CONTINENTAL U.S. HURRICANE LANDFALL FREQUENCY AND ASSOCIATED DAMAGE

Observations and Future Risks

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While neither U.S. landfalling hurricane frequency nor intensity shows a significant trend since 1900, growth in coastal population and wealth have led to increasing hurricane-related damage along the U.S. coastline.

Among weather-related disasters, landfalling tropical cyclones (TCs) are a leading cause of economic damage in the continental United States (CONUS) and globally (www.aonbenfield.com/catastropheinsight). The very active and destructive 2017 Atlantic hurricane season resulted in an excess of $125 billion in damage in the CONUS (Aon Benfield 2018). Landfalling TCs also accounted for 8 of the top 10 costliest U.S. insured losses from natural disaster events according to Aon Benfield through 2017. CONUS landfalling hurricane damage has risen dramatically since the start of the twentieth century after adjusting historical losses for inflation (Pielke et al. 2008). However, because property and wealth exposed to hurricane impact accumulate in exposed coastal locations, inflation adjustments alone cannot entirely capture the increased potential for losses if those same storms were to impact at today's levels of development.

Several studies have examined trends in CONUS hurricane losses since 1900 by normalizing historical damage to modern-day values by adjusting for inflation, population, and various individual wealth metrics, as well as other factors (Pielke and Landsea 1998; Pielke et al. 2008; Schmidt et al. 2010; Nordhaus 2010; Bouwer and Wouter Botzen 2011; Neumayer and Barthel 2011; Barthel and Neumayer 2012). These studies have typically shown no significant trend in CONUS landfalling normalized damage once societal change is considered (Pielke et al. 2008). This result is expected, as landfalling CONUS hurricanes have not increased in frequency or intensity from 1900 through 2017 (as shown below), meaning that an unbiased normalized loss record

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would be expected to show the same (lack of) trend. Independent climate and economic data indicate that the primary source of the increase in damage caused by hurricanes in recent decades is due to increases in exposure along the U.S. East and Gulf Coasts (Pielke et al. 2008; Bouwer and Wouter Botzen 2011).

This manuscript has three primary themes. Following a discussion of data sources, we examine trends in both CONUS landfalling hurricanes and CONUS normalized damage from 1900 to 2017. We then reexamine the relationship between El Niño–Southern Oscillation (ENSO) and CONUS landfalling hurricanes (Bove et al. 1998; Klotzbach 2011) along with the relationship with associated normalized damage (Pielke and Landsea 1998). This section also updates the impact that the phase of the Atlantic multidecadal oscillation (AMO)[1] has on CONUS landfalling hurricanes and damage (Landsea et al. 1999). The manuscript then examines potential future CONUS landfalling hurricane damage through analyses of current and projected trends in coastal exposure and finishes with a discussion and conclusions.

DATA AND METHODOLOGY. CONUS hurricane landfall data are extracted from the Atlantic Oceanographic and Meteorological Laboratory's (AOML) website for the periods 1900–60 and 1983–2016 (www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html). For the period 1961–82 for which the National Hurricane Center's (NHC) "best track" hurricane database (HURDAT2) reanalysis project (Landsea and Franklin 2013) is not yet complete, we calculated hurricane landfall locations directly from hurricane tracks plotted from HURDAT2 with landfall intensities constrained to be the same Saffir–Simpson category as listed on the AOML website (www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html). Landfall locations and intensities for the 2017 Atlantic hurricane season were taken from NHC operational advisories. Multiple landfalls by an individual TC were counted separately as long as they traveled over the open ocean for at least 100 miles between their individual landfalls. In the case of 2017, all three CONUS hurricanes (Harvey, Irma, and Nate) made multiple landfalls, but the second landfall was less than 100 miles from the first one; consequently, each storm was counted once in this analysis.

Base damage adjusted for inflation and normalized damage estimates for historical CONUS landfalling TCs were taken from the ICAT Damage Estimator (www.icatdamageestimator.com/), which is based on Pielke et al. (2008). Damage values in the ICAT database through 2016 were adjusted to 2017 dollars using the methodology of Pielke et al. (2008). The 2017 damage total was taken from individual storm estimates determined by Aon Benfield (2018).

The definition of ENSO events used here is the August–October-averaged oceanic Niño index (ONI). The ONI is the official index used by the National Oceanic and Atmospheric Administration (NOAA) to define ENSO events. We calculate the ONI from the NOAA Extended Reconstructed SST, version 4 (Huang et al. 2015). The August–October ONI is defined to be the August–October average of Niño-3.4 (5°S–5°N, 170°–120°W; Bamston et al. 1997) sea surface temperature (SST) anomalies calculated from 30-yr centered base periods updated every 5 years. Any August–October-averaged ONI greater than 0.5°C was classified as El Niño, an anomaly less than −0.5°C was classified as La Niña, and all other seasons were classified as ENSO neutral. Using this metric, 29 years were classified as El Niño, 29 years were classified as La Niña, and the remaining 60 years were classified as ENSO neutral.

Our definition of the AMO-classified seasons used the same approach as in Klotzbach and Gray (2008), whereby 1900–25 and 1970–94 were classified as negative AMO periods, and 1926–69 and 1995–2017 were classified as positive AMO periods. There is considerable uncertainty as to whether the Atlantic has in recent years reverted to a negative AMO phase (Klotzbach et al. 2015), but given the very active 2017 Atlantic hurricane season that has just occurred, we prefer to extend the positive AMO phase through to the present, recognizing that such a classification remains provisional. However, the results displayed for the AMO throughout the manuscript would not show significant differences were the 2013–17 period to be reclassified as a negative AMO phase.[2]

Statistical significance for trends in both landfall frequency and normalized damage were evaluated using a *t* test. All statistical significance tests must

[1] We note that there remains vigorous scientific discussion as to the origins of the AMO, with some arguing that the Atlantic meridional overturning circulation is the primary driver (Grossmann and Klotzbach 2009; Yan et al. 2017), while others argue that sulfate aerosol (Booth et al. 2012) or stochastic midlatitude atmospheric forcing plays a greater role (Clement et al. 2015).

[2] For example, the average positive (negative) AMO number of CONUS landfalling hurricanes per year is 1.94 (1.53) when treating 2013–17 as a continuation of a positive AMO phase, while the average number is 2.00 (1.50) when treating 2013–17 as a new negative AMO phase.

exceed the 5% level to be considered significant. For the remainder of the document, significant and insignificant trends refer to those that exceeded and failed to exceed the 5% level, respectively. Each year was counted as an individual degree of freedom, since there is little autocorrelation between one year's Atlantic hurricane activity (correlation coefficient $r = 0.11$) or damage ($r = 0.22$) and that experienced the following year. Monte Carlo simulations were conducted to determine the differences in mean and median values between climate modes and CONUS hurricane landfalls and damage. A total of 1,000 random time series with the same number of years as the climate mode being investigated were drawn from the full 118-yr dataset. For example, in the cases of both El Niño and La Niña, 1,000 time series, each 29-yr time series of the full 118-yr time series was drawn. If the observed value was either greater than the 95th percentile or less than the 5th percentile of the randomly drawn values, then the difference from the mean value of all seasons was said to be significant at the 5% level. However, such simple statistics should be interpreted with caution, as climate variables may or may not exhibit stationarity, and the textbook notion of observations serving as a sample from a population may not accurately represent out-of-sample climate processes (Saunders et al. 2017).

TRENDS IN CONUS LANDFALLING HURRICANES AND NORMALIZED HURRICANE DAMAGE. We begin by examining the long-term trend in CONUS landfalling hurricanes and damage since the start of the twentieth century. Inflation-adjusted CONUS hurricane losses show a significant increasing trend since 1900 (Fig. 1). However, there is an insignificant trend in CONUS landfalling hurricanes from 1900 to 2017 (Fig. 2a). When we examine only hurricanes that made landfall at major hurricane strength (Saffir–Simpson categories 3–5) (1-min sustained winds ≥96 kt; 1 kt = 0.51 m s^{-1}), which are responsible for greater than 80% of all normalized tropical cyclone–related damage (Pielke and Landsea 1998), we find a similar insignificant trend (Fig. 2b). We therefore conclude that the large increase in observed hurricane-associated inflation-adjusted CONUS damage (Pielke et al. 2008) is primarily due to increases in exposure as opposed to increasing frequency or intensity of hurricanes making CONUS landfall.

