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Economic losses from US hurricanes consistent with an influence from climate change

Francisco Estrada[1,2]*, W. J. Wouter Botzen[2] and Richard S. J. Tol[2,3,4,5,6]

Warming of the climate system and its impacts on biophysical and human systems have been widely documented. The frequency and intensity of extreme weather events have also changed, but the observed increases in natural disaster losses are often thought to result solely from societal change, such as increases in exposure and vulnerability. Here we analyse the economic losses from tropical cyclones in the United States, using a regression-based approach instead of a standard normalization procedure to changes in exposure and vulnerability, to minimize the chance of introducing a spurious trend. Unlike previous studies, we use statistical models to estimate the contributions of socioeconomic factors to the observed trend in losses and we account for non-normal and nonlinear characteristics of loss data. We identify an upward trend in economic losses between 1900 and 2005 that cannot be explained by commonly used socioeconomic variables. Based on records of geophysical data, we identify an upward trend in both the number and intensity of hurricanes in the North Atlantic basin as well as in the number of loss-generating tropical cyclone records in the United States that is consistent with the smoothed global average rise in surface air temperature. We estimate that, in 2005, US$2 to US$14 billion of the recorded annual losses could be attributable to climate change, 2 to 12% of that year's normalized losses. We suggest that damages from tropical cyclones cannot be dismissed when evaluating the current and future costs of climate change and the expected benefits of mitigation and adaptation strategies.

Data collected by Munich Re (ref. 1) show that worldwide economic losses from natural disasters have increased over the past decades. Determining the causes of this trend is a complex task because the development of natural disaster damages depends on the intricate interplay of chance and changes in vulnerability, the number and value of assets exposed to disasters, as well as in the hazard[2,3]. The latter can be due to either natural climate variability or climate change. Existing studies typically normalize original records of natural disaster damage by indicators that are assumed to reflect changes in exposure and vulnerability, and use ordinary least squares (OLS) regression to test whether a remaining (linear) time trend is present in normalized natural disaster damages[3]. The general finding from these studies is that there is no significant remaining trend in normalized natural disaster losses, from which the conclusion has been drawn that climate change has not increased natural disaster risks[3–10], although there are some exceptions[11–15]. However, this conclusion may be the result of the underlying methods. The IPCC SREX report identified uncertainties in methods as an important barrier for understanding trends in records of losses from extreme weather[16].

Normalization of loss data for socioeconomic change

The standard normalization procedure is useful for expressing the magnitude of losses relative to local population and wealth, as a metric of relative severity of disaster impacts. However, when used to separate the contribution of socioeconomic and climate variables to loss trends it has its limitations. Normalization is typically based on an assumption of proportionality[3,17]. Let D_t denote damage at time t due to an extreme weather event x_t given exposure y_t. Normalized damages ND_t are then:

$$ND_t = \frac{D_t}{y_t} = \frac{f(y_t, x_t)}{y_t} \tag{1}$$

where $f(.)$ is the impact function.

Suppose that $f(\cdot)$ is multiplicatively separable and equal to $f(y_t, x_t) = y_t^{\delta_t} h(x_t)$. Assume that y_t grows at a constant rate r. Then $(f(y_t)/y_t) = e^{(\delta_t - 1)rt}(f(y_0)/y_0)$, where $\delta_t - 1$ can be interpreted as the difference in growth rates between actual exposure and assumed exposure (Supplementary Information 1.1). Unless $\delta_t = 1$, trends or changes in the level will inadvertently be introduced to the normalized damage in equation (1).

Similarly, if $f(y_t, z_t, x_t) = y_t z_t^{\varepsilon} h(x_t)$, then normalization with y_t will be incomplete, and the normalized damages will trend by εs, where s is the growth rate of the omitted exposure variable z_t.

