Normalized Hurricane Damage in the Continental United States: 1900-2017

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Abstract. A normalization estimates damage from an historical extreme event were that same event to occur under contemporary societal conditions. This paper provides a major update the leading dataset on normalized US hurricane losses in the continental United States from 1900 to 2017. Over this period, hurricanes caused $1.9 trillion in normalized (2017) damage, or just over $16.1 billion annually.

Landfalling hurricanes in the continental United States (CONUS) are responsible for more than 2/3 of global catastrophe losses since 1980, according to data from Munich Re, a global reinsurance company.[1] The management of economic risks associated with hurricanes largely relies on "catastrophe models" which estimate losses from modeled 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 risk estimation has been employed since 1998, called "normalization."[4,5] A normalization estimates damage of an historical extreme event were it to occur under contemporary societal conditions. Normalization methodologies are widely

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employed for tropical cyclones, floods, tornadoes, fires, earthquakes and other phenomena in locations around the world.[6]

In this article we provide a comprehensive update of the leading dataset on normalized CONUS hurricane losses for the period from 1900-2017. Earlier versions of this dataset (1925-1995[4] and 1900-2005[5]) have been widely employed in insurance and reinsurance industry analyses, as well as in policy and research. Our new analysis provides a substantial advance on this earlier work. Specifically, we (a) extend the dataset by 12 years, to include the record-breaking 2017 Atlantic hurricane season, (b) establish loss estimates for dozens of historical storms of the early 20th century which previously lacked damage estimates (and thus did not appear in earlier datasets), (c) address methodological discontinuities newly introduced in US government hurricane loss data, and (d) perform updated consistency checks of normalization results with independent data on the long-term climatology of landfalling hurricanes.

Data and Methods

This study focuses on estimates of total *economic damage* related to hurricane landfalls along the US Gulf and Atlantic coasts from 1900-2017, defined as direct losses determined in the weeks and months following the event.[7] Not included in estimates of direct damage are indirect losses such as federal disaster aid, business interruption losses, pricing effects on agricultural commodities or longer term macroeconomic effects such as those associated with rebuilding and recovery activities. The US government's methods for assessing hurricane losses typically do not include losses from tropical cyclone-related riverine flooding. Such losses are included under a separate tabulation of flood losses kept by the US National Weather Service.[8]

Different methods exist for calculating a disaster's impacts, which leads to different loss estimates for the same event.[9, 10] Our methods seek to use a consistent approach to loss estimation over time to enable the application of a normalization methodology resulting in unbiased results. An "apples to apples" approach to loss estimation is important for documenting and understanding storms in relation to each other across time and relative loss trends over long periods.

Disaster damage data is inherently uncertain. For instance, different US government agency reports of major flood losses can differ by as much as 40% for significant events.[10] The criteria used to define a loss event (geographical, temporal, etc.) contribute to differences in loss datasets.[9,10] In this study, we use historical loss estimates from the National Hurricane Center (1900-1924, 1998-2015), *Monthly Weather Review* (1925-1997) and Swiss Re and Aon Benfield (2016-2017). The SI explains the data in more detail and how data collection methods used by the U.S. government in recent years are inconsistent with past methods.

Normalization Methodology #1: Pielke-Landsea 1998 (updated to PL17).

PL17 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 1929–2017 from the US Department of Commerce's Bureau of Economic Analysis

(BEA) and a dataset recommended by BEA for earlier years.[11] Increasing "wealth" simply means that people have a greater accumulation of material possessions (with an associated greater economic value) today as compared to the past, increasing loss potentials. Real national wealth is captured by the estimate of current-cost net stock of fixed assets and consumer durable goods produced by the BEA. We use population data from the US Census for the counties affected by each hurricane.[5]

The general formula for the PL17 normalized losses is

$$D_{2017} = D_y \times I_y \times RWPC_y \times P_{2017/y}$$

where

- D_{2017} = normalized damages in 2017 dollars;
- D_y = reported damages in current-year dollars;
- I_y = inflation adjustment;
- $RWPC_y$ = real wealth per capita adjustment; and
- $P_{2017/y}$ = county population adjustment.