We next employ the same methodology used in Pielke et al. (2008) to examine trends in CONUS hurricane damage since 1900 normalized to 2017 values, noting that there is currently an effort underway by Pielke and colleagues to comprehensively update Pielke et al. (2008). The long-term normalized hurricane damage record also shows no significant trend. One of the most notable items is the extreme year-to-year variability in the time series (Fig. 3). For example, the most damaging normalized CONUS landfalling hurricane is the Miami (Florida) hurricane of 1926, which is estimated to result in >$210 billion in damage were it to occur in 2017. If the normalization is unbiased, then no significant trend in CONUS normalized hurricane damage since 1900

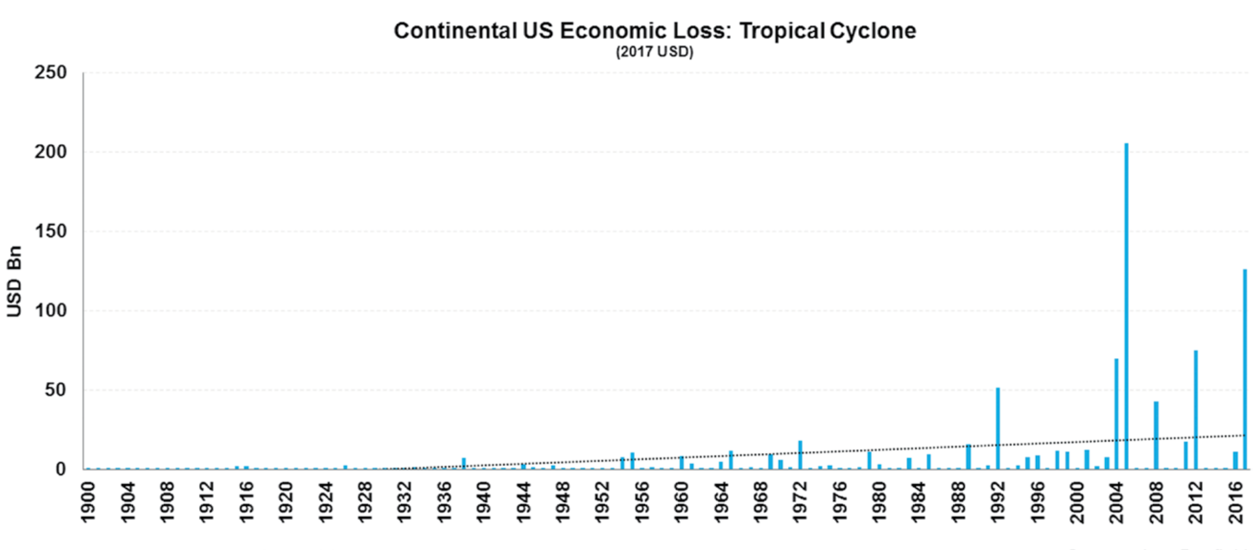

Fig. 1. CONUS total inflation-adjusted economic losses from TC landfalls (1900–2017). The dotted line represents the linear trend over the period. The *p* value for the linear trend is <0.01, indicating that the trend is significant.

is expected, which is consistent with no significant trend in landfalling hurricanes or major hurricanes.

The fact that both climate trends and normalization trends show no significant increases or decreases provides an indication that the normalization methodology is, in aggregate, unbiased.[3] In other words, the adjustments to economic data result in a time series with statistical properties that correspond with those of the climate time series, as would be expected from an unbiased normalization. Climate data provide an independent check on the normalization time series.

RELATIONSHIPS BETWEEN LARGE-SCALE CLIMATE MODES AND CONUS LANDFALLING TROPICAL CYCLONE FREQUENCY AND DAMAGE.

ENSO. We next examine how ENSO is related to the frequency and intensity of CONUS landfalling hurricanes. About 1.75 times as many hurricanes make CONUS landfall in La Niña seasons compared with El Niño seasons (Fig. 4a), although Jagger and Elsner (2006) found that the strongest storms making CONUS landfall occur in El Niño seasons. We find similar ENSO-related modulation in both Florida and East Coast landfalls as well as Gulf Coast landfalls. The La Niña-to-El Niño ratio is slightly larger for major hurricane landfalls than for all hurricane landfalls (Fig. 4b), which is also in keeping with prior research (Bove et al. 1998; Klotzbach 2011), although we note that the increase in hurricane landfalls observed in La Niña seasons from that observed in all seasons does not meet the 5% significance level. The stronger modulation of stronger hurricane activity is in keeping with physical reasoning, since more conducive environments are necessary to sustain major hurricane intensity as opposed to category 1–2 hurricane intensity. Gray (1984) documented that vertical wind shear in the Caribbean and farther east into the tropical Atlantic increased in El Niño seasons, creating conditions that were detrimental for TC formation and intensification. Tang and Neelin (2004) showed that El Niño also increases upper-tropospheric temperatures in the tropical Atlantic, thereby stabilizing the air column and suppressing deep

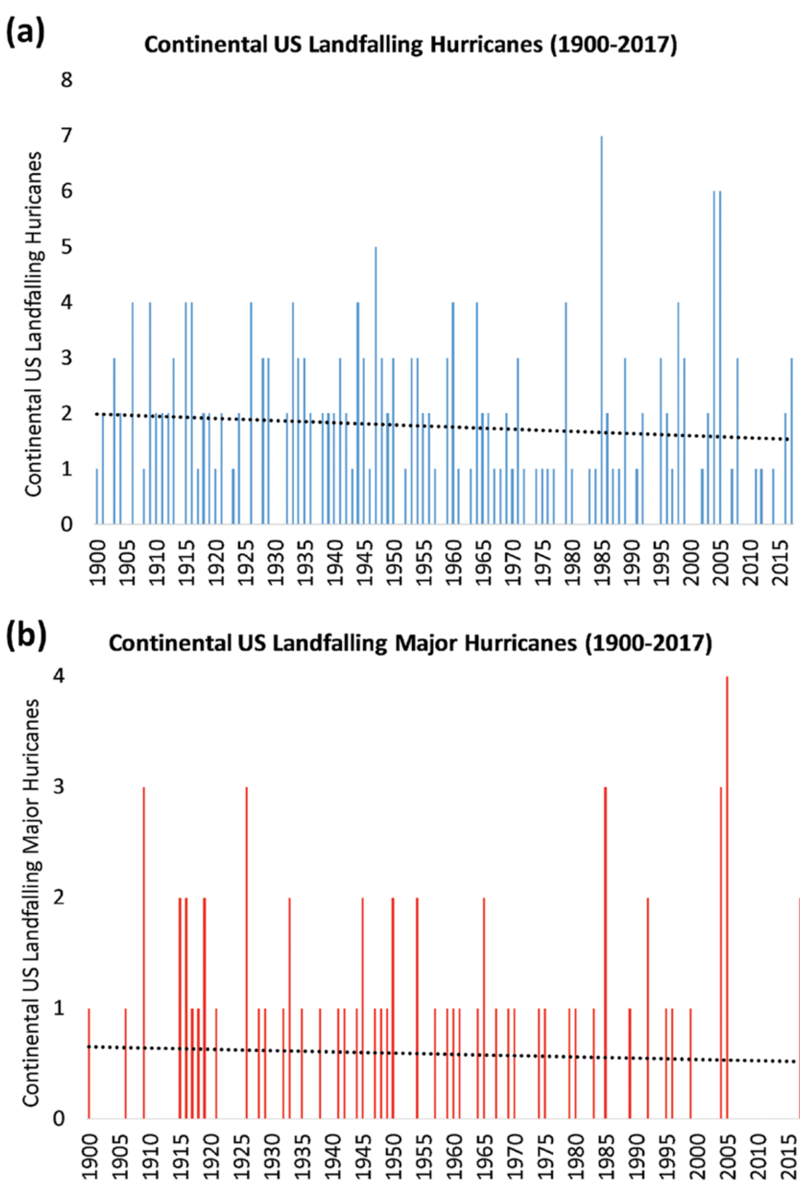

Fig. 2. (a) CONUS landfalling hurricanes by year from 1900 to 2017, and (b) CONUS landfalling major hurricanes by year from 1900 to 2017. The dotted lines represent linear trends over the period. The *p* values for the linear trends are 0.33 for landfalling hurricanes and 0.61 for landfalling major hurricanes, indicating that neither of these trends are significant.

[3] It is of course possible that there are numerous biases that are insignificant or cancel out each other.

convection. El Niño has also been shown to be associated with a weaker subtropical high, promoting the recurvature of TCs and reducing the frequency of CONUS hurricane landfall (Colbert and Soden 2012).

CONUS normalized hurricane damage shows a large increase in La Niña seasons compared with El Niño seasons, with neutral ENSO conditions having larger median damage than El Niño seasons but less than La Niña seasons (Fig. 5a). Normalized damage in El Niño seasons is significantly less than the median damage incurred in all seasons, while the observed median damage in La Niña seasons is significantly more than the median damage incurred in all seasons. The reduction in normalized damage in El Niño seasons and the increase in normalized damage in La Niña seasons are significant for Florida and the East Coast. The significance level of the reduction for Gulf Coast damage in El Niño is unable to be determined precisely, as ~25% of all Monte Carlo simulations for Gulf Coast damage returned a median damage of $0. Note that the combined Florida and East Coast and Gulf Coast median damage values do not sum to the CONUS total in Fig. 5, since median values are being plotted (as opposed to mean values).

