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To cite this article: Laura A Bakkensen *et al* 2018 *Environ. Res. Lett.* **13** 074034

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# Environmental Research Letters



## LETTER

# Climate costs of tropical cyclone losses also depend on rain

### OPEN ACCESS

RECEIVED  
7 February 2018

REVISED  
14 June 2018

ACCEPTED FOR PUBLICATION  
2 July 2018

PUBLISHED  
16 July 2018

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**Keywords:** tropical cyclone, rainfall, climate cost, climate change

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## Abstract

It is well established that climate change will lead to changes in tropical cyclone (TC) characteristics and affiliated impacts to human communities. While a growing social science literature estimates losses from TCs, almost all have characterized TCs by wind speed alone. However, TC winds are commonly accompanied by intense rainfall, both of which will likely be impacted by climate change. We assess the impact of rain on current and future TC losses and estimate the bias in loss calculations from omitting rainfall. Using a TC Integrated Assessment Model utilizing 60 000 simulated TCs making landfall in South Korea, we find rain to be a significant loss determinant. For both the wind-only and wind + rain cases, socioeconomic change will cause a decrease in fatalities and a large increase in property losses due to a shrinking population and growing wealth. Regarding climate change, the wind-only case considerably underestimates the climate costs of TC losses compared to the wind + rain case, driven by notable increases in future rainfall in contrast with minor wind intensity changes. While the relative impacts of TC wind versus rain under climate change will no doubt be different across countries, our results highlight the importance of accounting for both wind and rainfall in research and policy, especially in mitigation and adaptation planning.

## 1. Introduction

A large number of countries face threats from tropical cyclones (TCs), causing massive damage to property and humans alike. These impacts will likely grow over time as climate change is expected to strengthen the intensity of the most powerful TCs in parts of the world (Knutson *et al* 2010, Grossmann and Morgan 2011, Walsh *et al* 2016). Previous studies also suggest that the expected (percent) increase in TC-induced rainfall within 100 km of TC centers due to climate change will be larger than the (percent) increase in wind (Knutson *et al* 2010, Grossmann and Morgan 2011, Walsh *et al* 2016). In addition, recent studies on historical tropical cyclone (TC) damages have argued that TC rainfall is as important as wind in determining damages (Park *et al* 2015, 2016). While a growing literature studies the impacts of these events on human society as well as future losses under a changing climate (Pielke 2007, Mendelsohn *et al* 2012,

Peduzzi *et al* 2012, Ranson *et al* 2014, Bakkensen and Mendelsohn 2016), rainfall has been omitted from much of the previous literature analyzing TC damages and affiliated climate costs. The impact of omitting rainfall in analyses therefore remains important but unclear, especially for mountainous or flood prone countries across the globe.

In this study, using an original dataset containing the complete history of weather-station level records and official government data on local-level damages, fatalities, and people displaced from TCs striking South Korea, we assess the differential impacts of wind versus rain on TC losses. We perform a TC integrated assessment with two characterizations: wind + rain and wind-only. In addition to socioeconomic factors, the wind + rain model includes both wind and rain as explanatory variables of TC intensity while the wind-only includes only wind. We utilize the models to calculate the costs of climate and socioeconomic change.

## 2. Data and methods

### 2.1. Method

In order to estimate the impact of both socioeconomic and climate change on TC losses, we employ a TC integrated assessment model (TCIAM). The steps of the TCIAM build upon previous literature (Mendelsohn *et al* 2012) but with two major improvements. First, we include rainfall in our model to explicitly test the impact on our results. Second, we use more spatially refined data from South Korea.

The first step of our TCIAM is to estimate historical impact functions, including people displaced, fatalities, and damages. We explain these relationships through TC and socio-economic characteristics. Our unit of analysis is a TC-province, wherein we associate every TC making landfall in South Korea with observed conditions in each of the nine provinces. With the historical data collated, we estimate two base models, one wind + rain and one wind-only, in order to generate historical impact functions. We follow some of the previous literature (Bakkensen and Mendelsohn 2016) by taking the natural log of both the dependent and independent variables.