As an example, damage from Hurricane Frederic (1979) is calculated under PL17 as follows:

- D_{2017} = normalized damages in 2017 dollars;
- D_y = $2,300,000,000;
- Iy = 2.791;
- $RWPCy$ = 1.695;
- $P_{2017/y}$ = 1.412.

The 2017 normalized loss = \$2,300,000,000 × 2.791 × 1.695 × 1.412 = \$15,369,510,193

Frederic caused \$2.3 billion in total damage when it made landfall in 1979, but had it occurred in 2017, PL17 estimates it would have resulted in \$15.4 billion in total damage.

Normalization Method #2: Collins and Lowe 2001 (updated to CL17)[5,12]

CL17 utilizes county housing units; provided by the US Census for 1940–2017. We estimate housing units for 1900–1939 based on the county-level relationship of population and housing units from 1940–2017.

The general formula for the CL17 normalized losses is

$$D_{2017} = D_y \times I_y \times RWPHU_y \times HU_{2017/y}$$

where

- D_{2017} = normalized damages in 2017 dollars;
- D_y = reported damages in current-year dollars;
- I_y = inflation adjustment;
- $RWPHU_y$ = real wealth per housing unit adjustment;
- $HU_{2017/y}$ = county housing unit adjustment.

Under CL17, the Hurricane Frederic (1979) damage is calculated as follows:

- D_{2017} = normalized damages in 2017 dollars;
- D_y= \$2,300,000,000;

- *Iy* = 2.791;
- *RWPHUy* = 1.501;
- $HU_{2017/y}$ = 1.873.

The 2017 normalized loss = \$2,300,000,000 × 2.791 × 1.49 × 1.873 = \$18,049,451,321

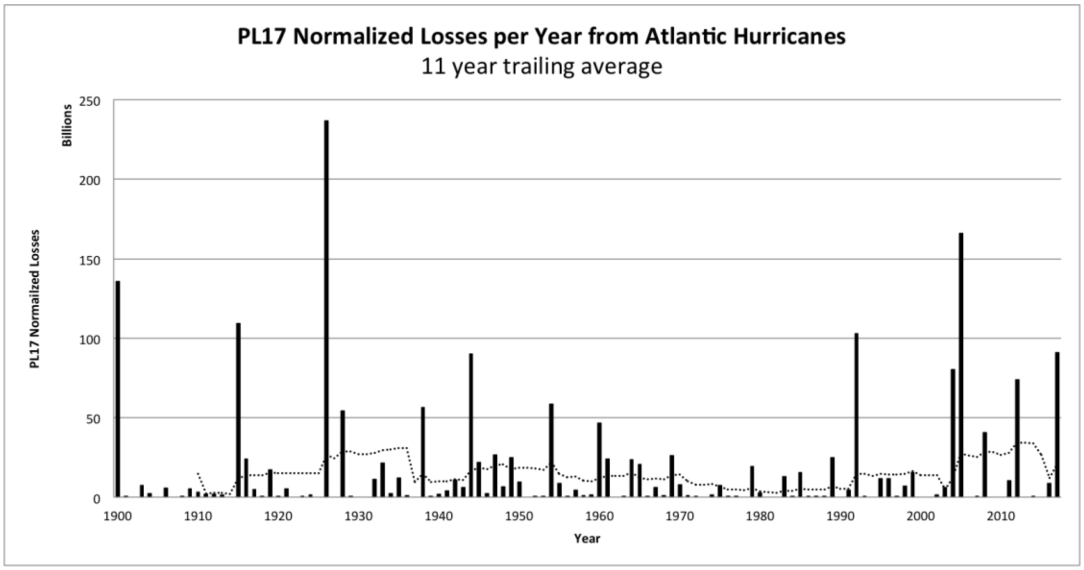
The estimated Frederic damage in 2017 by CL17 is thus \$18.0 billion.