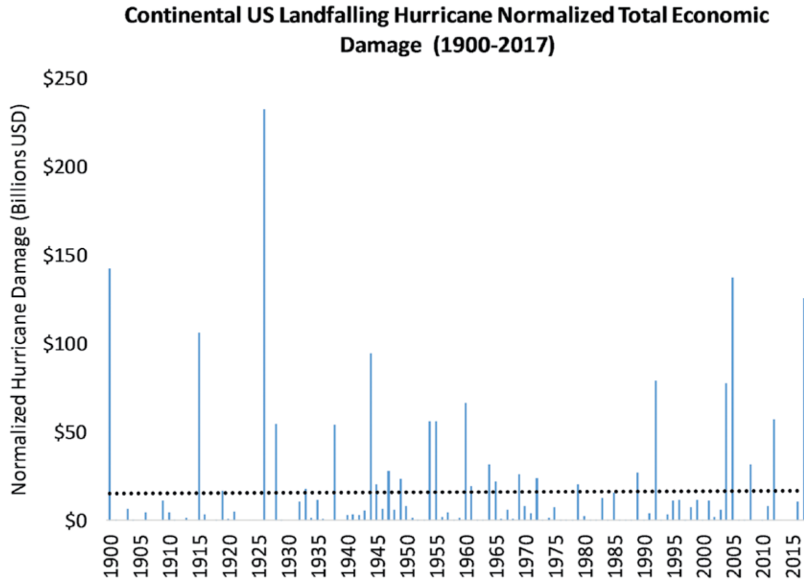

Fig. 3. Normalized CONUS landfalling hurricane damage from 1900 to 2017. The dotted line represents the linear trend in CONUS hurricane normalized damage during the period of record. The *p* value for the linear trend is 0.86, indicating that the trend is not significant.

Since 1900, a total of 37 years have had over $10 billion in normalized damage. Only four of those years were classified as El Niño seasons: 1965, 1969, 1972, and 2004. Two of these seasons (1969 and 2004) would qualify as weak El Niño seasons using the current operational definition of NOAA for ENSO strength, as their ONI values were <1°C. Both 1965 and 1972 would qualify as strong El Niño seasons. As would be expected given the volatile nature of the normalized damage time series, the standard deviation of the damage is much larger than the median value (Fig. 5b). These conclusions are consistent with those of Pielke and Landsea (1999) using 21 years of additional data.

AMO. Our focus now turns to the AMO (Goldenberg et al. 2001) and its relationship with CONUS hurricane landfall frequency. Klotzbach and Gray (2008) demonstrated a significant modulation in both basinwide and Florida and East Coast landfalling hurricane frequency. We find similar results, with a significant increase in both CONUS and Florida and East Coast landfalling hurricanes in positive AMO phases (Fig. 6a) and a significant decrease in negative AMO phases from the average of all hurricane seasons. Little signal is observed for hurricanes making landfall along the Gulf Coast. This is likely due to different formation mechanisms for Florida and the East Coast versus Gulf Coast systems. Hurricanes making landfall in Florida and along the East Coast often form from Cape Verde hurricanes or develop in the Caribbean, which are areas where the AMO plays a significant role (Klotzbach and Gray 2008) (Fig. 7). Hurricanes making landfall along the Gulf Coast can form from these mechanisms but can also form in either the Bay of Campeche or in the Gulf of Mexico. TCs forming in the Gulf of Mexico or in the subtropical Atlantic are not as significantly modulated by the AMO (Goldenberg et al. 2001).

When examining CONUS major hurricane landfalls, we find a significant modulation between positive and negative AMO phases for Florida and East Coast landfalls, while we continue to find very little difference for the Gulf Coast (Fig. 6b). The difference in CONUS landfalls between AMO phases also is not statistically significant. Median U.S. normalized hurricane damage shows statistically significant modulations by the AMO, with ~9 times as much median damage in a positive AMO season compared with a negative AMO season (Fig. 8a). The difference is also significant for Florida and the East Coast, with over $800 million in median damage for Florida and the East Coast in a positive AMO compared with $69 million in a negative AMO. While the differences in median damage are considerable for the Gulf Coast as well ($105 million for positive AMO vs $4 million for negative AMO), these differences are not statistically significant. As was the case with ENSO, the standard deviation of year-to-year normalized damage by AMO phase is quite large, indicating the high levels of volatility in the normalized damage time series (Fig. 8b).

BACKGROUND FACTORS FOR CONUS LANDFALLING HURRICANE DAMAGE.

Population and housing. With the historical hurricane landfall and financial cost trends established, the focus can now shift toward the future and what trends may be experienced in the decades to come given observed socioeconomic and demographic shifts. Of particular interest to many sectors—including local, state, and federal government agencies, as well as the insurance industry—is the continued pattern of population increases along coasts, and in turn greater exposures to hurricanes.

Decadal data from the U.S. Census Bureau from 1900 to 2010 show that the population of the United States grew from 132 million to 309 million, equal to an annual growth rate of 2.8%. However, when breaking the country into six distinct regions (Atlantic, Gulf Coast, noncoastal South, Midwest, West, coastal West) (Fig. 9a), there are vastly different annual growth rates and total counts of residents since 1940 across each of these regions (Fig. 9b). This is particularly true during the past ~50 years. Partial decadal census data from 2010 to 2016 show a continuation of these trends, with the U.S. population now estimated at 323 million.

From 1970 to 2016, regional annual rates of growth were as follows:

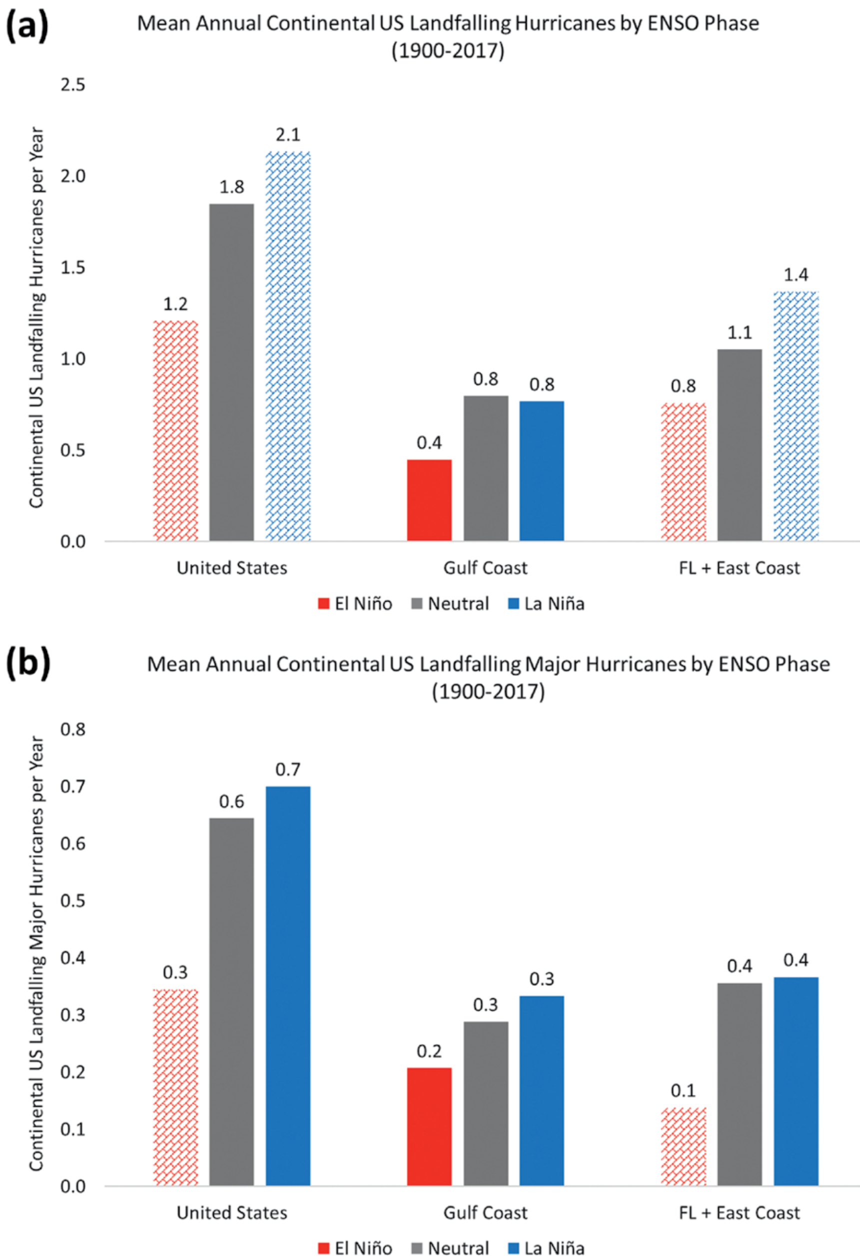

Fig. 4. (a) Mean annual CONUS landfalling hurricanes by ENSO phase from 1900 to 2017, and (b) mean annual CONUS landfalling major hurricanes by ENSO phase from 1900 to 2017. Differences that are significant at the 5% level are plotted with diagonal hatching.