Spurious trends can also be introduced in the normalized damages by an incorrect identification of the relevant variables driving the increases in exposure and vulnerability. These trends can occur because some of these drivers are unobserved, for example, when building standards improve over time and vulnerability is consequently reduced (Supplementary Information 1.2.3 and 1.2.4 and Supplementary Table 3). Inappropriate spatial resolution may also invoke a trend (Supplementary Information 1.2.1, 1.2.2 and 1.2.4 and Supplementary Figs 1–6, and Supplementary Tables 1 and 2).

A spurious trend may cancel out any signal related to climate change, or be mistaken for such a signal. The standard normalization procedure does not test for the adequacy of the normalization

[1]Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Ciudad Universitaria, Circuito Exterior, 04510 Mexico DF, Mexico. [2]Institute for Environmental Studies, VU University, 1081 HV Amsterdam, The Netherlands. [3]Department of Economics, University of Sussex, Falmer BN1 9SL, UK. [4]Department of Spatial Economics, VU University, 1081 HV Amsterdam, The Netherlands. [5]Tinbergen Institute, 1082 MS Amsterdam, The Netherlands. [6]CESifo, 81679 Munich, Germany. *e-mail: feporrua@atmosfera.unam.mx

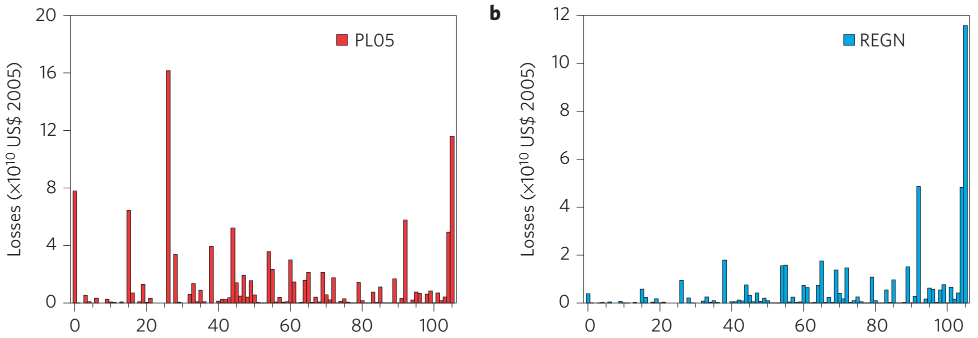

Figure 1 | Normalized US tropical cyclone losses per year for the period 1900 to 2005. a, Normalized losses using the standard procedure (PL05), which assumes a proportional relationship between losses and population and wealth. **b**, Normalized losses using the regression-based (REGN) procedure, which allows an estimation of the elasticities of damages to wealth and population.

variables, nor does it provide an objective method to evaluate if the losses have been correctly adjusted. It is simply assumed that this is the case.

If a regression-based approach is used instead of proportionally normalizing the loss record, the problem of spurious trends can be minimized. Note that ND_t in equation (1) is equal to the exponential of $\alpha + u_t$ from:

$$\ln(D_t) = \alpha + \delta \ln(y_t) + u_t \quad (2)$$

if the restriction $\delta = 1$ is imposed (Supplementary Information 1.1). The objective of regression (2) is to empirically test the validity of this restriction, which implicitly underlies the normalization procedure in equation (1), and to estimate a more appropriate value for δ. Owing to regression properties $\alpha + u_t$ will be orthogonal to y_t, and will contain the variability and nonstationary signals that are not explained by the scaling variable y_t, such as climate change. Such signals can be uncovered using trend analysis and Box–Cox transformations[18] (Supplementary Information 2). The results presented below are robust to single-step normalization and trend estimation (Supplementary Information 3.3.4).