In the model, the natural log of the loss ( $L_{it}$ ), operationalized separately as damages, fatalities, or displaced persons from TC  $t$  in province  $i$  is a function of population density ( $P_{it}$ ), GDP per capita ( $I_{it}$ ), maximum wind speed in the province ( $W_{it}$ ), and cumulative TC-lifetime rainfall in the province ( $R_{it}$ ). We explicitly account for the zero loss provinces hit by TCs by adding one to each loss such that the observations with no losses are not dropped from the estimation. This allows us to use our full sample and also estimate the model including very low loss observations. The model is shown in equation (1) below.

$$\ln(L + 1)_{it} = \beta_0 + \beta_1 \ln P_{it} + \beta_2 \ln I_{it} + \beta_3 \ln W_{it} + \beta_4 \ln R_{it} + \mu_{it}. \quad (1)$$

Lastly, we exactly replicate equation (1) but remove the rainfall variable. This allows us to explicitly test the impact of omitting rain on climate change impact calculations. We select this parsimonious functional form in line with previous literature (Bakkensen and Mendelsohn 2016) as losses are co-determined by human and TC factors, and also, as detailed below, to utilize well established projections of future conditions. We note that the included variables also represent factors omitted from the analysis but correlated with the included variables such as institutions or adaptation (Kahn 2005, Fankhauser and McDermott 2014).

The second step of the TCIAM is future projections. For climate projections, we utilize 60 000 TC tracks that make landfall in South Korea simulated by Kerry Emanuel and Wind Risk Tech LLC (Emanuel 2013, WindRiskTech 2018, Lu *et al* 2018) within six global climate models (GCMs) (Emanuel 2013): Community Climate System Model (CCSM4), Geophysical Fluid

Dynamics Laboratory Climate Model (CM3), Hadley Global Environment Model (HadGEM2-ES), Model for Interdisciplinary Research On Climate (MIROC5), Max Planck Institute Climate Model (MPI-ESM-MR), and Meteorological Research Institute Climate Model (MRI-CGCM3). Half of the tracks are simulated under current (1980–2000) climate conditions and half are simulated under future (2080–2100) under a representative concentration pathway 8.5 (RCP8.5) scenario. For socioeconomic projections, we use a benchmark storyline assuming a 2% per year rate of economic growth and medium-scale population projections from the United Nations. Coupled with the historical regression results, we are able to estimate the simulated damages, fatalities, and people displaced from each track. We use this to estimate the impact of socioeconomic change on TC losses, assuming climate holds constant at its current level. We then estimate the impact of climate change on TC losses, assuming future socioeconomic conditions.

Projections into the future are always contingent on a host of assumptions. Hence, in order to check the robustness of our results, we make use of sensitivity analysis whenever possible. While we cannot easily alter the overall RCP8.5 climate change assumption (which would necessitate the generation of hundreds of thousands of additional simulated TC tracks), we attempt to ascertain the sensitivity of the results at all other stages. For our historical impact functions, we employ four additional regression models. In addition, in work not shown, we test 17 different future socioeconomic projections including storylines from the sustained socioeconomic pathways (SSP) (O'Neill *et al* 2014), the Fourth Assessment Report (AR4) pathways (Nakicenovic *et al* 2000), and assumptions using a 1% (low), 2% (medium) and 3% (high) growth rate in population and GDP per capita. Our sensitivity analysis shows that our conclusion does not vary considerably with each sensitivity analysis employed (not shown).

### 2.2. Data

We build our historical loss dataset at the TC-providence level from 1979–2010. We collect socioeconomic data on GDP per capita and population density at the province level across South Korea from the Organization for Economic Cooperation and Development (OECD). This raw province-level data only goes back to 1990. Therefore, we extrapolate our socio-economic variables back to the year 1979. For this extrapolation, we use two different methods. In the first method, we calculate the average 10 year growth rate (1990–1999) of each individual province and use this growth rate to extrapolate the data back to 1979 for the respective provinces. In the second method, we take the proportion of the provincial characteristics with respect to the national figures for the 10 year period of 1990–1999. Assuming the relative position of each province to the nation stays constant over time, we use this proportion to extrapolate the individual province's

share of the national figures. The data for population and land area are available at the national level from the OECD database, through which we calculate the population density at the national level going back to the year 1979. We obtain national GDP per capita growth rates from the World Bank. To extrapolate back the data for 1979, we use the 5 year average growth rate (1981–1985) to estimate the growth rate for the year 1980. We employ these two methods of extrapolation mainly to test the robustness of our results. We find no significant difference in the results across the two extrapolation methods.