West, 3.9%; Gulf Coast, 2.7%; coastal West, 2.1%; noncoastal South, 1.2%; Atlantic, 0.8%; and Midwest, 0.4%. The national growth rate was 1.3%. When breaking down the data into raw totals, during the 47 years from 1970 to 2016, the actual population increase was as follows: Gulf Coast, +33.7 million; Atlantic, +26.5 million; coastal West, +25.1 million; West, +16.7 million; Midwest, +11.4 million; and noncoastal South, +6.4 million. This indicates that over 60 million more people are now living in states directly exposed to TC landfall than in 1970.

In the years since the last official decadal census in 2010, an even more pronounced trend of coastal growth has occurred, as some of the greatest rates of population growth were found in particularly vulnerable hurricane landfall locations. Of the top 20 fastest-growing counties from 2010 to 2016, 13 were in hurricane-prone states, including 12 in either Florida or Texas (Table 1). While much of the growth is occurring in ocean-bordering counties, which are most prone to high-impact damage at the point of TC landfall, a significant portion of growth is found in areas farther inland. This means that there is an increased risk of exposed inland population and property to be impacted by hurricanes in their weakening or posttropical phases. Recent examples such as Hurricane Irma (2017), Hurricane Sandy (2012), and Hurricane Ike (2008) highlighted damage from high winds, prolonged rainfall and flooding, and severe convective storms that were recorded well inland from the initial landfall location.

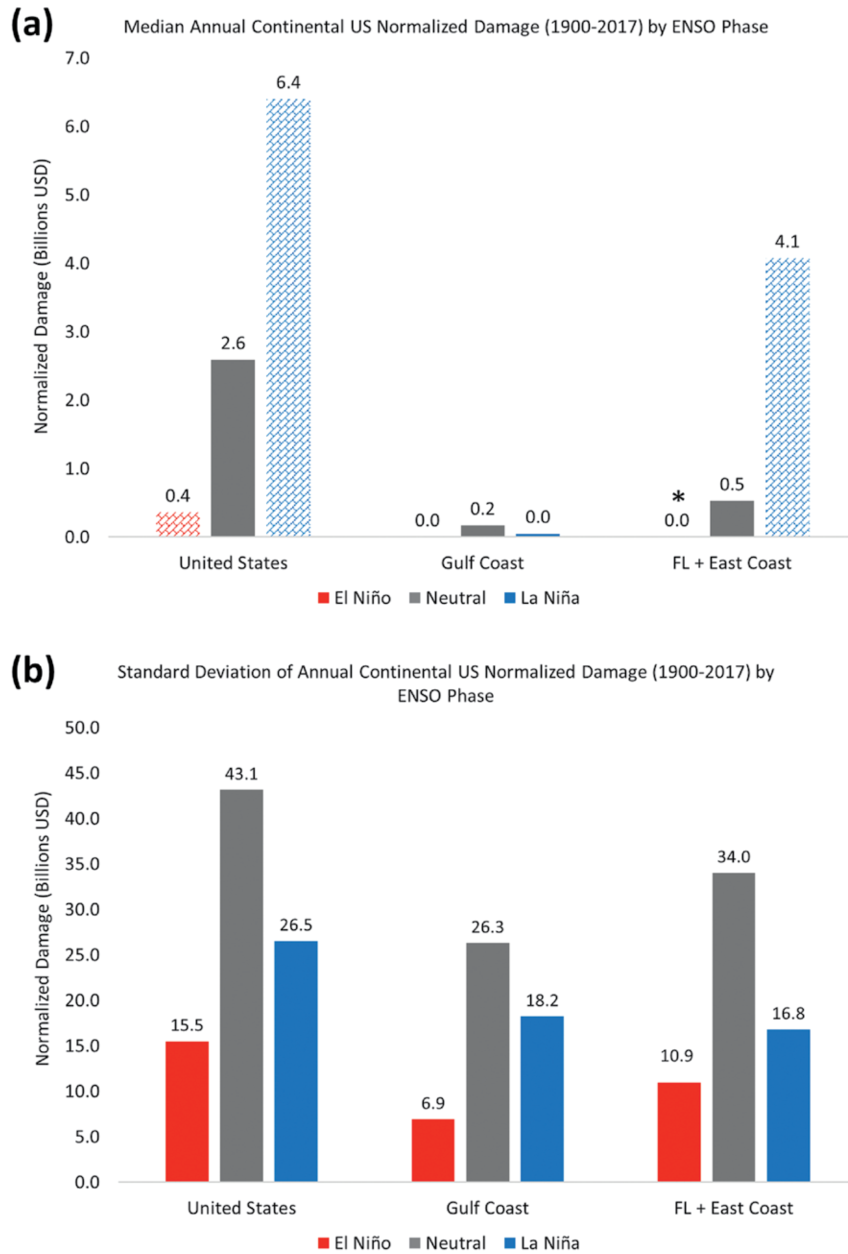

Fig. 5. (a) Median and (b) standard deviation of annual CONUS normalized hurricane damage by ENSO phase. Differences in the median that are significant at the 5% level are plotted with diagonal hatching. The asterisk in (a) above the El Niño bar in the Florida and East Coast column indicates that this difference is significant at the 5% level (the hatching would not display since the value is so small).

Unsurprisingly, the growth in population has directly correlated to an accelerated rate of exposure[4] increase in these same areas. Further analysis using housing count data from the U.S. Census Bureau

[4] For this exercise, an *exposure* is defined as any public, residential, and commercial building or other physical structure, as well as the wealth that it contains.

shows that annual national housing units grew from 37 million (1940; first year of data collection) to 136 million (2016). This corresponds to a national average annual growth rate of 3.5% during the 77-yr period.

Similar to the trends seen with population, there has been a wide spread of housing unit growth rate and aggregated count among the six identified regions since 1970 (Fig. 10). The regional annual rate of housing count growth was as follows: West, 5.5%; Gulf Coast, 3.8%; coastal West, 2.4%; noncoastal South, 2.2%; Atlantic 1.6%; and Midwest, 1.3%. The national rate during this time was 2.1%. The higher rate of growth for housing count versus population suggests that more people have bought multiple properties during this time, increasing the volume and scope of exposure. In addition, U.S. Census Bureau data show a slow decline in the average number of people per household from 3.14 in 1970 to 2.53 in 2016, providing another possible explanation for the increase in housing units. Further studies have shown that household composition and structure has also continued to evolve over time. For instance, the number of households identified as "family" in U.S. Census Bureau surveys conducted between 1940 and 2010 has shown a decrease from 90% to 66%, while "nonfamily" households increased from 10% to 34% (Jacobson et al. 2012).

When breaking down the data into raw totals, from 1970 to 2016, the actual regional housing unit increase was as follows: Atlantic, +18.1 million; Gulf Coast, +16.3 million; Midwest, +11.0 million; coastal West, +9.9 million; West, +7.7 million; and noncoastal South, +4.0 million. Most strikingly, the two most vulnerable regions for hurricane landfall—Atlantic and Gulf Coast—combined for over 34 million new homes, or 51% of all new housing units during this time.

