ANALYSIS
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Normalized hurricane damage in the continental United States 1900–2017

Jessica Weinkle[1], Chris Landsea[2], Douglas Collins[3], Rade Musulin[4], Ryan P. Crompton[5], Philip J. Klotzbach[6] and Roger Pielke Jr[7]*

Direct economic losses result when a hurricane encounters an exposed, vulnerable society. A normalization estimates direct economic losses from a historical extreme event if that same event was to occur under contemporary societal conditions. Under the global indicator framework of United Nations Sustainable Development Goals, the reduction of direct economic losses as a proportion of total economic activity is identified as a key indicator of progress in the mitigation of disaster impacts. Understanding loss trends in the context of development can therefore aid in assessing sustainable development. This analysis provides a major update to the leading dataset on normalized US hurricane losses in the continental United States from 1900 to 2017. Over this period, 197 hurricanes resulted in 206 landfalls with about US$2 trillion in normalized (2018) damage, or just under US$17 billion annually. Consistent with observed trends in the frequency and intensity of hurricane landfalls along the continental United States since 1900, the updated normalized loss estimates also show no trend. A more detailed comparison of trends in hurricanes and normalized losses over various periods in the twentieth century to 2017 demonstrates a very high degree of consistency.

Landfalling hurricanes in the continental United States (CONUS) are responsible for more than two-thirds of total global catastrophe losses since 1980, according to data from Munich Re, a global reinsurance company, which are consistent with the academic literature on disaster loss trends and the assessments of the Intergovernmental Panel on Climate Change (IPCC)[1]. The management of economic risks associated with hurricanes largely relies on 'catastrophe models', which estimate losses from modelled storms in the context of contemporary data on exposure and vulnerability[2,3]. As a complement to such model-based approaches, an empirical approach to hurricane loss estimation called normalization was first published in 1998, and then updated and extended in 2008[4,5]. A normalization estimates direct economic losses (damage) from an historical extreme event were it to occur under contemporary societal conditions. Normalization methodologies are widely employed for tropical cyclones, floods, tornadoes, fires, earthquakes and other phenomena in locations around the world[6].

The United Nations global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development have identified direct economic losses from disasters in the context of economic growth as a key indicator[7]. With respect to weather disasters, according to the IPCC, disentangling the relative roles of variability and changes in climate from changes in vulnerability and exposure could contribute information useful to sustainable development[8]. Future changes in the climatology of tropical cyclones (called hurricanes in the North Atlantic) are highly uncertain[9]. However, research is robust in concluding that, for many decades into the future, the primary driver behind increasing economic losses related to hurricanes is expected to be societal growth[10,11].

In this analysis we provide a comprehensive update of the leading dataset on normalized CONUS hurricane losses for the period 1900–2017. Earlier versions of this dataset (1925–1995[4] and 1900–2005[5]) have been widely used in insurance and reinsurance industry analyses[12], as well as in subsequent research and in policy settings. Our analysis provides a substantial advance on this earlier work. Specifically, we (1) extend the dataset by 12 years, through the 2017 Atlantic hurricane season, (2) introduce loss estimates for dozens of historical storms of the early twentieth century that previously lacked damage estimates (and thus did not appear in earlier datasets), (3) address methodological discontinuities newly introduced in US government hurricane loss records and (4) perform updated consistency checks of normalization results with independent data on the long-term climatology of landfalling CONUS hurricanes.

Results

Figure 1 shows normalized hurricane damage in the period 1900–2017 for the Pielke Landsea 2018 (PL18) and Collins Lowe 2018 (CL18) methodologies. Total normalized losses over the 118-year study period are about US$2 trillion under either method or an average of US$16.7 billion per year. The figure also shows a trailing 11-year average, indicating that losses on a decadal scale were larger in the earlier part of the twentieth century, lower in the 1970s and 1980s, and then higher again in the first decades of the twenty-first century. Over the entire dataset there is no significant trend in normalized losses, CONUS hurricane landfalls or CONUS intense hurricane landfalls (discussed in greater detail in the Supplementary Information).

