of nonlinearities or threshold effects in the temperature-damage relationship, we also estimate separate distributions for changes in temperature greater than and less than two degrees Celsius. For each type of storm, basin, and temperature range, we calculate the mean, standard deviation, and percentiles of the distribution of logged treatment effects, treating each as one observation, under the assumption that:

$$\ln(1 + \alpha_{si}) \sim N(\mu, \ \sigma) \tag{3}$$

In estimating these distributions, we cluster all treatment effects by study, so that if a study provides multiple treatment effects, each is weighted by the inverse of the total number of treatment effects provided by the study (Nelson and Kennedy 2009). In addition, within each study, we weight each treatment effect by baseline storm losses in the geography represented by that observation, with the weights for each study normalized to sum to unity. The net effect of these clustering and weighting assumptions is to treat all of the treatment effects from a single study as having "one vote", with greater importance given to treatment effects that represent geographic areas with higher baseline losses.

Unlike a traditional meta-analysis, in which the treatment effects would be weighted by their statistical precision, we do not include precision weights. The motivation for this choice is twofold. First, many of the studies in our dataset do not report standard errors or confidence intervals for their projections. Second, the goal of our analysis is to characterize the range of projections across different studies, climate scenarios, models, and geographies.

Additionally, unlike in a traditional meta-analysis, we do not assume that the loss estimates in our meta-data are simply imprecise estimates of the same common treatment effect. Instead, we assume that different studies, climate scenarios, models, and geographies produce genuinely different estimates of the temperature-damage relationship.

4 Results

Figure 1 uses a graphical approach to present the distribution of predicted temperature-loss relationships for tropical cyclones. The top panel in the figure shows the distribution of effects by study, with each point representing a different combination of geography, methodology, and climate change scenario, and the size of the point representing its weight. Results are categorized by basin. The bottom panel shows histograms of the weighted effects, also disaggregated by basin. The x-axis in both panels represents the treatment effect of temperature on losses, expressed as a percentage change in losses per degree C of warming.

Figure 1 shows that even within individual studies, there is wide variation in the predicted effect of temperature on storm losses, depending on geography, methodology assumptions,

Table 3 Distribution of the predicted effect of temperature on storm losses

	Mean and standard deviation of treatment effects		
	All ΔT	ΔT<2 °C	ΔT≥2 °C
Tropical cyclones			
North Atlantic	0.154 (0.182)	0.119 (0.232)	0.168 (0.161)
Observations	107	29	78
Studies	11	4	9
Western North Pacific	0.063 (0.168)	–	0.063 (0.168)
Observations	29	–	29
Studies	4	–	4
Other/Multiple	0.144 (0.167)	–	0.144 (0.167)
Observations	42	–	42
Studies	2	–	2
Wind storms			
Europe	0.078 (0.063)	0.077 (0.068)	0.079 (0.062)
Observations	300	139	161
Studies	8	2	7

The table shows variation in the predicted effect of changes in surface air temperature on storm losses, based on different studies, methodologies, and geographies. Specifically, the table shows the estimated mean and standard deviation parameters (μ and σ) for the lognormal distribution in Eq. (3). Note that the numbers in parenthesis in the table represent standard deviations of the distribution of coefficients (not the standard error of the mean). All estimates are weighted by absolute baseline loss within each study, with each study receiving equal weight. Column (1) shows results based on all observations in our sample; Column (2) shows results only for estimates that predicted losses for changes in temperature less than 2 °C; and Column (3) shows results only for estimates that predicted losses for changes in temperature greater than or equal to 2 °C

and climate change scenario. For example, the North Atlantic projections in Mendelsohn et al. (2011) imply that the predicted increase in loss per 1 °C increase in temperature varies anywhere from −20 to +70 %. This variation is also apparent across studies. However, despite this uncertainty, the histograms in the bottom panel show that the projections appear to be roughly log-normally distributed, with most falling within the general range of −10 to +50 %. The histograms also show that in all three basins, the majority of projections are positive. This suggests that although the predicted magnitude of the effects of climate change on tropical cyclone losses may vary across models, most predict that it will cause damages to increase.

Figure 2 uses a similar approach to illustrate variation in the effects of temperature on wind storm losses in Europe. The shape of the distribution resembles the distribution for tropical cyclones, but the magnitude of predicted losses is much smaller. Almost all projected changes in wind storm losses are between −10 and +35 % per 1 °C of warming, with the majority of predictions being positive between 0 and +20 %.