One final metric regarding housing units examined here is the actual size of single-family homes. Since the U.S. Census Bureau first started collecting data on single-family home size, the average home has grown from 1,660 square feet (1973) to 2,640 square feet (2016) (1 ft^2 ≈ 0.09 m^2), or by

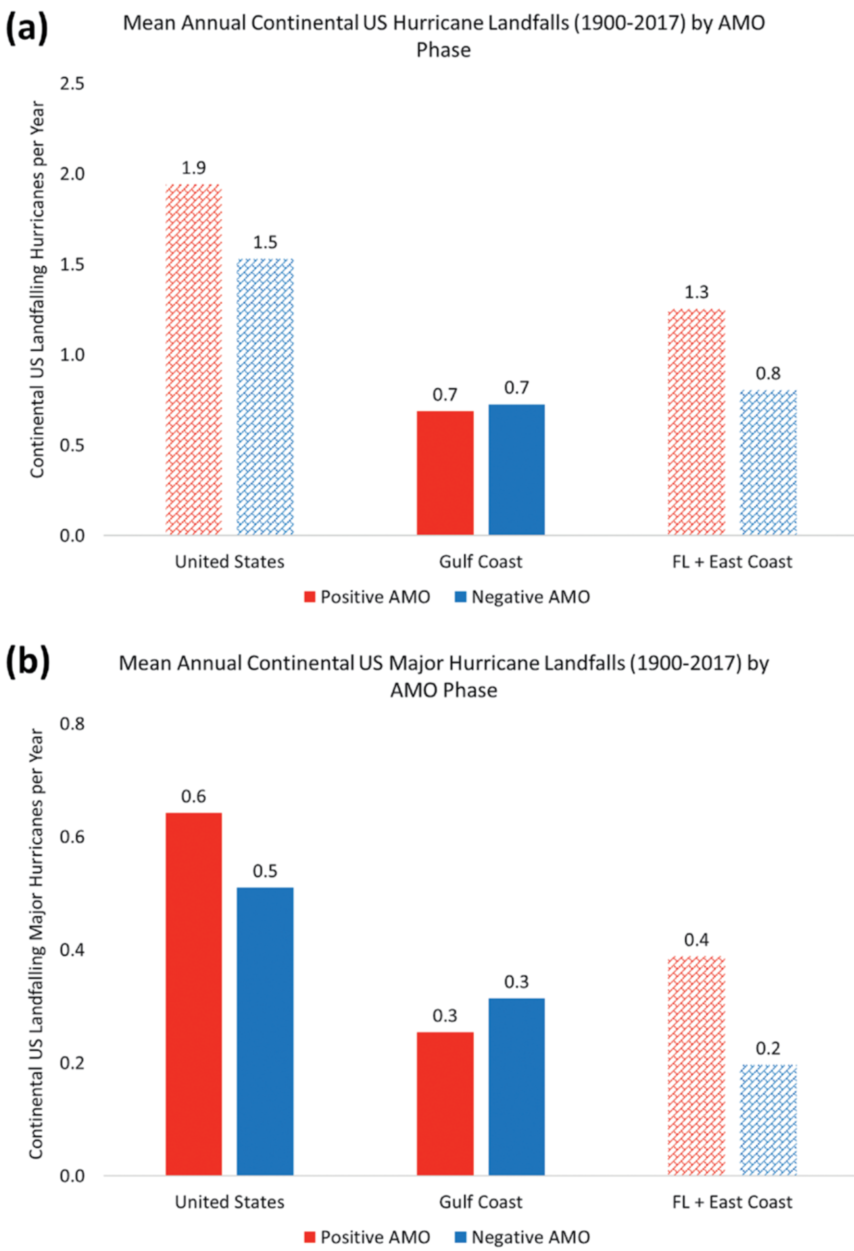

Fig. 6. (a) Mean annual CONUS landfalling hurricanes by AMO phase from 1900 to 2017, and (b) mean annual CONUS landfalling major hurricanes by AMO phase from 1900 to 2017. Differences that are significant at the 5% level are plotted with diagonal hatching.

59%. The two regions, as defined by the U.S. Census Bureau, that have noted the greatest growth in size are the Northeast and South (Fig. 11). Larger homes often require greater cost and more material to build. When a hurricane makes landfall, the combined costs to rebuild or fix a home—plus higher costs often associated with demand surge at construction and home retail sectors—often enhance the final damage bill beyond a home's original value.

An important point regarding housing unit exposure and financial losses in TC-prone areas is the quality of construction and efficiency of building codes. Damage assessments conducted by one of this paper's authors (S. Bowen) following Hurricanes Harvey, Irma, and Maria in 2017 found that structures either built to modernized code and/or with proper elevation in areas identified in the most current Federal Emergency Management Agency (FEMA) flood zones often reported minimal damage. In Texas, the worst flood damage from Harvey often occurred to older-built structures constructed at ground level; while in Florida, structures built prior to current stringent codes developed after Hurricane Andrew (1992) performed much more poorly in areas where Irma's radius of maximum winds occurred. Many other studies have delved more deeply into the positive impact of improved building codes over time with respect to hurricane-force

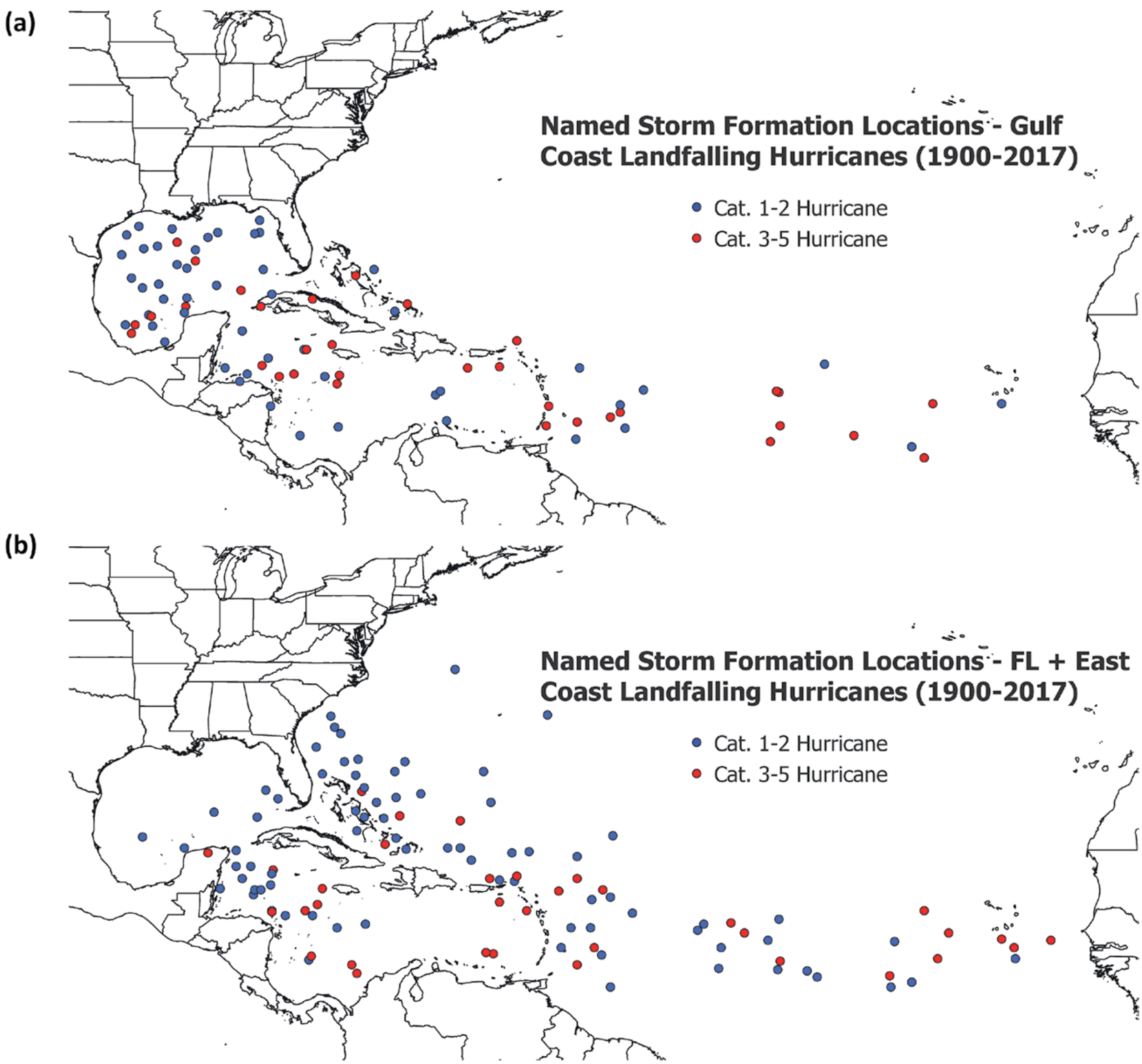

Fig. 7. (a) Named-storm formation location for all Gulf Coast landfalling hurricanes from 1900 to 2017, and (b) named-storm formation location for all Florida and East Coast landfalling hurricanes from 1900 to 2017.

winds, notably in Florida (Done et al. 2017). Simply put, when homes and structures are built properly to recommended modernized guidelines in TC-prone or flood-risk areas, the magnitude of damage can be reduced. Future work with academia and private sector groups will prove critical to continued improvements in future building codes and their enforcement. One particular private sector group conducting such studies, the Insurance Institute for Business and Home Safety (IBHS), is an insurance industry organization that focuses entirely on independent scientific research and whose mission statement includes to "identify and promote the most effective ways to strengthen homes, businesses and communities against natural disasters and other causes of loss" (https://disastersafety.org/about/).[5]