A trend in normalized US tropical cyclone losses

Using this approach, we investigate the presence of a trend in hurricane and storm damages in the US, which make up a significant proportion of global insured property damages[1]. We use the data set analysed by Pielke[5], based on NOAA data[19–21], which is one of the most commonly used, publicly available data sets on weather-related disasters (Supplementary Information 3.1). Most of the previous analyses of this data apply the standard normalization procedure and find that the trend in these losses can be explained by increases in population and wealth on the US coast[4,5,22,23]. For comparison, the same normalization variables used in past studies are used here, namely coastal population $P_{i,t}$ (where i denotes county) and national real wealth per capita $RWPC_t$, defined as the current-cost net stock of fixed assets plus the annual production of consumer durable goods, adjusted by inflation and population (all at the national level).

Applying the regression-based normalization method reveals that the standard normalization approach over-adjusts losses. In particular, the coefficient of $P_{i,t}$ is not significantly different from zero, and the joint restriction that both coefficients are equal to one is strongly rejected (Table 1 and Supplementary Information 3.2 and Supplementary Fig. 8). Figure 1 shows the regression-based normalized losses (REGN) and the adjusted losses obtained from the standard normalization procedure (PL05) in Pielke[5]. A significant linear trend is found in REGN, indicating that normalized losses from hurricane and storm damages have been increasing at a rate of US$136 (±US$51 two block-bootstrap standard errors[24]) million dollars a year during the past century, and that the losses in 2005 are about US$14 (±US$5.3) billion dollars larger than if there was no trend (Table 2).

Table 1 | Coefficient values and t-statistics of the normalization regression $\ln(D_{it}) = \mu + \gamma \ln(P_{it}) + \delta \ln(RWPC_{it}) + \varepsilon_t$.

μ	γ	δ
19.300***	−0.175	−0.927*
(42.112)	(−0.755)	(−1.887)

*** and * denote statistical significance at the 1% and 10% levels, respectively. t-statistics are given in parentheses. Heteroscedasticity and autocorrelation consistent (HAC) standard errors and covariance were estimated using the Bartlett kernel and Newey–West bandwidth selection.

In contrast, a trend of US$1.5 million dollars a year can be found for PL05, but this is not statistically significant (Table 2). However, PL05 apply the normal, linear regression model to highly skewed (non-normal) loss data[15]. Strong deviations from normality can render hypothesis testing on the estimated coefficients invalid. When a Box–Cox transformation is applied to the normalized data, there is a statistically significant positive (but nonlinear) trend in the data. This is also true for the natural logarithm applied by PL05 (p-value < 0.001). In other words, the lack of a potential signal after normalization[4,5] is not robust to the model specification.

Special attention should be paid to the role of well-known modes of natural variability, as low-frequency oscillations can be mistaken for a trend. Linear and nonlinear trends in REGN are statistically significant even when the accumulated cyclonic energy (ACE) or the annual number of hurricanes (NHUR) in the North Atlantic basin are added to the regression model to account for natural variability and low-frequency oscillations. The estimated slope coefficients for the linear trend are between US$74 and US$97 million dollars per year, depending on whether NHUR or ACE are included as regressors (Table 2). The estimated slope coefficients for the nonlinear trend implied by the Box–Cox transformation show that losses in 2005 were US$4.56 (US$1.04–US$14.6) billion larger than if there was no trend (Table 3). Including ACE and NHUR as regressors decreases the magnitude of the losses explained by the trend to US$2.88 (US$0.66–US$9.02) and US$2.37 (US$0.48–US$8.57) billion, respectively. As discussed below, both ACE and NHUR contain positive trends and, therefore, the increase in damages accounted for a time trend is lower when these variables are included.

The observed trend in REGN should be carefully interpreted as it may be caused by several factors. This trend could result from an incomplete inclusion of socioeconomic drivers of changes in exposure and vulnerability. Furthermore, the data representing these changes may not have adequate characteristics for the analysis (for example, temporal and spatial coverage; Supplementary Information 1

Table 2 | Linear estimates of increases in normalized losses per year and per °C increase in global temperature.