Table 3 presents complete statistical results for the distribution of normalized effects for both tropical cyclones and wind storms. In the following discussion, we interpret the means presented in the table as approximate percentage changes, following Eq. (3).[5] Column (1)

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[5] This interpretation is approximate, but the error is small. For example, the North Atlantic mean parameter of 0.154 actually represents a percentage change of 16.6 % (because exp(0.154)-1=0.166).
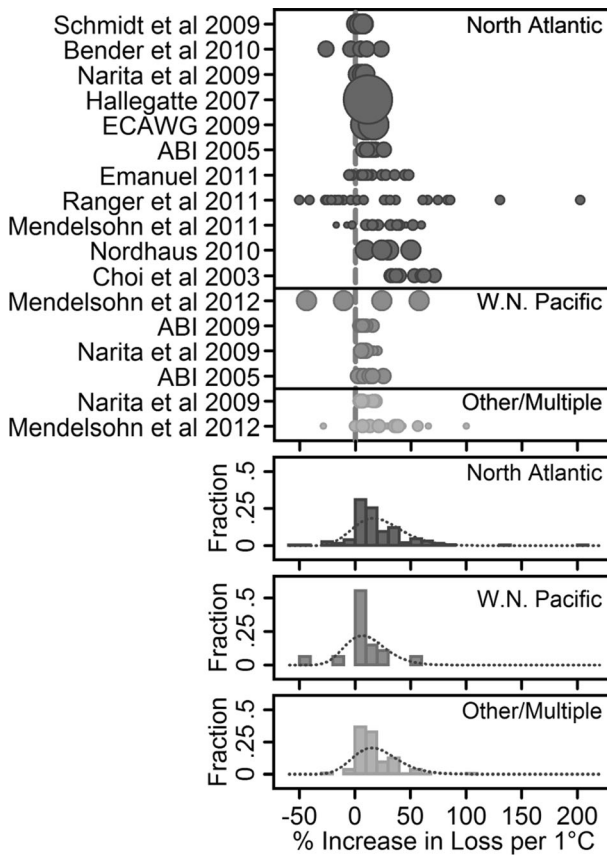
Fig. 1 The effect of temperature on tropical cyclone damages. Each point in the scatterplot in top part of the figure represents a unique estimate of the treatment effect of surface air temperature on losses, based on a particular study, methodology, geography, and temperature change. The marker size represents the weight assigned to the treatment effect, and reflects both the baseline damages in that geography as well as the inverse of the number of estimates provided by the study. Weights are calculated separately for each of the three basins. The histograms in the bottom part of the figure show the distribution of estimates in each basin, along with a dotted line that represents a fitted log-normal distribution

displays results for the full sample, pooling together all climate change scenarios. Across all estimates, the average predicted increase in tropical cyclone losses per degree Celsius of warming is +15 % in the North Atlantic, +6 % in the Western North Pacific, and +14 % in the other/multiple basins category. The average predicted increase in wind storm losses in Europe is +8 % per degree Celsius of warming.

Because the climate system is highly nonlinear (Dare and McBride 2011; Bender et al. 2010; Knutson et al. 2010), there is no a priori reason to expect that the per-degree effect of temperature on losses is the same for small and large changes in temperature. To explore whether there may be nonlinearities, Columns (2) and (3) of Table 3 present the distribution of treatment effects for climate change scenarios that involve changes in temperature less than 2 °C, and greater than or equal to 2 °C, respectively. The columns show that in the North Atlantic tropical cyclone basin, the average predicted change in losses is +12 % per °C for changes in temperature less than 2 °C, and +17 % per °C for changes in temperature greater than
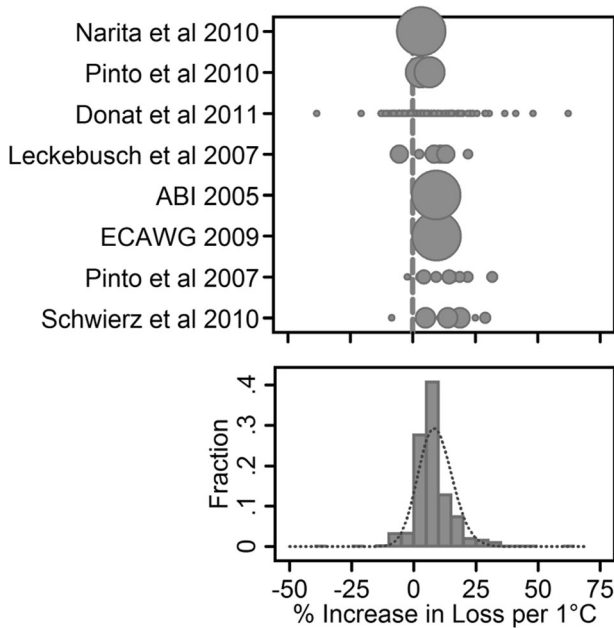
Fig. 2 The effect of temperature on wind storm damages in Europe. Each point in the scatterplot in top part of the figure represents a unique estimate of the treatment effect of surface air temperature on losses, based on a particular study, methodology, geography, and temperature change. The marker size represents the weight assigned to the model, and reflects both the baseline damages in that geography as well as the inverse of the number of estimates provided by the study. The histogram in the bottom part of the figure shows the distribution of estimates, along with dotted line that represents a fitted log-normal distribution