Observed loss data were collected from the South Korean National Disaster Information Center (NDIC). The center records the amount of direct property losses, number of individuals displaced from their homes, and the count of fatalities caused by various natural extreme phenomena for each province and megacity, along with the timing of the events. Data for smaller administrative district is also provided (Park *et al* 2015, 2016), but are too numerous for the current study, so we aggregate it to the province level. The nine provinces (with affiliated major cities in parentheses) are: Gyeonggi-do (Seoul), Chungcheongbuk-do, Chungcheongnam-do (Daejeon), Jeonlabuk-do, Jeonlanam-do (Gwangju), Jeju-do, Gyeongsangnam-do (Busan and Ulsan), Gyeongsangbuk-do (Daegu), and Gangwon-do. The damages data are inflation adjusted to a 2005 base year and expressed in Korean won but converted to US dollars for the paper.

Some of the damage entries do not include any information on the triggering event, so we match a damage entry to a TC if the damage period from the NDIC overlaps with any days of either one of the TC influencing periods from the two other datasets. Following previous literature (Park *et al* 2015, 2016), we define the TC influencing period by the union of the following three factors: (1) the event period described in the NDIC data, (2) the event period in the *Typhoon White Book* issued by the National Typhoon Center of Korea, and (3) the days in which best track TC records showed TCs within 3 degrees of the South Korean peninsula. The *Typhoon White Book* defines TC events as those whose centers entered in 32°N–40°N and 120°E–138°E. We find the TC latitude and longitude information from the international best track archive for climate stewardship (IBTrACS) (Knapp *et al* 2010). TCs used here include tropical depressions, tropical storms, and typhoons since tropical depressions are as important as stronger ones such as tropical storms and typhoons in determining damage over Korea (Park *et al* 2016). Since the IBTrACS dataset provides TC location data with a 6 hour interval, which is too coarse to obtain an exact influencing period, the data is linearly interpolated to a 1-hourly interval following Park *et al* (2011, 2014).

We use weather-station level data to construct historical records of the geographic extent and intensity of TCs across South Korea. Daily accumulated rainfall

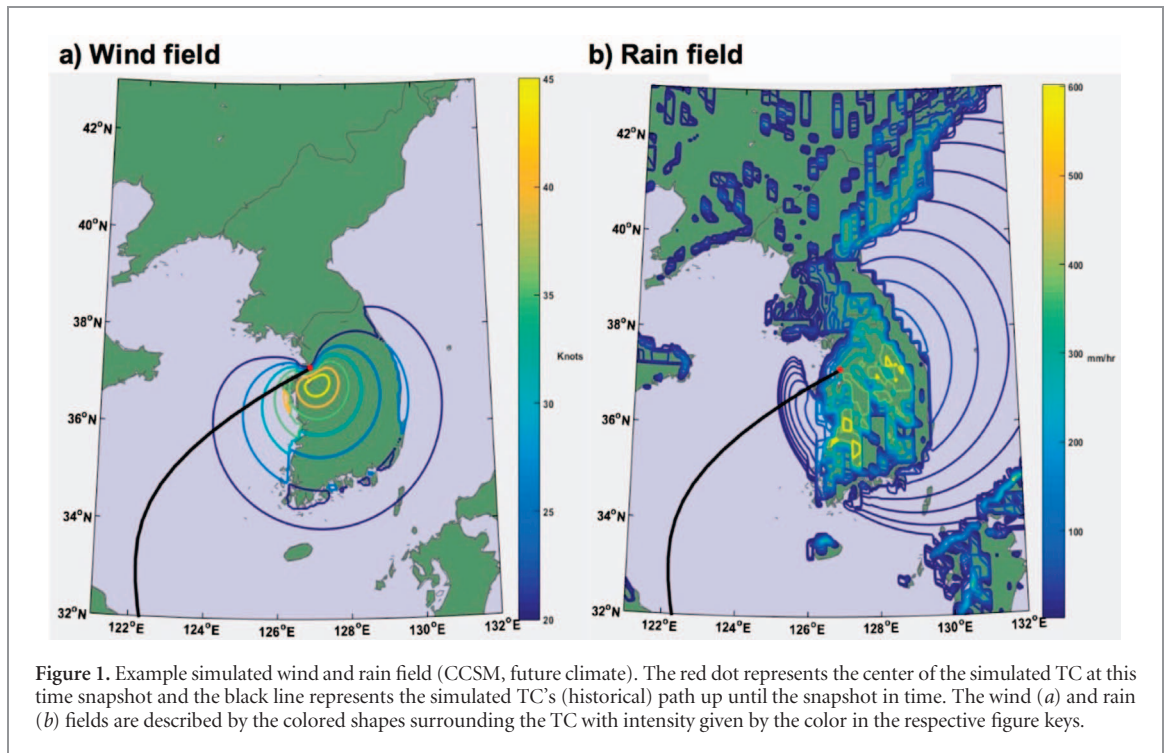
and daily maximum wind speed were utilized to estimate TC-induced rainfall and wind intensity for each region. The weather-station data are gathered from 60 different locations which are almost evenly distributed over the entire country. Within each province, we select the highest observed wind and rain totals for a given province-TC. We also estimate the wind fields and rain fields of the simulated TCs. Just as in the historical data, we utilize 60 000 tracks that make landfall in South Korea and then select the maximum wind and rain totals within a province across a grid of 525 points. Specifically, we divide the space between latitudes 33 and 39 in intervals of 0.25 degrees and the space between longitudes 125 and 130 in intervals of 0.25 degrees for a total of 525 grid points. It is this detailed simulation data that allows us to capitalize on the spatially refined historical data in our analysis.