The greatest annual normalized damage occurred in 1926 (US$244 billion, PL18), exceeding the next greatest loss year (2005) by about US$74 billion. Most of the 1926 estimate comes from the Great Miami Hurricane of 1926, estimated to have caused damage of US$105 million in 1926 US dollars (US$76 million in Florida and US$29 million on its second landfall in Mississippi). The hurricane devastated Miami, bringing the 1920s Florida land boom to a close and initiating an early onset of the Great Depression in this region[13].

[1]University of North Carolina Wilmington, Wilmington, NC, USA. [2]National Oceanic and Atmospheric Administration, Miami, FL, USA. [3]Climate Index Working Group Chair, Casualty Actuarial Society, Harpswell, ME, USA. [4]FB Alliance Insurance, Schaumburg, IL, USA. [5]Risk Frontiers, St Leonards, NSW, Australia. [6]Colorado State University, Fort Collins, CO, USA. [7]University of Colorado Boulder, Boulder, CO, USA. *e-mail: pielke@colorado.edu

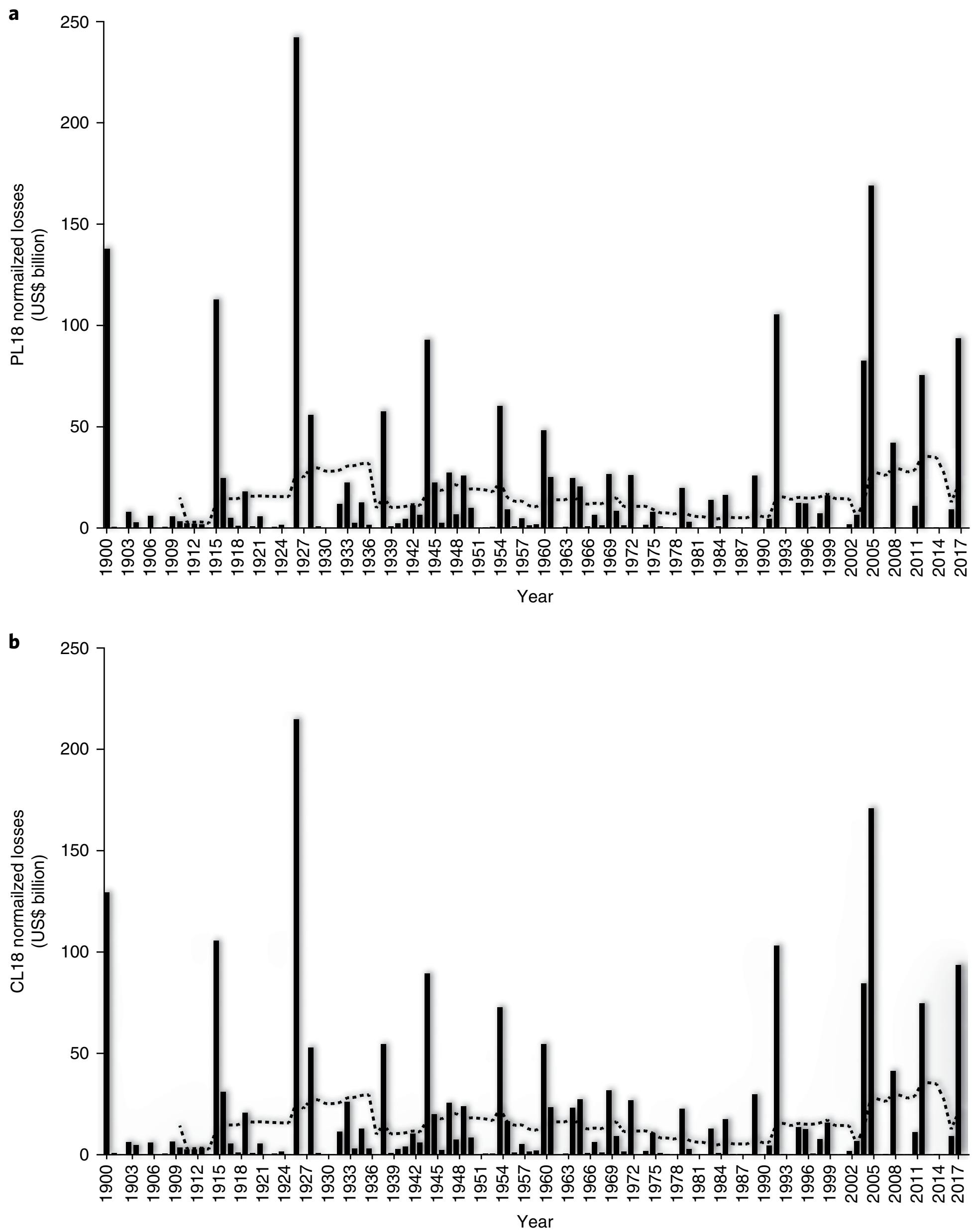

Fig. 1 | Normalized CONUS hurricane damage from 1900 to 2017. a, Total normalized losses per year for PL18 methodology. **b**, Total normalized losses per year for CL18 methodology. The black dotted line represents an 11-year trailing average.

The rapid increase in normalized losses for the Great Miami Hurricane of 1926 reflects the region's rapid growth. We estimated direct economic losses of US$75 billion in 1995[4], US$157 billion in 2005[5] and US$236 billion in 2017 (PL18), as Miami-Dade County's population grew from ~100,000 in 1926 to ~2,700,000 in 2017.