or equal to 2 °C. In contrast, for European wind storms, the average predicted change in losses per degree Celsius is about +8 %, regardless of absolute temperature change.

Figure 3 shows graphical information about the functional form of the relationship between temperature and losses, for the three storm basins for which sufficient data are available. For each basin, the left-hand graph plots the total (not normalized) percentage change in losses as a function of the change in temperature. The right-hand graph presents histograms of the normalized treatment effect, for changes in temperature less than 2 °C and greater than or equal to 2 °C.

In Panel (a) of Fig. 3, the scatterplot shows that predicted tropical cyclone losses in the North Atlantic increase with temperature, with a visually-suggestive upward jump at approximately +2.5 °C. However, the histogram shows that the distributions of normalized treatment effects above and below 2 °C overlap substantially. Given this overlap, combined with the fact that only a few studies have estimated losses for changes in temperatures below 2 °C, we conclude that there is not yet sufficient evidence to reach a definite conclusion about the functional form of the temperature-damage relationship in the North Atlantic. The scatterplots in Panels (b) and (c) of Fig. 3 also show that Western North Pacific tropical cyclone losses and European wind storm losses are increasing in temperature. However, the magnitude of the effects is smaller, and the data are too noisy to support any particular functional form.

Finally, Table 4 uses the estimated distribution of treatment effects to predict the change in losses from a 2.5 °C increase in global surface air temperatures. Such a temperature change is within the range likely under the IPCC's RCP 4.5 and RCP 6.0 scenarios by the end of the 21st century (IPCC, 2013). Table 4 shows that the mean predicted percentage increases in loss are +
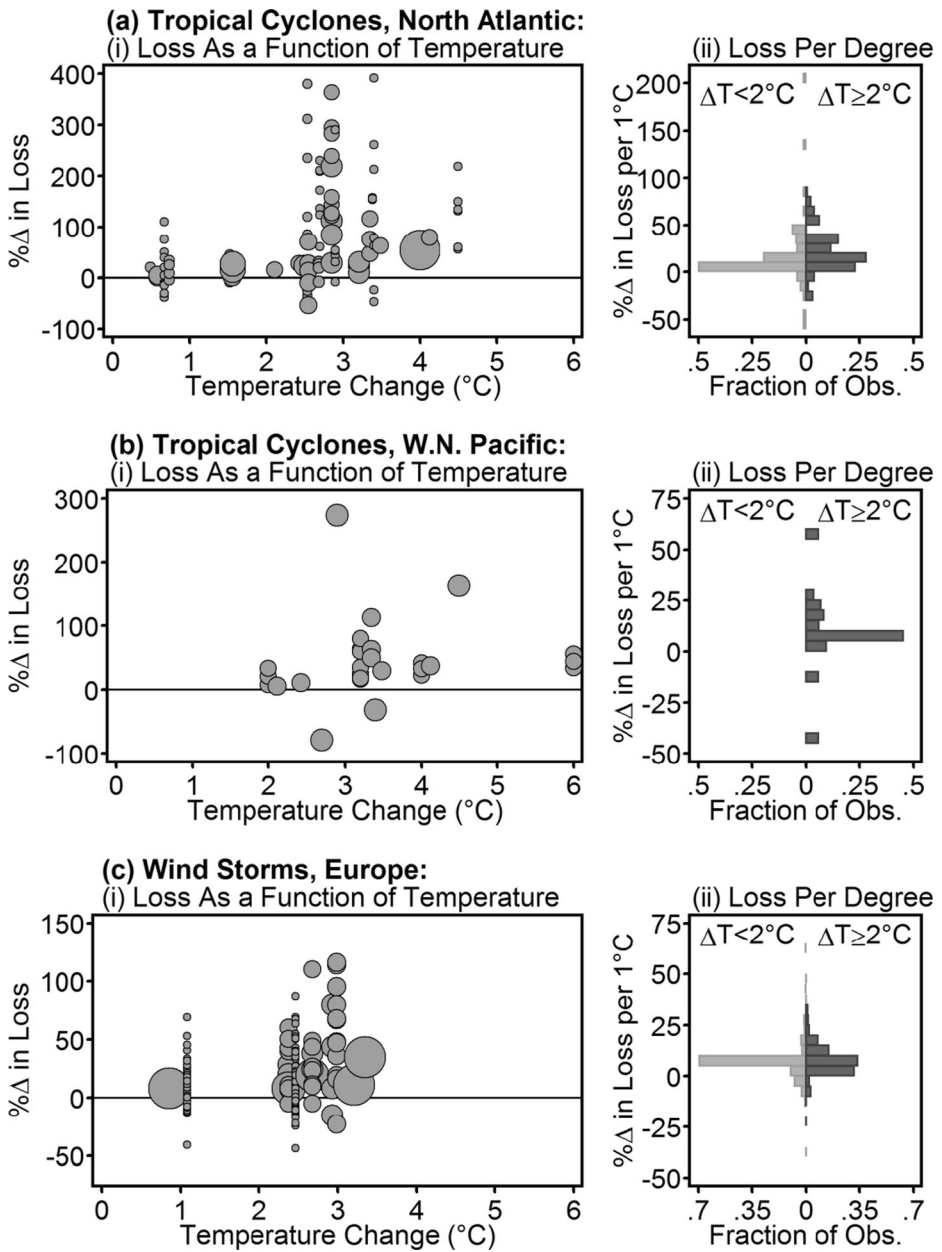