### 3. Results

#### 3.1. The impact of climate change on TC wind and rain

Our simulation track data allow for the generation of track-specific wind and rain fields over any spatial geography (here, South Korea). We display these wind and rain fields for a randomly chosen track in figure 1. This figure highlights our concern: given the simulated wind field in figure 1(a), the TC landfall exhibits very weak winds of around 45 knots (approximately 52 mph) and only impacts a small geographic area. Based on wind alone, this TC would likely lead to few losses as the TC is no longer hurricane strength. However, the rain field for the same TC track in figure 1(b) paints a very different picture. Here, the rain is highly intense, falling at an instantaneous rate of 600 mm hr<sup>-1</sup> (approximately 2 ft hr<sup>-1</sup>), and also impacts a much larger geographic area, thereby likely triggering intense damages. Thus, while we find wind and rain are correlated ( $r = 0.41$ ), relying on wind to estimate losses may lead to bias in the resulting estimates. This anecdotal evidence suggests the important impact of rainfall in determining losses from TCs.

From these simulations, we compare maximum wind and rain characteristics at the province level for each track and calculate the percent change from current to future climate conditions. Table 1 presents the results. We first note that climate change greatly impacts TC rainfall, increasing it by an average of almost 45% across the six models. In contrast, the wind signal is quite weak, with an average intensity increase of only 1.15%. This is again suggestive evidence that characterizing TC losses by wind alone may lead to a misestimation of losses and especially calculations of the cost of climate change. As discussed in the introduction, the larger future change in rain relative to wind, shown here in South Korea, is consistent with the global trend (Knutson *et al* 2010, Grossmann and Morgan 2011, Walsh *et al* 2016). We also note that,



**Table 1.** Climate change impacts on TC characteristics. The climate change impact statistics represent the average change across the nine provinces. It was calculated as the (equally-weighted) average of the change in respective statistics across all province-TC landfalls in current (1980–2000) and future (2080–2100) climate assuming an IPCC RCP 8.5 climate change scenario.

Model	Wind	Rain
CCSM4	1.49%	24.21%
CM3	1.12%	67.86%
HADGEM2-ES	−1.42%	48.91%
MIROC5	9.40%	61.12%
MPI-CGCM3	−0.84%	39.87%
MRI-ESM-MR	−2.84%	25.14%
Average	1.15%	44.52%

while there is broad agreement in the relative qualitative magnitudes of wind versus rain impacts, there remains cross-model disagreement in the point estimates, with the MIROC5 model estimating the strongest future impacts at 61% and 9.4% for rain and wind changes, respectively, while CCSM4 finds only a 24% and 1.5% increase, respectively. We note that while all models predict increases in rain intensity, only half the models predict increases in wind intensity for South Korea. Thus, future work may bring insight into ameliorating the cross-model differences that we take as given.