Dependent variable	Trend	*G*	ACE	NHUR	NE	Increase in losses by year 2005 (US$ billions)	Increase in losses per 1 °C increase (US$ billions)
REGN	1.36×10^{8} (1.89)*** (-7.80×10^{6}, 2.80×10^{8}) [8.61×10^{7}, 1.86×10^{8}]*	–	–	–	–	14.3 (−0.82–29.4) [9.03–19.53]*	
REGN	97843433 (2.20)** (8.98×10^{6}, 1.46×10^{8})* [5.15×10^{7}, 1.45×10^{8}]*	–	81170729 (1.63)	–	–	10.3 (0.94–19.6)* [5.4–15.2]*	
REGN	74133092 (2.30)** (1.03×10^{7}, 1.40×10^{8}) [2.35×10^{7}, 1.23×10^{8}]*	–	–	1.90×10^{9} (1.35)	–	7.8 (1.09–14.65) [2.56–12.92]*	
PL05	15225829 (0.21) (-1.33×10^{8}, 1.62×10^{8}) [-8.68×10^{7}, 1.20×10^{8}]	–	–	–	–	1.5 (−14.02–17.01) [−9.04–12.81]	
REGN	–	2.79×10^{10} (1.89)*** (-1.40×10^{9}, 5.70×10^{10}) [1.87×10^{10}, 3.73×10^{10}]*	–	–	–		28.0 (−1.40–57.40) [18.60–37.00]*
REGN	–	2.12×10^{10} (2.03)** (4.00×10^{8}, 4.20×10^{10})* [1.21×10^{10}, 3.03×10^{10}]*	70179079 (1.70)***	–	–		21.1 (4.00–42.00)* [12.10–30.30]*
REGN	–	1.88×10^{10} (2.20)** (1.72×10^{9}, 3.59×10^{10})* [8.88×10^{9}, 2.82×10^{10}]*	–	1.62×10^{9} (1.33)	–		18.80 (1.72–35.88)* [8.88–28.20]*
REGN	–	1.86×10^{10} (1.79)*** [-2.20×10^{9}, 3.94×10^{10}] [8.24×10^{9}, 2.87×10^{10}]*	–	–	1.97×10^{9} (1.56)		18.80 (−2.20–39.40) [8.24–28.70]*

G is the exponentially smoothed annual global surface air temperature, ACE is the seasonal accumulated cyclonic energy, NHUR is the seasonal number of hurricanes in the North Atlantic, NE is the number of landfalling hurricanes in the United States. *t*-statistics are given in parentheses. ** and *** denote statistical significance at the 5% and 10% levels, respectively. HAC standard errors and covariance were estimated when heteroskedasticity and autocorrelation was found using the Bartlett kernel and Newey–West bandwidth selection. Two-standard-error confidence intervals are shown in parentheses. 95% confidence intervals using block-bootstrap with a block size of ten observations are shown in brackets[24]. *Indicates that the confidence interval does not include zero.

and 2). Systematic biases in the loss data itself could also produce a trend, although this possibility has been previously analysed and discarded[5]. Recognizing the limitations and uncertainty characterizing this data, here we focus on a different question: can the trend in REGN be consistent with the observed changes in climate?

A trend in tropical cyclone activity

There is low confidence regarding the robustness of long-term trends in tropical cyclone activity due to data quality and to the variety of methods for estimating undercounts of these events in the earlier part of the century[16,25,26]. These problems have led to mixed conclusions. Some studies[5,23] explain the lack of trend in hurricane losses by the apparent lack of a trend in the strength and number of hurricanes in the North Atlantic. Other studies, however, report increases in both the number and strength of hurricanes in the North Atlantic[25,27–29]. Hurricane activity in the North Atlantic basin has increased since 1970, although there is low confidence in the human contribution to this increase[16,25,26,29–31].

For assessing trends in tropical cyclone activity, we analyse three different data sets: hurricanes that occurred in the North Atlantic basin, the US hurricane landfall reanalysis data (NOAA) and the hurricane and storm data inferred from the loss record analysed in this paper. In all cases, the Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO) and the Southern Oscillation Index (SOI) are included in the analysis to account for low-frequency natural oscillations.