Continental US Hurricane Landfalls 1900 to 2017

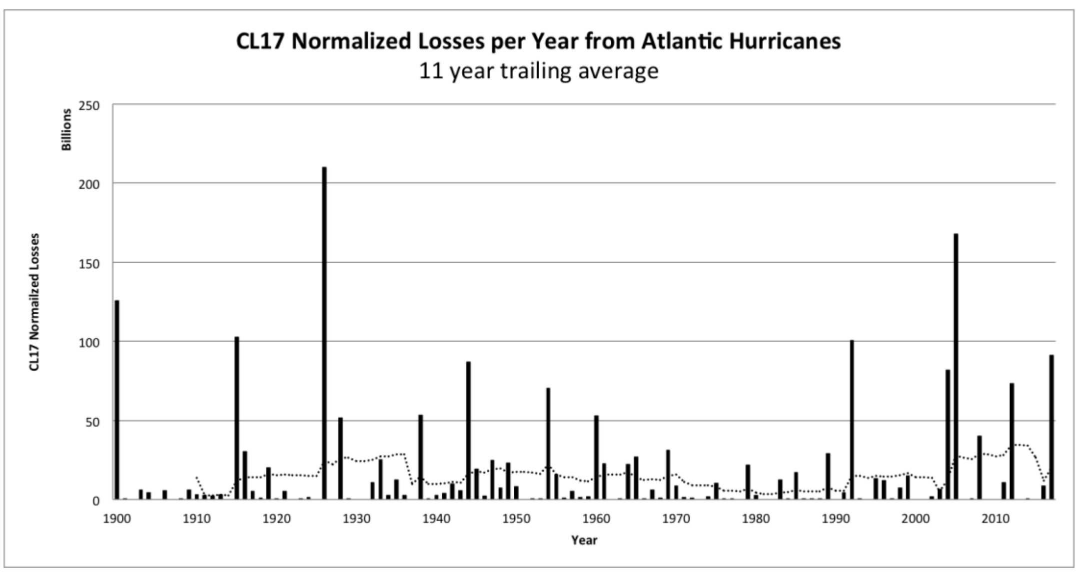
The current study includes 197 storms resulting in 206 landfalls with hurricane-force winds (>74 mph, 119 kph) over land as listed by NOAA HURDAT from 1900 to 2017.[13] In addition, there were an additional 157 landfalling tropical and subtropical storms during this period, but because these weaker storms accounted for <2% of the total losses during 1900-2005 they are not included in this study.[5] For six of the storms used in the analysis, severe inland flooding complicates the loss estimation. We discuss these issues in depth in the accompanying SI. Because these storms are few in number and somewhat evenly distributed over the data record, our results are insensitive to any "leakage" of inland flood losses from these storms into the normalization dataset.

For the 37 landfalling hurricanes without an original loss estimate we improve upon previous normalization studies[4, 5] by estimating losses for these storms based on the median normalized losses of the same category event making landfall in a similarly populated region. Of these storms, 29 are Category 1, 7 are Category 2, and 1 is Category 3, with most occurring prior to 1950. In the historical record there are also 4 post-tropical cyclones of hurricane strength at landfall, 3 of which (1905, 1924 and 1925) are excluded from this whereas Superstorm Sandy is included (and discussed in the SI).

Results



a)



b)

Figure 1 (a-b). Hurricane damage normalization 1900- 2017. A) Total normalized losses per year for PL17. B) Total normalized losses per year for CL17. Black line represents 11-year moving average.

Figure 1 shows normalized hurricane damage 1900 to 2017 for PL17 and CL17. Total normalized losses over the 118-year study period are about $1.9 trillion under either method, or an average of $16.1 billion per year. The greatest normalized damage occurred in 1926 ($237 billion, PL17), exceeding the next greatest loss year (2005) by about $70 billion. Most of the 1926 estimate comes from the Great Miami Hurricane of 1926, estimated to have caused damages of $105 million in 1926 dollars ($76 million in Florida and $29 million on its second landfall in Mississippi). The hurricane devastated Miami, bringing the 1920's Florida land boom to a close and initiating an early onset of the Great Depression in this region.[14] The rapid increase in normalized losses for the Great Miami Hurricane of 1926 reflect the region's rapid growth: we estimated direct economic losses of $75 billion in 1995[4], $157 billion in 2005[5], and $229 billion in 2017 (PL17).

Table 1 shows the top 50 most damaging events, ranked by PL17 along with corresponding rankings of CL17. Notably, Hurricane Katrina has fallen in the table since 2005[5] reflecting demographic and economic changes in the region of its Louisiana landfall following the storm. Socio-economic changes have slowed the rate of growth in the normalized Katrina loss relative to other storms which struck locations where population, wealth and housing have grown at a faster rate since 2005, leading to a drop in where Katrina appears in the table.