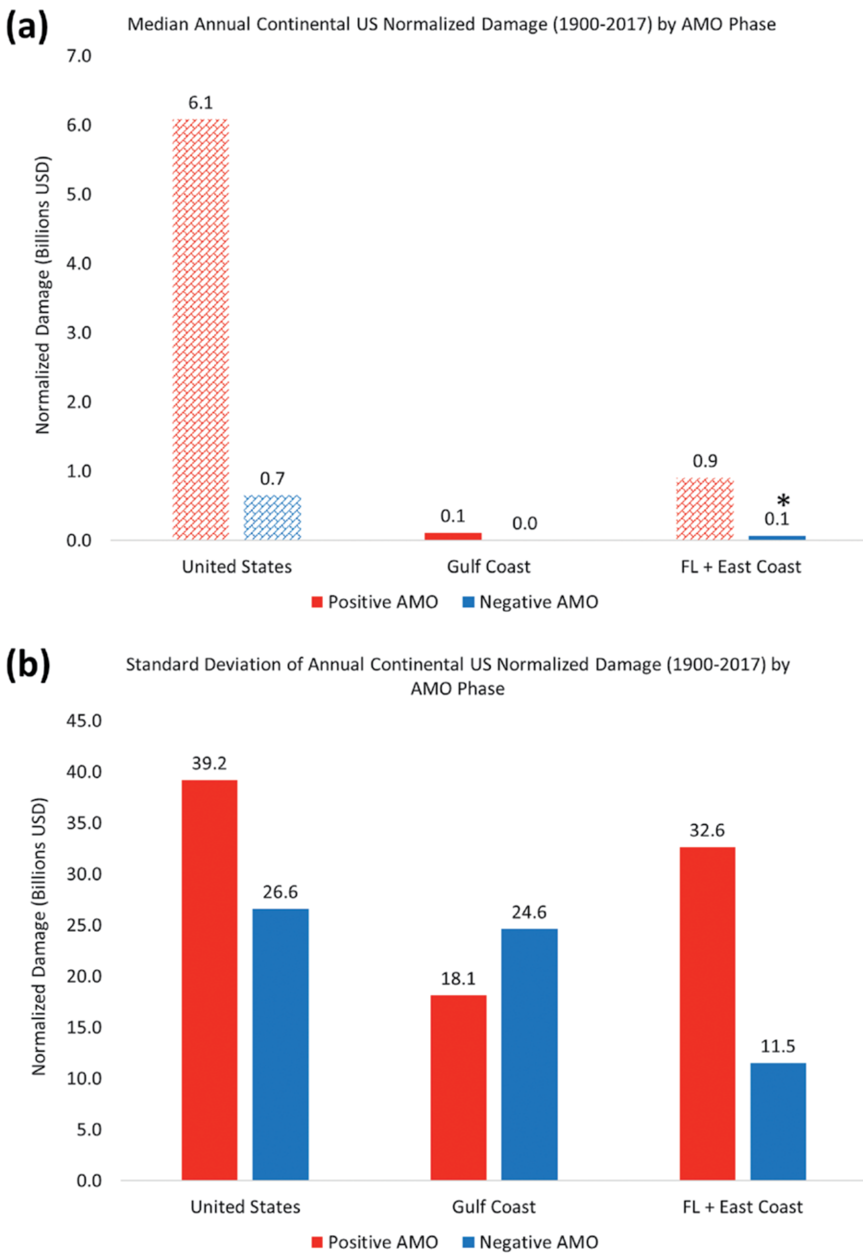

Fig. 8. (a) Median and (b) standard deviation of annual CONUS normalized hurricane damage by AMO phase. Differences that are significant at the 5% level are plotted with diagonal hatching. The asterisk in (a) above the negative AMO bar in the Florida and East Coast column indicates that this difference is significant at the 5% level (the hatching would not display since the value is so small).

Wealth. Another data metric highlighting the expectation of greater future TC-related catastrophe losses is the general increase in wealth. Using available data from the U.S. Bureau of Economic Analysis (BEA; 1980–2016), nationwide gross domestic product (GDP) has trended upward at an annual average of 2.8%. Using the "real" inflation-adjusted BEA dataset, with losses indexed/chained to 2009 dollars, the BEA cites GDP growth from $6.1 trillion (1987) to $16.3 trillion (2016). Index/chained datasets help provide a more accurate picture of the economy and better capture changes in spending patterns and prices (Landefeld et al. 2003). Similar to population count and exposure growth, the increases in GDP are more pronounced in certain states and regions of the country. For this study we are particularly interested in the performance of GDP

[5] IBHS, headquartered in Tampa, Florida, has an entire research center in Richburg, South Carolina, dedicated to testing residential and commercial construction materials, practices, and systems.

growth since the start of the most recent positive AMO phase in 1995 (Fig. 12).

The breakout of regional growth during the 22-yr time frame included the coastal West at +3.3%, the Gulf Coast at +3.2%, the West at +3.1%, the Atlantic at +2.5%, noncoastal South at +2.5%, and the Midwest at +2.0%. The national average was 2.7%. When focusing specifically on three states historically prone to landfall events, we find that the annual rate of growth is higher than the U.S. average: Texas, +4.0%; North Carolina, +2.9%; and Florida, 2.8%. This further supports the claim that the accelerated economic growth in these states would additionally lead to more expensive damage and rebuilding costs. The population, housing, and wealth dataset analyses put into strong context the current and future TC risk and are essential data points for the many public and private agencies that are responsible for warning, protecting, and assisting in recovery.

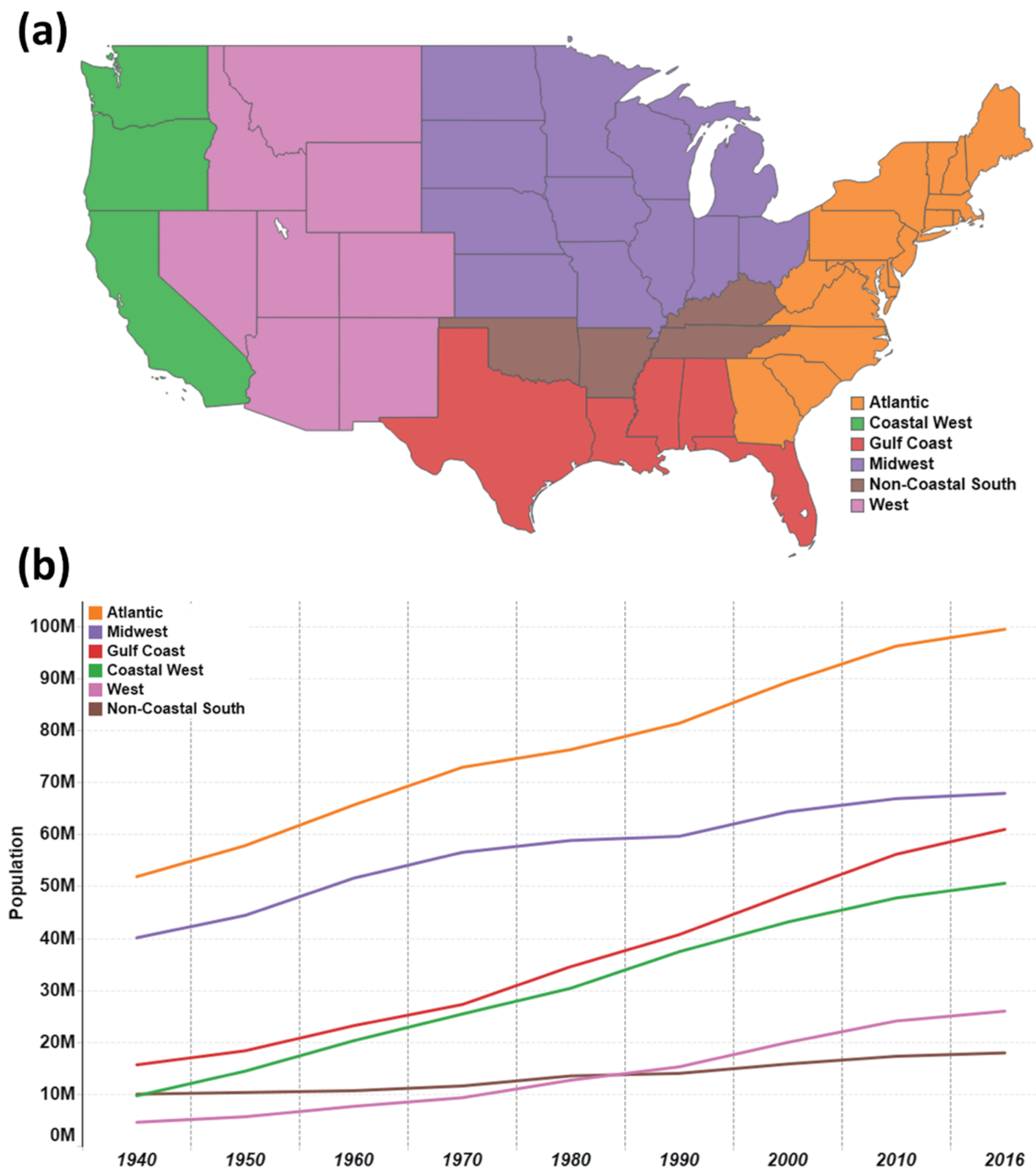

Fig. 9. (a) CONUS map showing six regions as defined in this manuscript and (b) CONUS decadal population by region (1940–2016).