Table 1 shows the top 50 most damaging hurricane landfalls, ranked by PL18 along with corresponding rankings for CL18. Notably, Hurricane Katrina has fallen in the table since 2005[5], reflecting a slower rate of growth of normalized loss relative to other hurricanes, which struck locations where population, wealth and housing have grown at a faster rate since 2005.

The normalization results allow for a comparison of analogue storms. For instance, Hurricane Irma (2017), a large Category 4 storm, followed a similar path over Florida to that of Category 4 Hurricane Donna (1960). Normalized damage from Donna is US$48.4 billion (PL18) and US$54.9 billion (CL18), larger than the estimate of US$30 billion based on Aon Benfield's losses reported for Irma (Aon Benfield's losses are discussed in the Supplementary Information). The difference in Irma's preliminary loss estimate and Donna's normalized losses may be due to the slightly higher wind speed of Donna at landfall and the rate at which Irma weakened over land compared to Donna[14]. Single-storm analogues may provide useful context to decision-makers in industry and other settings (for example, one company in the insurance industry has operationalized an earlier version of the normalized hurricane dataset as an online tool allowing for comparisons of historical analogues with present-day storms, http://www.icatdamageestimator.com) but a more rigorous way to evaluate normalization results is to compare trends in the overall damage record to trends in hurricane climatology, as discussed below and in the Supplementary Information.

Table 2 displays the number of years in the 118-year dataset in which normalized losses exceeded various thresholds. Over this

Table 1 | The top 50 most damaging landfalling hurricanes, ranked based on PL18 methodology, storm category at landfall and location