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 damages from Donna are $46.7 billion (PL17) and $52.9 billion (CL17), larger than Aon Benfield's $30 billion total economic loss estimate for Irma. 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 as compared to Donna.[15] Single-storm analogues may provide useful context to industry,[16] but a more rigorous way to evaluate normalization results is to compare the overall damage record to hurricane climatology, as discussed below.

Table 1: Top 50 most damaging landfalling hurricanes. Storms are ranked based on PL17 methodology. The CL17 normalized damage figures are included along with the associated ranking in parentheses.

Rank	Year	Hurricane	Category	States	PL17 Damage (US$ billions)	CL17 Damage (US$ billions)
1	1926	Great Miami	4	AL,MS,FL	229.1	202.3 (1)
2	1900	Galveston	4	TX	135.6	125.7 (2)
3	2005	Katrina	3	FL,LA,MS,AL	114.0	115.7 (3)
4	1915	Galveston	4	TX,LA	105.9	98.4 (5)
5	1992	Andrew	5	FL,LA	102.9	100.7 (4)
6	2012	Sandy	1	NY	71.4	70.9 (6)
7	1944	Cuba-Florida	3	FL	70.6	68.4 (7)
8	2017	Harvey	4	TX	60.0	60.0 (8)
9	1938	Great New England	3	LA,NY	56.4	53.3 (9)
10	1928	Lake Okeechobee	4	FL,GA,SC	52.6	49.6 (11)
11	1960	Donna	4	FL,NC,VA,NY, CT, RI, MA	46.7	52.9 (10)
12	2008	Ike	2	TX,LA	33.9	33.5 (14)
13	1954	Hazel	4	SC,NC	31.9	46.5 (12)
14	2005	Wilma	3	FL	30.9	30.9 (15)
15	2017	Irma	4	FL	30.0	30.0 (13)

16	2004	Charley	4	FL,SC	25.9	26.4	(19)
17	1969	Camille	5	LA, MS	25.9	30.8	(16)
18	2004	Ivan	3	AL,FL	25.0	25.9	(20)
19	1989	Hugo	4	SC,NC	24.4	28.2	(17)
20	1961	Carla	4	TX	24.2	22.5	(21)
21	1947	Fort Lauderdale	4	FL,LA,MS	23.4	21.1	(25)
22	1949	Florida	4	FL,GA	23.4	21.7	(22)
23	1954	Carol	3	NC,NY,CT,RI,MA	23.0	21.5	(23)
24	1965	Betsy	3	FL,LA	20.5	26.9	(18)
25	1944	Great Atlantic	2	NC,VA,NY, NJ,RI,CT,MA	19.1	17.6	(28)
26	1945	Homestead	4	FL	18.8	16.0	(29)
27	1919	Florida Keys	4	FL,TX	17.4	20.1	(26)
28	2004	Frances	2	FL	15.9	15.9	(30)
29	1916	Gulf Coast	3	MS,AL,FL	15.7	21.1	(24)
30	1979	Frederic	3	AL,MS	15.4	18.0	(27)
31	2005	Rita	3	LA,TX	14.6	14.5	(32)
32	1999	Floyd	2	NC	13.4	13.1	(34)
33	1983	Alicia	3	TX	13.1	12.3	(35)
34	2004	Jeanne	3	FL	13.0	13.4	(33)
35	1933	Chesapeake-Potomac	1	NC,VA,MD	12.4	15.7	(31)
36	1964	Dora	2	FL	11.9	10.6	(39)
37	1932	Freeport	4	TX	11.1	10.4	(40)
38	1996	Fran	3	NC	10.7	11.0	(36)
39	2011	Irene	1	NC	10.5	10.6	(38)
40	1942	Matagorda	3	TX	10.4	9.7	(43)
41	1995	Opal	3	FL,AL	9.7	10.8	(37)
42	1935	Yankee	2	FL	9.5	8.3	(46)
43	2016	Matthew	1	FL,GA,SC,NC	8.3	8.3	(45)
44	1970	Celia	3	TX	8.0	8.7	(44)

45	1964	Cleo	2	FL	7.7	7.0	(47)
46	1975	Eloise	3	FL, AL	7.5	10.2	(41)
47	1903	Florida	1	FL	7.3	5.6	(57)
48	1950	King	4	FL	6.6	5.7	(56)
49	1926	Nassau	2	FL	6.2	6.1	(48)
50	1943	Surprise	2	TX	6.1	5.7	(55)

Table 2 displays the number of years in the 118-year dataset where normalized losses exceeded various thresholds. Over this period there was an ~30% annual chance of hurricane losses in the CONUS exceeding $10 billion and a ~4% annual chance of exceeding $100 billion. On average, about 1 in every 5 years there were no losses at all.