Our analysis of the North Atlantic basin shows that there are slight but highly significant trends in NHUR and ACE. Low-frequency oscillations and common modes of variability—such as AMO, PDO and SOI—cannot account for these trends (Supplementary Information 3 and Supplementary Tables 11, 12, 14 and 15). The results are mixed for landfalling hurricanes and storms. The statistical models of the NOAA reanalysis of landfalling hurricanes in the US reveal no trend in frequency or intensity (Supplementary Information 3 and Supplementary Tables 17 and 18). However, the relation between this finding and the existence of a trend in the

Table 3 | Nonlinear estimates of increases in normalized losses in 2005 and for a 1 °C increase in global temperature.

Dependent variable	Intercept	Trend	G	ACE	NHUR	Increase in losses by year 2005 (US$ billions)	Increase in losses for 1 °C raise in G (US$ billions)
PL05(λ)	210.4207 (5.53)**	1.4150 (2.52)**	–	–	–	4.54 (0.31–20.90)	–
ln(1+PL05)	12.74957 (6.57)**	0.1053 (4.21)**	–	–	–	21.9 (0.11–4,200.00)	–
PL05(λ)	285.4523 (17.98)**	–	289.8909 (3.59)**	–	–	11.00 (2.75–29.00)	54.80 (8.64–204.00)
PL05(λ)	154.6100 (5.71)**	–	149.1260 (1.98)***	1.4695 (5.64)**	–	3.43 (−0.02–11.70)	11.50 (−0.04–59.80)
REGN(λ)	103.3125 (5.05)**	1.8629 (5.54)**	–	–	–	4.56 (1.04–14.60)	–
REGN(λ)	41.7837 (2.02)**	1.4134 (4.67)**	–	0.9588 (5.87)**	–	2.88 (0.66–9.02)	–
REGN(λ)	40.4366 (1.79)***	1.2416 (3.75)**	–	–	19.0628 (4.85)**	2.37 (0.48–8.57)	–
REGN(λ)	201.9134 (20.06)**	–	311.2391 (6.07)**	–	–	11.7 (4.69–24.90)	87.70 (25.40–240.00)
REGN(λ)	122.4804 (7.04)**	–	225.7823 (4.67)**	0.8921 (5.33)**	–	5.52 (1.90–12.70)	31.80 (7.41–98.60)
REGN(λ)	112.1281 (5.09)**	–	210.5428 (4.04)**	–	17.8716 (4.49)**	4.76 (1.38–12.00)	26.00 (4.84–90.90)

t-statistics are given in parentheses. ** and *** denote statistical significance at the 5% and 10% levels, respectively. *PL05*(λ), *REGN*(λ) are the Box–Cox transformation of PL05 and REGN with $\lambda = 0.19$ and $\lambda = 0.18$, respectively.

economic losses requires further examination. A large percentage of the events driving the economic losses in the US are storms, accounting for 41% of the loss-causing events since 1970 and 34% since 1940. Whereas the reanalysis data on landfalling hurricanes covers the full period of study, NOAA's reanalysis of the landfalling storms data is available only for the periods 1851–1950 and 1990–2013. This discontinuity makes the reanalysis data less appropriate for investigating the drivers behind the observed economic losses from hurricanes and storms in the US.

Given these limitations, we turn to the number of landfalling hurricanes and storms in the US (NE) represented by the sum of events per year reported in the damage data set of Pielke[5]. However, there is a known systematic bias in this series due to an undercount of damaging storms. Of the 40 landfalling storms with no reported damages in the official government records, and therefore not present in Pielke's data set, 32 of them occurred before 1940 and only 8 afterwards[5]. For this reason we analysed NE using two different sample periods: 1900–2005 and 1940–2005. The results show that regardless of the sample period, NE contains a significant trend even when the aforementioned variables of natural variability are accounted for (Supplementary Information 3 and Supplementary Tables 13 and 16a–e).