Rank	Year	Hurricane	Category	States	PL18 damage (US$ billion)	CL18 damage (US$ billion)	
1	1926	Great Miami	4	AL, MS, FL	235.9	208.3	(1)
2	1900	Galveston	4	TX	138.6	130.2	(2)
3	2005	Katrina	3	FL, LA, MS, AL	116.9	118.8	(3)
4	1915	Galveston	4	TX, LA	109.8	102.0	(5)
5	1992	Andrew	5	FL, LA	106.0	103.9	(4)
6	2012	Sandy	1	NY	73.5	72.8	(6)
7	1944	Cuba-Florida	3	FL	73.5	71.2	(7)
8	2017	Harvey	4	TX	62.2	62.1	(8)
9	1938	Great New England	3	LA, NY	57.8	54.7	(10)
10	1928	Lake Okeechobee	4	FL, GA, SC	54.4	51.2	(11)
11	1960	Donna	4	FL, NC, VA, NY, CT, RI, MA	48.4	54.9	(9)
12	2008	Ike	2	TX, LA	35.2	34.7	(13)
13	1954	Hazel	4	SC, NC	33.2	48.5	(12)
14	2005	Wilma	3	FL	31.9	31.9	(14)
15	2017	Irma	4	FL	31.0	31.0	(16)
16	2004	Charley	4	FL, SC	26.9	27.5	(18)
17	1969	Camille	5	LA, MS	26.4	31.6	(15)
18	1972	Agnes	1	FL, MD, NY, PA, VA	26.0	26.9	(20)
19	2004	Ivan	3	AL, FL	25.9	26.9	(21)
20	1989	Hugo	4	SC, NC	25.1	29.2	(17)
21	1961	Carla	4	TX	25.1	23.3	(22)
22	1949	Florida	4	FL,GA	24.2	22.5	(23)
23	1947	Fort Lauderdale	4	FL, LA, MS	24.0	21.7	(26)
24	1954	Carol	3	NC, NY, CT, RI, MA	23.5	22.1	(24)
25	1965	Betsy	3	FL, LA	20.5	27.2	(19)
26	1944	Great Atlantic	2	NC, VA, NY, NJ, RI, CT, MA	19.6	18.1	(29)
27	1945	Homestead	4	FL	19.4	16.5	(30)
28	1919	Florida Keys	4	FL,TX	17.8	20.7	(27)
29	2004	Frances	2	FL	16.5	16.5	(31)
30	1916	Gulf Coast	3	MS, AL, FL	16.2	21.8	(25)
31	1979	Frederic	3	AL, MS	15.8	18.6	(28)
32	2005	Rita	3	LA,TX	14.9	14.8	(33)
33	1999	Floyd	2	NC	13.9	13.7	(35)
34	1983	Alicia	3	TX	13.6	12.8	(36)
35	2004	Jeanne	3	FL	13.6	13.9	(34)
36	1933	Chesapeake-Potomac	1	NC, VA, MD	12.8	16.2	(32)
37	1964	Dora	2	FL	12.3	10.9	(39)
38	1932	Freeport	4	TX	11.5	10.8	(41)
39	1996	Fran	3	NC	11.1	11.4	(37)
40	2011	Irene	1	NC	10.8	10.9	(40)
41	1942	Matagorda	3	TX	10.8	10.0	(44)
42	1995	Opal	3	FL, AL	10.0	11.2	(38)
43	1935	Yankee	2	FL	9.8	8.5	(47)
44	2016	Matthew	1	FL, GA, SC, NC	8.6	8.6	(46)
45	1970	Celia	3	TX	8.3	8.9	(45)
46	1964	Cleo	2	FL	7.9	7.2	(48)
47	1975	Eloise	3	FL, AL	7.7	10.6	(42)
48	1903	Florida	1	FL	7.4	5.7	(58)
49	1950	King	4	FL	6.8	5.8	(57)
50	1926	Nassau	2	FL	6.4	6.4	(49)

The CL18 normalized damage figures are included along with the associated ranking in parentheses.

Table 2 | Number of years from 1900 to 2017 that CONUS normalized losses exceeded certain values of 2018 US dollars

Methodology	Equal to US$0	Exceeding			
		US$10 billion	US$50 billion	US$75 billion	US$100 billion
PL18	25 (21.2%)	36 (30.5%)	12 (10.2%)	9 (7.6%)	5 (4.2%)
CL18	25 (21.2%)	38 (32.2%)	13 (11.0%)	9 (7.6%)	5 (4.2%)

period there was approximately a 30% annual chance of hurricane losses in the CONUS exceeding US$10 billion and approximately a 4% annual chance of exceeding US$100 billion. On average, about one year in every five had zero CONUS losses.

Table 3 shows normalized damage by month. Historically, approximately 95% of CONUS normalized hurricane damage occurs during the months of August, September and October, with half of all CONUS damage occurring during September. About 86% of damage occurs before 1 October.

Table 4 shows normalized damage by Saffir–Simpson category at landfall. Major hurricanes (Category 3+) account for about 33% of landfalls and more than 80% of total damage. Despite the relatively large losses caused by individual Category 5 hurricanes, only three in the historical record have made landfall in the CONUS. Interestingly, despite their much greater loss potential, the three Category 5 landfalls account for the smallest percentage of total losses of the five Saffir–Simpson classification categories, and less than the total losses caused by the 85 Category 1 hurricanes over the same period.