Fig. 3 Predicted change in storm damages as a function of temperature. The figure shows how predicted storm losses vary as a function of the change in global surface air temperature. Panel (**a**) shows losses from tropical cyclones in the North Atlantic basin; Panel (**b**) shows losses from tropical cyclones in the Western North Pacific basin; and Panel (**c**) shows losses from wind storms in Europe. In the left-hand graphs, each circle represents a separate estimate of the predicted percent change in losses, for a particular study, geography, methodology, and temperature change. The size of each circle is inversely proportional to the number of observations provided by the study. The right-hand panels show histograms of the distribution of predicted losses per degree of temperature change. The lighter bars represent estimates based on scenarios with temperature changes less than 2 °C; the dark bars represent scenarios with temperature changes greater than or equal to 2 °C

Table 4 Predicted change in losses from a 2.5°C temperature increase

	Mean % change in losses	Range including 95 % of predicted changes in loss		Percent of predicted changes in loss ≥0 %	
		Parametric model	Empirical CDF	Parametric model	Empirical CDF
Tropical cyclones					
North Atlantic	62.8	[−39.8, 257.8]	[−52.2, 276.7]	80.1	89.9
W.N. Pacific	27.8	[−48.7, 166.5]	[−62.4, 211.6]	64.5	90.9
Wind storms					
Europe	23.2	[−10.6, 65.6]	[−13.0, 76.0]	89.4	93.0

This table presents the distribution of predicted changes in storm losses if surface air temperatures were to increase by 2.5 °C from current levels, while holding population and economic growth constant. The first column shows the percent increase in losses implied by the multi-model mean, including all observations. The second and third columns present ranges that capture 95 % of predictions from the ensemble. The fourth and fifth columns report the percent of predicted changes in loss that are greater than zero. The parametric model results are based on the means and standard deviations estimated in column (1) of Table 3. The empirical CDF results are based on the empirical distribution of the normalized treatment effects, taking into account the weights assigned to each observation. Note that all ranges in this table represent the full distribution of predicted change in losses, not the sampling distribution of the multi-model mean