A climate change signal in tropical cyclone losses

Despite all the uncertainty due to data quality and availability, results from both the basin level and landfall data suggest that the upward trend in REGN is consistent with changes in its climatic drivers. However, observed warming is characterized by a nonlinear trend[30,32]. We extend our study to test if the trend in REGN and in its climatic drivers would be consistent with a general representation of the observed nonlinear warming trend. For this purpose, the linear trend is replaced by the exponentially smoothed global surface air temperature (G) as a crude proxy for the observed warming trend[33].

The models for REGN show that G is highly significant and that this variable can appropriately cancel out the nonstationarities in the losses. According to the linear models, the estimates of increases in losses per degree celsius are between US$19 billion and US$28 billion (Table 2 and Supplementary Information 3.2). Applying the appropriate Box–Cox transformation (see Supplementary Tables 8 and 10a–d), the observed warming could have contributed to increased hurricane and storm losses in the range of US$4.8 to US$11.7 billion in 2005. A 1 °C rise in G would increase losses by between US$26 and US$88 billion (Table 3). Our sensitivity analyses show that G is highly statistically significant even when the dominant modes of natural variability are taken into account. At the same time our results show that the nonlinear trends in HNUR, ACE and NE can be accounted for by the trend in G, producing stationary residuals (Supplementary Tables 11–13), also when controlling for AMO, PDO and SOI.

Increases in wealth and population alone cannot account for the observed trend in hurricane losses. The remaining trend in itself does not prove the existence of a climate change signal, as it could be due to causes not considered here (Supplementary Information 3.3.1, 3.3.2 and 3.3.5). However it implies that previous studies that have ruled out this possibility on the basis of a lack of such a trend are not valid. The variety of statistical models we present suggest that part of the increase in hurricane and storm losses in the US is at least consistent with observed global warming: there is substantial evidence of a positive trend in losses and also of positive trends in determinant drivers of losses such as ACE, NHUR and NE. The commonly accepted conclusion that a trend in adjusted natural disaster losses is absent is probably caused by methodological shortcomings in previous studies. In this paper, an improved approach is presented, and the empirical evidence suggests that climate change could have increased past costs of natural disasters. This finding can have major implications for the design of climate policy in the context of loss and damage from climate change at national and global scales. It suggests that a more cautious attitude is warranted when evaluating the current and future costs of climate change as well as the expected benefits of mitigation and adaptation strategies.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

F.E., W.J.W.B. and R.S.J.T. designed the study, analysed the data and wrote the paper. These authors contributed equally to the study. All authors discussed the results and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to F.E.

Competing financial interests

The authors declare no competing financial interests.

Methods

A full description of Methods is available in the online Supplementary Information of this paper. All socioeconomic data used here are taken from the Center for Science and Technology Policy Research and cover the period 1900–2005 (http://sciencepolicy.colorado.edu/publications/special/normalized_hurricane_damages.html). The database of landfalling hurricanes and storms in the US is taken from the Re-Analysis Project of NOAA (http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html). The revised HURDAT basin-wide data set on hurricanes and storms is available at http://www.aoml.noaa.gov/hrd/hurdat/comparison_table.html. The climate indices used in this study are available at: Accumulated Cyclonic Energy http://climexp.knmi.nl/data/iatlantic_annual_ace.dat; the number of hurricanes in the Atlantic basin http://climexp.knmi.nl/data/itcat.dat; the Atlantic Multidecadal Oscillation http://www.esrl.noaa.gov; the Southern Oscillation Index http://www.cgd.ucar.edu/cas/catalog/climind/SOI.signal.ascii; the Pacific Decadal Oscillation http://jisao.washington.edu/pdo/PDO.latest; global mean surface temperature http://data.giss.nasa.gov/gistemp.