Additional data and analyses on the normalized loss datasets can be found in the Supplementary Information.

Consistency check with climate trend data. Long-term trends in hurricane landfall frequency and intensity provide a useful means of evaluating the results of a normalization methodology. A normalization should not be used to explore climate trends; climate data better serve that purpose. However, climate data can be used to perform a consistency check with a normalization[15]. Trends in an unbiased normalization dataset should match corresponding trends in the incidence of extreme events for countries such as the United States that have heavily populated coastlines. After all, the goal of a normalization is to remove the signal of societal changes from a loss dataset as much as possible. Thus, if relevant extreme events have become more (less) common or more (less) intense, then over the same period we would expect a normalized loss dataset to show a corresponding increasing (decreasing) trend.

A consistency check can also reveal biases that may be introduced into a normalization, such as might occur if there are trends in broad patterns of exposure. For instance, if housing stock were to become progressively more resistant (vulnerable) to damage then similar storms at different points in time would result in less (more) damage. In the absence of a trend in hurricane frequency or intensity, such trends in housing stock would eventually lead to a divergence between observed trends in the normalization and trends in hurricane climatology. Because we do not see such a divergence, regardless of time period chosen (as discussed in the Supplementary Information), we are confident that no such biases are present (or, more likely, various biases that might exist cancel each other out so that there is no discernible net bias observed in the results).

Given that there are no significant trends in the frequency or intensity of landfalling CONUS hurricanes since 1900[16,17], we would expect an unbiased normalization to also exhibit no trend over this time period. We observe very strong consistency between trends in normalized losses and official National Oceanic and Atmospheric Administration (NOAA) data on CONUS hurricane landfalls from various starting dates in the twentieth century (see the Supplementary Information for a more in-depth discussion of trends and statistical test results), indicating that the results of our normalization methods do not display bias with respect to the climatological record of CONUS hurricanes. Our results are also consistent with previous iterations of the normalized hurricane damage dataset[5,18]. (However, there is at least one alternative view in the literature, which is inconsistent with the conclusions of the IPCC[19]).

Table 3 | Total CONUS normalized damage (PL18) by month from 1900 to 2017

Month	Total damage (US$ million)	Total damage (%)
June	35,996	1.8
July	42,749	2.2
August	615,825	31.3
September	988,575	50.3
October	271,654	13.8
November	11,430	0.6
Total	1,966,229	100

Discussion

Landfalling hurricanes contribute significantly to disaster losses both in the CONUS and globally. Large loss years such as 2017 remind us of the magnitude of losses that are possible when several major hurricanes make landfall in a single year. However, our normalization analyses suggest that the losses in 2017 are far from a worst-case scenario. Losses from a single storm striking the CONUS, analogous to the Great Miami hurricane of 1926, could result in twice the total direct economic loss amounts of 2017, totalling well over US$200 billion. Loss potentials are certainly higher than this for conceivable storms for which there is no historical analogue since 1900.

As growth continues, the United States should thus expect much greater hurricane damage in its future. Understanding the role of societal changes in loss potential, how such changes evolve over time and the role of disaster mitigation policies that might address loss potentials is essential to the design and implementation of effective actions under the targets of the Sustainable Development Goals[7,8].

Recently, the CONUS has experienced a long period of good fortune with respect to landfalling hurricanes, notably the 11-year stretch of no major CONUS hurricane landfalls that ended in 2017[20]. Consequently, if coming years see storms make landfall at rates and intensities closer to observed historical averages, then we should expect larger losses than those observed from 2006 to 2016. In addition, over climate timescales, any increases in major hurricane frequency or intensity[8–11] above historical rates would lead to even greater losses. Whatever the future brings, addressing exposure and vulnerability to hurricanes will remain a permanent priority for communities along the US Gulf and Atlantic coasts seeking to implement sustainable and robust disaster mitigation policies in the face of an uncertain climate future[8].