Table 1. Top 20 U.S. counties in terms of population growth from 2010 to 2016. Boldface counties are in states that are prone to hurricane impacts.

Rank	County	State	2010	2011	2012	2013	2014	2015	2016	Absolute change	Relative change (%)
1	**Harris**	Texas	4,108,308	4,179,717	4,259,206	4,346,883	4,441,928	4,533,341	4,589,928	481,620	10.35
2	Maricopa	Arizona	3,825,616	3,870,806	3,942,959	4,011,219	4,083,931	4,161,637	4,242,997	417,381	8.78
3	Los Angeles	California	9,825,473	9,888,476	9,953,555	10,015,436	10,066,615	10,112,255	10,137,915	312,442	2.92
4	San Diego	California	3,104,346	3,140,692	3,181,513	3,218,419	3,258,856	3,290,245	3,317,749	213,403	5.99
5	King	Washington	1,937,786	1,972,444	2,008,763	2,045,874	2,078,886	2,114,256	2,149,970	212,184	9.11
6	**Bexar**	Texas	1,723,006	1,755,342	1,788,530	1,822,056	1,858,749	1,895,482	1,928,680	205,674	10.01
7	**Miami-Dade**	Florida	2,507,362	2,573,361	2,607,979	2,641,273	2,667,299	2,692,593	2,712,945	205,583	7.39
8	**Dallas**	Texas	2,372,450	2,407,305	2,452,421	2,479,810	2,512,281	2,545,775	2,574,984	202,534	7.31
9	Clark	Nevada	1,953,216	1,966,295	1,995,815	2,025,096	2,064,899	2,109,289	2,155,664	202,448	7.99
10	**Tarrant**	Texas	1,817,687	1,848,347	1,882,352	1,912,501	1,944,512	1,981,410	2,016,872	199,185	9.01
11	Riverside	California	2,202,226	2,236,146	2,264,919	2,291,452	2,322,455	2,352,892	2,387,741	185,515	6.84
12	**Travis**	Texas	1,030,569	1,061,858	1,096,122	1,120,948	1,149,668	1,174,818	1,199,323	168,754	14.00
13	**Orange**	Florida	1,148,716	1,169,806	1,202,048	1,225,366	1,253,631	1,284,864	1,314,367	165,651	11.85
14	**Broward**	Florida	1,753,125	1,787,889	1,816,552	1,840,051	1,865,385	1,887,281	1,909,632	156,507	7.65
15	Orange	California	3,017,647	3,053,884	3,084,935	3,112,576	3,134,438	3,156,573	3,172,532	154,885	4.60
16	**Collin**	Texas	788,741	814,607	837,229	858,098	885,175	913,079	939,585	150,844	15.76
17	**Fort Bend**	Texas	590,433	606,962	625,796	653,252	684,646	713,849	741,237	150,804	20.90
18	**Hillsborough**	Florida	1,233,839	1,271,205	1,281,677	1,293,189	1,317,116	1,347,077	1,376,238	142,399	9.18
19	**Wake**	North Carolina	906,949	929,208	952,296	973,920	997,897	1,021,974	1,046,791	139,842	12.68
20	**Denton**	Texas	666,736	685,376	707,475	728,282	752,820	778,491	806,180	139,444	16.76

Insurance. Beyond analyzing the overall economic cost of TCs in the United States, another important measure that helps explain the growth of exposure, population, and wealth are the claims paid by public and private insurance entities. Insured losses are the portion of economic damage that is covered by insurance. A public insured loss is identified as a claim paid via the Federal Emergency Management Agency's National Flood Insurance Program (NFIP) or the U.S. Department of Agriculture's Risk Management Agency crop insurance program. Private insured losses are claims paid directly by corporate for-profit entities.

Losses resulting from TC damage did not become significant for the insurance industry in the United States until the 1950s (Fig. 13). This coincided with the first introduction of homeowners insurance in September 1950 by the Insurance Company of North America in which a singular policy would protect against "loss caused by fire, theft, lightning, wind, explosion, hail, riot, vehicle damage, vandalism and smoke" (*Los Angeles Times*, 31 October 1954). Hurricanes Carol and Hazel—both of which led to notable damage across the Northeast and mid-Atlantic—combined to cause $258 million in nominal insurance payouts in 1954 ($2.3 billion in 2017 when adjusted for inflation). TC landfalls often drive growth in property and casualty insurance take-up rates, defined as the percentage of eligible people or properties in which active insurance policies are held and premiums as homeowners and businesses recognize the need to protect themselves should disaster strike.

In the next several decades, numerous significant hurricane landfalls, such as Betsy (1965), Hugo (1989), Andrew (1992), and the 2004 and 2005 hurricane seasons, all led to greater public and private insurance industry response to the peril. Hurricane Betsy caused extensive damage in Louisiana and was thought to be the first nominal billion-dollar

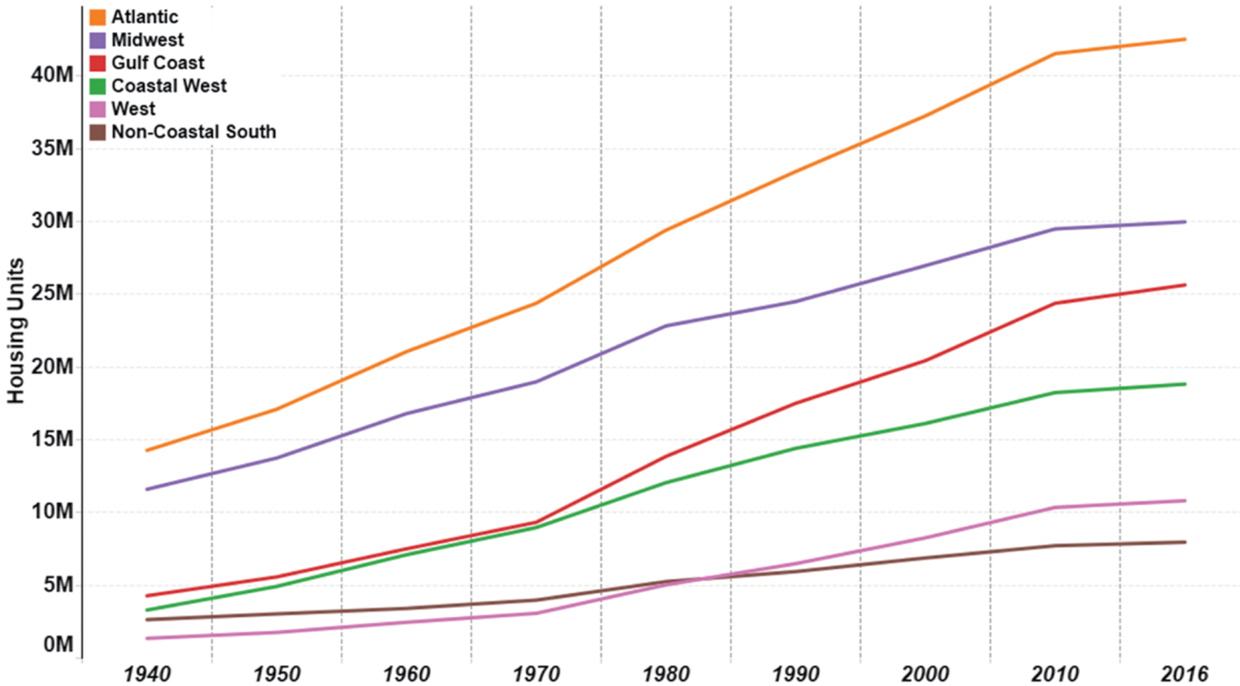

Fig. 10. CONUS decadal housing unit count (in millions) by region (1940–2016).