### 3.2. The impact of socioeconomic change on TC losses

Table 2 presents our results for the impact of future socioeconomic change on TC losses, both for wind + rain and wind-only models. First, in our wind + rain model, we estimate large reductions in the counts of people displaced and fatalities by TCs of −62% and −35%, respectively, due to the economic growth and

population decline that are both protective for people displaced and fatalities. As Korea currently suffers an average of 137 fatalities per year and 31 thousand people displaced annually, these totals will fall to approximately 89 fatalities and 11.8 thousand displaced. Turning to direct damages to property, we find a large increase in property losses of 193% driven by more property in harm's way due to economic growth as suggested by previous studies (Pielke *et al* 2008, Zhang *et al* 2009, Fengjin and Ziniu 2010). This will lead to large increases in property losses averaging from approximately \$525 million (2005 USD) to more than \$1.5 billion per year. However, South Korea will be a much richer country in the future, so while the aggregate total of damages will increase, it will represent a decreasing share of gross domestic product. Thus, it is important to highlight that localities can expect increases in damages driven by changes in human communities, regardless of climate change, while economic growth protects lives, as previous literature has shown (Kahn 2005, Toya and Skidmore 2007, Kellenberg and Mobarak 2008).

Finally, in row 2 of table 2, we re-run our results using only wind to characterize TC losses but identical analysis in all other respects. In the regression results not shown, we find the omission of rain leads to an upward bias of the socioeconomic change results, due to the positive correlation between rain and the socioeconomic variables. Note that the inclusion of rainfall in the regression model does not lead to overfitting or multicollinearity problems. Thus, while rain and wind are held constant in the socioeconomic change analysis, losses will scale more quickly with the wind-only model due to the larger estimated regression coefficient.

**Table 2.** Socioeconomic change impacts on TC losses. The results in this table represent the estimated change in TC losses due to socioeconomic change only, holding climate constant at its current condition. The projection assumes constant 2% annual GDP growth and the medium outlook population projections from the United Nations.

	Displaced	Fatalities	Damages
Wind + rain	−62%	−35%	193%
Wind only	−51%	−29%	333%

cients on the socioeconomic variables. The wind-only model slightly underestimates (less negative) both the decreases in people displaced and fatalities, given the similar relationships in the historical loss functions. However, the damages from socioeconomic change are estimated to be approximately 330%, an overestimate of more than 50% due to the much higher socioeconomic coefficients for damages.

### 3.3. The impact of climate change on TC losses

Finally, we turn to the impact of climate change on TC losses in South Korea. Table 3 presents our results for each of the three losses—persons displaced, fatalities, and property damages—across each of the six climate models. Since the internal variability of each model possibly reduces or amplifies the climate change effect on TC activity, our discussion is made mainly based on averages of all model results (i.e. multi-model ensemble). We find that, due especially to the intensification of rainfall, people displaced and fatalities are expected to increase by an average of 31% and 8%, respectively. The greatest increases are seen, however, in property damages, which will increase an estimated 105% on average. On top of the future baseline with socioeconomic changes incorporated, this will increase losses from \$1.5 billion to \$3.1 billion in losses per year, a six-fold increase from the current status quo. While the point estimates vary, all climate models consistently predict non-decreasing losses due to climate change. Lastly, we compare the impact of wind-only and wind + rain models, found in columns 4 through 6 in table 3. We find that overall, the wind-only model severely underestimates the climate change impacts due to the very small change in future wind compared to current wind intensity. Without accounting for rain, damages would appear unchanged by climate change for this country context, a striking contrast to the wind + rain model. Despite the large variance in magnitude between the climate models, all of the models suggest consistent conclusion, i.e. the importance of rainfall in loss estimates.

## 4. Discussion

This paper makes three contributions to the literature. First, we assess the differential impact of precipitation on TC losses after controlling for TC intensity. We run our TCIAM using wind and rain and then with wind only to be able to directly compare the