Methods

The current study includes 197 storms resulting in 206 landfalls with hurricane-force winds (119 km h^{-1}) over land as listed by NOAA HURDAT2 from 1900

Table 4 | Total CONUS normalized hurricane damage by Saffir–Simpson Scale category at landfall from 1900 to 2017

Category	Count	Total damage (US$ million)	Mean damage (US$ million)	Median damage (US$ million)	Damage relative to a Category 1 landfall	Total damage (%)	Total per storm (%)
(a) PL18 methodology							
1	85	183,799	2,137	287	1.0	9.4	0.1
2	51	211,127	4,140	1,659	5.8	10.7	0.2
3	47	574,773	12,229	4,769	16.6	29.2	0.6
4	20	864,775	43,239	25,110	87.4	44.0	2.2
5	3	131,755	43,918	26,414	91.9	6.7	2.2
Total	206	1,966,229					
(b) CL18 methodology							
1	85	192,027	2,233	308	1.0	9.7	0.1
2	51	217,788	4,270	1,942	6.3	11.0	0.2
3	47	598,755	12,739	5,204	16.9	30.3	0.7
4	20	830,283	41,514	25,386	82.6	42.0	2.1
5	3	135,995	45,332	31,552	102.6	6.9	2.3
Total	206	1,974,848					

to 2017[21]. In addition, there were 157 landfalling tropical and subtropical storms during this period, but because these weaker storms accounted for <2% of the total losses during the period 1900–2005 they are not included in this study[5]. The data record is such that six of the hurricanes used in the analysis include direct economic losses from at least some severe inland flooding (these are Storm 2 in 1916, Agnes in 1972, Eloise in 1975, Floyd in 1999, Matthew in 2016 and Harvey in 2017). We discuss these data in the Supplementary Information. Because these storms are few in number and somewhat distributed over the data record, we expect that our results are insensitive to any 'leakage' of the inclusion of such widespread inland flood losses from these storms into the normalization dataset.

For the 37 landfalling hurricanes without an original loss estimate, we improve on previous normalization studies[4,5] by introducing losses for these hurricanes based on the median normalized losses of the same category event making landfall in a similarly populated region. Of these hurricanes, 29 are Category 1, seven are Category 2 and one is Category 3, with most occurring before 1950. In the historical record there are also four post-tropical cyclones of hurricane strength at landfall, of which three (1905, 1924 and 1925) are excluded from this analysis due to a lack of damage estimates, whereas Superstorm Sandy, also a post-tropical cyclone of hurricane strength at landfall, is included (and discussed in the Supplementary Information).

This study focuses on estimates of total direct economic losses (damage) related to hurricane landfalls along the US Gulf and Atlantic coasts from 1900 to 2017, defined as direct losses determined in the weeks and months following the event[22,23]. Not included in estimates of direct damage are indirect losses such as federal disaster aid, business interruption losses, pricing effects on agricultural commodities or other longer-term macroeconomic effects, such as those associated with rebuilding and recovery activities, and how these effects may influence economic growth[24]. The US National Hurricane Center's methods for assessing hurricane losses have historically included storm surge and wind-related losses but have inconsistently included losses from inland tropical cyclone-related rainfall and riverine flooding. Overall US rainfall and riverine flood losses are tabulated separately by the US National Weather Service[25].

We emphasize that the timescale of this study, dating to 1900, precludes the use of contemporary loss estimates and economic data for the full period of the study. We discuss data limitations in detail in the Supplementary Information. Despite the very real data limitations, the resulting normalization passes a consistency check with independent climate data (see the Supplementary Information) and is also consistent with independent results from industry catastrophe models[12]. Thus we have confidence that the normalized results, while not perfect, nonetheless offer valuable information on how much damage hurricanes of the past would cause under today's societal conditions under the loss accounting methods underlying the US National Hurricane Center's long-term dataset.

Different methods exist for calculating a disaster's economic impacts, which can lead to different loss estimates for the same event[22,23,26,27]. For instance, reports from various US government agencies of major flood losses have produced loss estimates differing by as much as 40% for significant events[27]. Our methods seek to use a consistent approach to loss estimation over time to enable the application of a normalization methodology that results in unbiased results. An 'apples to apples' approach to loss estimation is important for documenting and understanding hurricanes in relation to each other across time and relative loss trends over long periods.