Table 2: Number of years from 1900-2017 that CONUS normalized losses exceeded certain values of 2017 dollars.

Methodology	Equal to $0	Exceeding			
		$10 billion	$50 billion	$75 billion	$100 billion
PL17	25	35	12	8	5
CL17	25	36	13	8	5

Table 3 shows normalized damage by month. Historically, approximately 97% of CONUS hurricane damage occurs during the months of August, September and October with half of all CONUS damage occurring during September.

Table 3: Total CONUS normalized damage (PL17) by month from 1900-2017.

Month	Total Damage ($ millions)	Total Damage (%)
June	10,313	0.5%
July	41,447	2.2%
August	597,543	31.7%
September	960,144	51.0%
October	262,624	13.9%
November	11,094	0.6%
Total	1,899,165	100%

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

Additional data and analyses can be found in the supplementary information.

Table 4: Total CONUS normalized hurricane damage by Saffir-Simpson Scale category at landfall: 1900-2017.

Category	Count	Total Damage ($ millions)	Mean Damage ($ millions)	Median Damage ($ millions)	Damage Relative to a	Total Damage (%)	Total per storm (%)

					Category 1 Landfall		
(a) PL Methodology							
1	85	153,843	1,810	278	1.0	8.2	0.1
2	51	204,737	4,014	1,639	5.9	10.9	0.2
3	47	558,622	11,886	4,678	16.8	29.7	0.6
4	20	837,807	42,890	24,275	87.3	44.5	2.2
5	3	128,156	42,719	25,913	93.2	6.8	2.3
Total	206	1,883,165					
(b) CL Methodology							
1	85	161,119	1,896	300	1.0	8.5	0.1
2	51	210,951	4,136	1,901	6.3	11.2	0.2
3	47	581,215	12,366	5,098	17.0	30.8	0.7
4	20	802,650	40,133	24,466	81.6	42.5	2.1
5	3	132,119	44,040	30,833	102.9	7.0	2.3
Total	206	1,888,055					

Consistency Check with Climate Trend Data

Long-term trends in hurricane landfall frequency and intensity provide a useful in evaluating the results of a normalization methodology. Trends in an unbiased normalization dataset should match corresponding trends in the incidence of extreme events for countries like the US that have heavily populated coastlines. After all, the goal of a normalization is, to the degree possible, to remove the signal of societal changes from a loss dataset. 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.

Given there are no trends in the frequency or intensity of landfalling US hurricanes[17, 16] since 1900, we would expect an unbiased normalization to also have no trend. That is what is observed here (see Figure 1 a and b), indicating that the results of our normalization methods are not biased with respect to the climatological record of US hurricanes. Our results are also consistent with other research on this topic that used a previous iteration of the normalized hurricane damage dataset.[5,18] We should thus have confidence in the normalization methods and results.

Discussion

Landfalling hurricanes contribute significantly to disaster losses both in the CONUS and globally. Large loss years like 2017 remind us of what is 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 US, analogous to the Great Miami hurricane of 1926, could result in twice the total loss amounts of 2017, totaling well over $200 billion. Loss potentials are certainly higher than this for conceivable storms for which there is no historical analogue. The United States should expect much larger hurricane damage in its future, of this there is certainty.

As coastal communities continue to grow in wealth and population, loss potentials will continue to increase. The US has arguably experienced a long period of good fortune with respect to landfalling hurricanes, notably the 11-year stretch of no major CONUS hurricane landfalls which ended in 2017.[19] In future years we should continue to expect larger losses than observed in the recent past.[18] In addition, any increases in major hurricane frequency or intensity[17,20] would lead to even greater losses than those driven by socio-economic factors alone. Whatever the future brings, addressing vulnerability to hurricanes will remain a permanent priority for communities along the US Gulf and Atlantic coasts.

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