resulting projections. Second, we utilize a proven climate change integrated assessment methodology (Mendelsohn *et al* 2012), and apply it to the context of South Korea. Instead of country level data that is used by some of the previous literature, we use detailed local-level data from new data sources including weather-station level atmospheric data, local-level official government loss reports, and province-level socioeconomic data. Thus, we are able to more accurately estimate heterogeneity in impacts, including across sub-country regions, and also model fatalities and people displaced, in addition to direct property damages. Third, we employ additional sensitivity analysis in attempt to better estimate a bound on the uncertainty inherent in integrated assessment models. Notably, we include six GCMs to incorporate climate model uncertainty, 60 000 simulated TC tracks with affiliated wind and rain fields to better sketch out the underlying distribution of TC characteristics. In addition, in results not shown, we find qualitatively consistent results upon re-estimating our model using 16 additional future projections for socioeconomic change, including across the SSPs (O'Neill *et al* 2014), IPCC SRES projections (Nakicenovic *et al* 2000), and assuming combinations of constant annual population and GDP growth rates of 1, 2, and 3%. Here we find the omitted rainfall variable to be a significant determinant of losses. While the relative impacts of TC wind versus rain under climate change is likely to be heterogeneous across countries, our results motivate the importance of accounting for both in research and policy decisions.

We note the important limitations of this analysis. First, according to our results, future losses over South Korea likely increases, yet we hold the frequency of TCs constant due to the fixed number of simulated TC tracks utilized. Many studies have shown that future TC frequency will decrease (Knutson *et al* 2010, Grossmann and Morgan 2011, Walsh *et al* 2016) so it is reasonable to expect that TCs affecting South Korea will decrease. If this is the case, our loss projection would be overestimated. However, some of the studies argued that TC frequency will increase over the western North Pacific (Emanuel 2013, Park *et al* 2017). Furthermore, it is much harder to precisely project the future frequency of TC affecting a small country like South Korea due to large uncertainty. Thus, we leave this for future work.

Second, we do not include a very relevant third category of impacts from TCs, namely storm surge, nor do we account for sea level rise, both of which are important in determining losses (Seo and Bakkensen 2016, 2017). In addition, there may be other factors omitted from the analysis that are correlated with rainfall, thereby potentially biasing this analysis. It is also noted that while our 60 000 tracks would be equivalent to almost 900 years of observational data for each climate model/climate scenario pair, it still may not fully replicate the entire underlying TC distribution. As the rarest of TC events (i.e. those that are particularly strong or unusual) are typically the most damaging,

**Table 3.** Climate change impacts on TC losses. The results in this table represent the estimated change in TC losses due to climate change only, including changes in TC characteristics, holding socioeconomic conditions constant at their future levels.

Model	Displaced wind + rain	Fatalities wind + rain	Damages wind + rain	Displaced wind-only	Fatalities wind-only	Damages wind-only
CCSM4	14%	5%	33%	3%	1%	5%
CM3	44%	11%	182%	6%	1%	−2%
HADGEM2-ES	19%	6%	31%	−7%	−1%	−11%
MIROC5	76%	17%	286%	44%	10%	23%
MPI-CGCM3	23%	6%	90%	0%	−1%	−4%
MRI-ESM-MR	7%	2%	10%	−6%	−3%	−10%
Average	31%	8%	105%	6%	1%	0%

we note this limitation to our approach. Moreover, we do not explore alternatives to the WindRiskTech LLC TC model. While we account for adaptation in our historical loss functions, we assume that these relationships hold for the coming century. With that said, our results highlight the importance of accounting for rainfall when estimating current relationships between TCs and losses as well as calculating the future costs of socioeconomic and climate change.

Lastly, while the relative impacts of TC wind versus rain under climate change are likely to be heterogeneous across countries, and therefore these particular quantitative results will likely not hold true for every nation, it is nonetheless important to account for wind and rain in research and policy decisions. More specifically, in a mountainous country like South Korea, losses could be more sensitive to rainfall; the regression coefficient of rainfall over a mountainous area may be higher than that over a flat region. Thus, future work could explore this. Our main conclusion regarding the importance of rainfall, however, may still be valid for many other countries as future rainfall is generally projected to increase at a faster rate relative to wind speed increase under climate change (Knutson *et al* 2010, Grossmann and Morgan 2011, Walsh *et al* 2016). However, adaptation strategies must still be tailored to the unique conditions of each country to ensure the efficient management of natural disaster risks. More broadly, these results contribute to refining estimates for the social costs of carbon and motivate important policy discussion surrounding optimal adaptation and mitigation strategies in a changing world.

## Acknowledgments

This work was funded by the Korea Meteorological Administration Research and Program under Grant [KMI2018-03413]. The authors would like to thank Kerry Emanuel and Wind Risk Tech LLC for generating the simulated tropical cyclone data used in this paper.

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