The criteria used to define a loss event (geographical, temporal and so on) contribute to differences across loss datasets[22,23]. In this study, we use historical loss estimates from the National Hurricane Center (1900–1924, 1996–2014), *Monthly Weather Review* (1925–1995) and Swiss Re and Aon Benfield (2015–2017). The Supplementary Information explains the data in more detail and how newly introduced data collection methods of the US government are inconsistent with past methods.

We employ the same two methods used in a previous normalization.[5] The first, PL18, normalizes using adjustments based on data from 1900 for inflation, per-capita wealth and affected county population. The second, CL18, normalizes using adjustments based on data from 1900 by inflation, per-capita wealth and county housing units. Further details follow and are discussed in the Supplementary Information.

Normalization methodology 1. PL18 (ref. [5]) adjusts historical loss data for inflation, per-capita wealth and the population of affected counties. To adjust for inflation, we use the implicit price deflator for gross domestic product for the years 1929–2018 from the US Department of Commerce's Bureau of Economic Analysis (BEA) and a dataset recommended by BEA for earlier years. For the years before 1926, based on guidance from the US Bureau of Economic Analysis, we employ ref. [28]. Increasing 'wealth' simply means that people have a greater accumulation of material possessions (with an associated greater economic value) today compared to the past, increasing loss potentials[29]. Real national wealth is captured by the estimate of current-cost net stock of fixed assets and consumer durable goods produced by the BEA. To adjust for population, we use data from the US Census for the counties affected by each hurricane[5].

The general formula for the PL18 normalized losses is

$$D_{2018} = D_y \times I_y \times \mathrm{RWPC}_y \times P_{2018/y}$$

where D_{2018} is normalized damage in 2018 US dollars; D_y is reported damage in current-year US dollars; I_y is inflation adjustment; RWPC_y is real wealth per-capita adjustment; and $P_{2018/y}$ is county population adjustment.

As an example, damage from Hurricane Frederic (1979) is calculated under PL18 as follows: D_y is US\$2,300,000,000; I_y is 2.806; RWPC_y is 1.723; and $P_{2018/y}$ is 1.423.

The 2018 normalized loss is equal to US\$2,300,000,000 × 2.806 × 1.723 × 1.423 = US\$15,827,205,699.

Frederic caused US\$2.3 billion in total damage when it made landfall in 1979, but had it occurred in 2018, PL18 estimates it would have resulted in US\$15.8 billion in total damage.

Normalization method 2. CL18 (refs [5,18]) uses county housing units, provided by the US Census from 1940 to 2018. We estimate housing units from 1900 to 1939 based on the county-level relationship of population and housing units from 1940 to 2018.

The general formula for the CL18 normalized losses is

$$D_{2018} = D_y \times I_y \times \mathrm{RWPHU}_y \times \mathrm{HU}_{2018/y}$$

where D_{2018} is normalized damage in 2018 US dollars; D_y is reported damage in current-year US dollars; I_y is inflation adjustment; $RWPHU_y$ is real wealth per housing unit adjustment; and

$HU_{2018/y}$ is county housing unit adjustment.Under CL18, the Hurricane Frederic (1979) damage is calculated as follows: D_y is US\$2,300,000,000; I_y is 2.806; $RWPHU_y$ is 1.521; and $HU_{2018/y}$ is 1.898.

The 2018 normalized loss is equal to

US\$2,300,000,000 × 2.791 × 1.49 × 1.873 = US\$18,636,661,732.

The estimated Frederic damage in 2018 by CL18 is thus US\$18.6 billion.

Data availability

Data used to perform this study can be found in the Supplementary Information as an Excel spreadsheet. Any further data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions

J.W. and R.P. designed the study. J.W. performed the normalization calculations. C.L., P.J.K., D.C. and R.P. contributed data for the analysis. J.W., C.L., D.C., R.M., R.P.C., P.J.K. and R.P. analysed the data. J.W. and R.P. wrote the paper with contributions from C.L., D.C., R.M., R.P.C., P.J.K. J.W., C.L., D.C., R.M., R.P.C., P.J.K. and R.P. participated in the response to reviews, which were prepared by R.P.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to R.P.