63 % in the North Atlantic tropical cyclone basin, +28 % in the Western North Pacific tropical cyclone basin, and +23 % for wind storms in Europe. The uncertainty intervals surrounding these averages consist mostly of positive values. For example, in the North Atlantic, 90 % of the estimates in our dataset predict that climate change will cause an increase in hurricane losses, and a parametric uncertainty interval that includes 95 % of predictions ranges from −40 to +258 %. This wide range illustrates the substantial disagreements remaining in the literature about climatic influences on damages from extreme weather. The uncertainty intervals for Western North Pacific tropical cyclone basin and for European wind storms are similarly centered on positive values, although smaller in magnitude.

5 Discussion

Overall, our analysis produces three main empirical results. First, we find that most estimates of the temperature-loss relationship predict that climate change will cause tropical cyclone and wind storm damages to increase. Although a minority of estimates predict that climate change will lead to reduced losses, approximately 90 % of North Atlantic tropical cyclone predictions, 91 % of Western North Pacific tropical cyclone predictions, and 93 % of wind storm predictions suggest that losses will increase.

Second, we find considerable variation in the magnitude of predicted changes in storm losses, both across types of storms and across geographic regions. Potential losses are largest for hurricanes in the North Atlantic basin, where a 95 % uncertainty interval includes an increase in losses of as much as +258 % (under a +2.5 °C change in global surface air temperature). Predicted changes in losses for Western North Pacific tropical cyclones and for European wind storms are smaller, with upper uncertainty interval values of approximately +167 % and +66 %, respectively, under a +2.5 °C increase. To put these predictions in context, recent scientific estimates suggest that although climate change is likely to cause the global frequency of tropical cyclones to decline or possibly to remain unchanged, many studies predict that mean maximum

wind speed and rainfall rates will increase in the North Atlantic and Western North Pacific basins (IPCC, 2012; Knutson et al. 2010). Furthermore, although most scientific studies predict that climate change will cause an overall decrease in the number of extratropical cyclones in the northern hemisphere, the number of extreme (very low pressure) winter cyclones may increase in certain regions, including in the Northeast Atlantic near central Europe (Ulbrich et al. 2009).

Third, our analysis shows that existing models of storm damages under climate change generate a wide range of predictions, with a small minority of models predicting very large increases in future losses. This wide range, both across and within studies, appears to be driven by fundamental methodological disagreements. It is not our intention to take a position on which methodological approaches are best. However, we do view our results as a clear signal that additional research is needed to resolve these methodological conflicts. Following the example set by the scientific literature on general circulation models (e.g., the World Climate Research Programme's Coupled Model Intercomparison Project), a useful first step towards this goal would be for future studies to facilitate comparison of results by adopting a common reporting framework for modeling assumptions, scenarios, and outputs.

We acknowledge that the results presented in this paper have a number of uncertainties and limitations. For example, we have insufficient observations to draw inferences about future damages in tropical cyclone basins outside of the North Atlantic and Western North Pacific. Another important limitation is that we characterize the range of *predictions* of changes in losses. There is no reason to expect that the average bias across studies is zero: it is possible that all existing studies could suffer from some shared methodological issue that leads them to produce damage change predictions that are all systematically too high or low (Jun et al. 2008). For this reason, we urge caution in interpreting the measures of central tendency presented in this paper.

Our study also makes a number of simplifying assumptions about the relationship between climate change and storm damages. For example, we assume that changes in surface air temperature will have an instantaneous effect on storm damages, and that coastal communities will not adapt to future climatic conditions. The purpose of these simplifications is to combine the results from the currently available, albeit limited, dataset of studies in a way that allows for statistical analysis. However, as the literature on climate change and storms continues to grow, we hope these assumptions will be tested.

6 Conclusion

This paper provides the first quantitative synthesis of the rapidly growing literature on future tropical and extratropical cyclone damages under climate change. Using an ensemble of 478 estimates of the temperature-damage relationship from nineteen studies, we estimate a probability distribution for the predicted impact of atmospheric temperatures on future storm damages. We find that most estimates predict that climate change will cause an increase in losses, and that the magnitude of potential increases in losses could be substantial, particularly in the North Atlantic. Overall, we conclude that existing models provide strong but not conclusive support for the hypothesis that climate change will cause tropical cyclone and wind storm damages to increase.

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