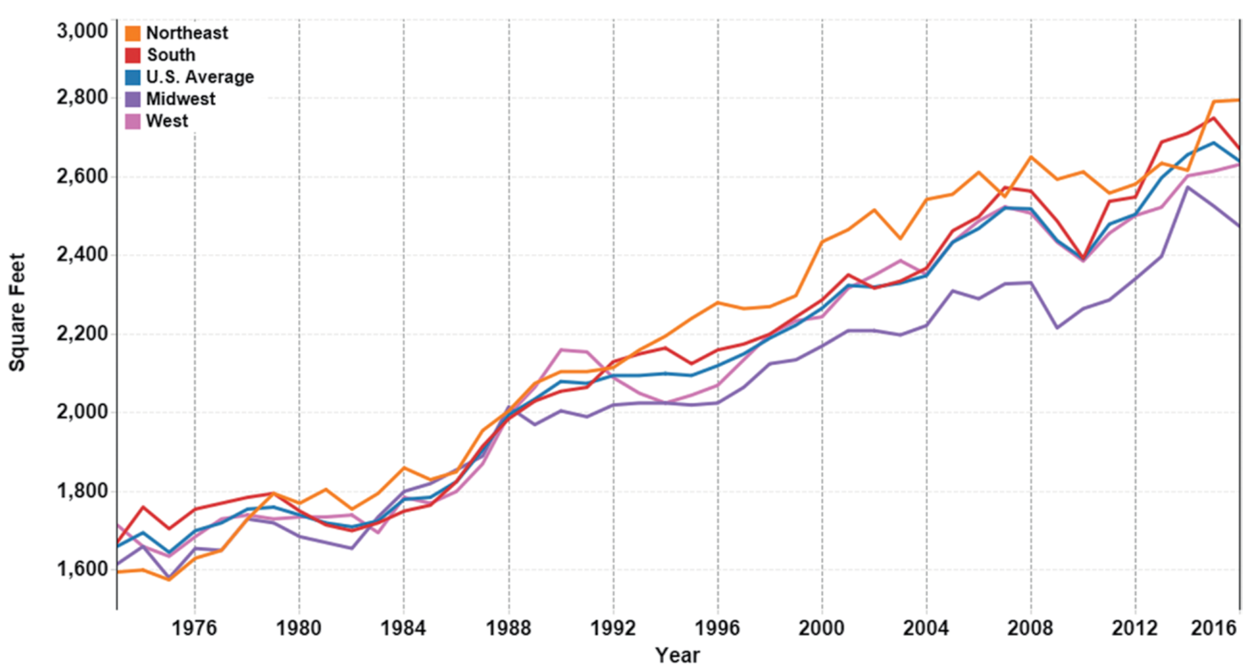

Fig. 11. Average size of a CONUS single-family home by region as defined by the U.S. Census Bureau (1973–2016).

TC event in the United States— earning the name "Billion-Dollar Betsy" (Sugg 1966). Much of the damage was caused by coastal and inland flood inundation. At the time no defined flood insurance program existed, and since private insurers viewed floods as too risky, the federal government established the NFIP to provide an alternative to disaster assistance to meet the escalating costs of home, building, and content repairs (FEMA 2002). It was often considered by the public that wind was the primary threat from hurricanes, but Betsy helped change the narrative. Andrew, in particular, changed how the private insurance industry market viewed hurricane risk, especially in the state of Florida. Some of the profound changes that Andrew made for the insurance industry included more carefully assessed and managed coastal exposure, greater use of global reinsurance capital (*reinsurance* can be simply defined as insurance for insurance companies), major growth in the sophistication and usage of catastrophe modeling, and increased focus on modernized and enforced building codes (McChristian 2012).

At the end of 2016, there were roughly 5.1 million NFIP active policies in place in the United States, the fewest number since 2005. By the start of the 2017 Atlantic hurricane season, that total had dipped slightly below 5.0 million. Historically, there was a gradual rise in policies from the late 1970s to the late 2000s following notable hurricane landfalls (Fig. 14a). With an extended stretch of lessened hurricane landfalls [and no major (category 3+) hurricane landfalls in more than a decade] (Hall and Hereid 2015), there was a steady drop in national NFIP coverage as well as total insured value (TIV) (Fig. 14b) prior to the 2017 season. State-level data from FEMA indicates that the number of NFIP policies often increase following major events. Following the 2004 and 2005 seasons, the number of NFIP "earned contract counts" in Florida increased from 1.28 million in 2004 to a peak of 1.51 million in 2007—that number dropped to under 1.25 million by 2016.

With costly coastal exposures continuing to increase along the Gulf Coast and East Coast, this enhances the risk of greater spikes in catastrophe loss on an economic basis when the next hurricanes come ashore. For NFIP, flood payout spikes coincide with hurricane landfalls (Fig. 14c).

With more housing units and fewer NFIP policies in place, this leads to the likelihood of a greater portion of the economic cost not being covered by insurance during future events. A large portion of hurricane damage is often flood related, and in the case of Hurricane Harvey (2017), only 30% of that storm's impacts—estimated $100 billion economic loss—were covered by insurance given high coastal and inland flood inundation throughout southeast Texas (Aon Benfield 2018). Less than 20% of homeowners in Harris County in Texas had active NFIP policies in place at the time of landfall, and given Harvey's remarkable flood footprint, much of the damage occurred in areas outside of the demarcated 100- or 500-yr flood zones.[6] To put recent NFIP trends into

[6] To view address-level FEMA flood-zone mapping, visit the FEMA Flood Map Service Center website (https://msc.fema.gov/portal/search).

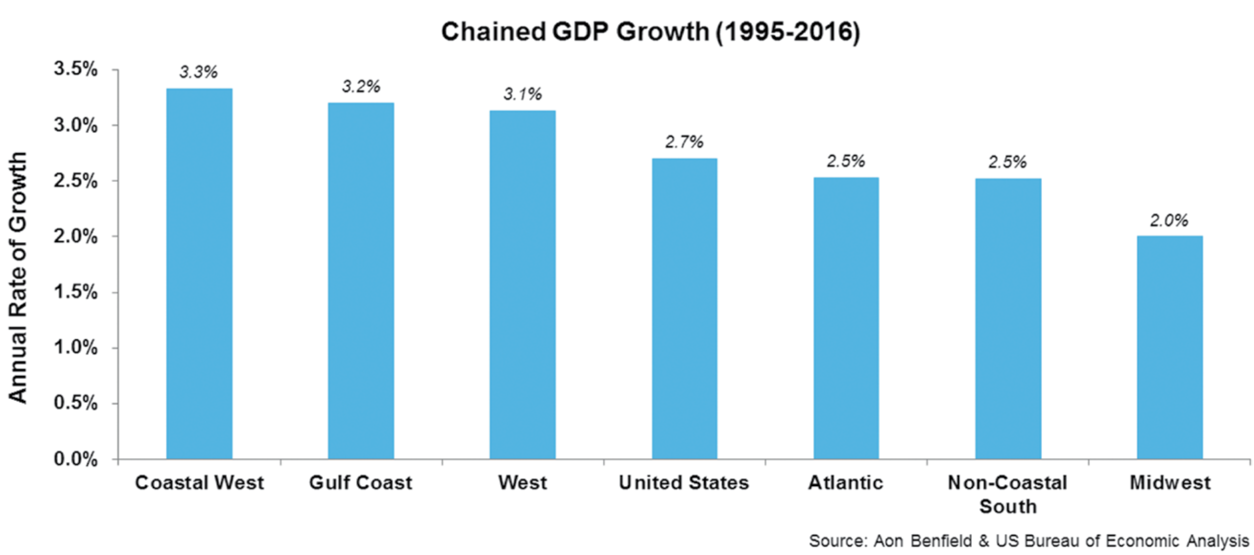

Fig. 12. Real GDP growth by region (1995–2016).

perspective, we use the state of Florida as an example. At the end of 2011, Florida had active NFIP policies in place with a total insured value of $471 billion. By the middle of 2017, a decline in active policies also coincided with TIV dropping to $422 billion despite hundreds of thousands of new single-family homes being built during that time. Table 2 provides regional breakouts of 2017 NFIP policies and TIV.

Using data as of early 2017, 14 of the top 20 states receiving the greatest amount of NFIP payouts are found in ocean-bordering states prone to hurricane landfall (Fig. 15). For greater context, the five Gulf Coast states have received more than 60% (or $34.5 billion) of all nominal NFIP payouts. The payouts are somewhat unsurprising given that more than 84%—or nearly 4.2 million—of all NFIP policies currently in place are found in the Gulf Coast and Atlantic regions. The TIV of these active policies in the Gulf Coast and Atlantic regions covers $1.05 trillion (85%) in residential and commercial property assets. Whether fully insured or not, this further highlights the growing risk in these states given the tremendous aggregated value of properties located in hurricane-prone locations.

These data strongly suggest that the combination of increased population, greater exposure, the quality of building construction, and further modifications of building codes have played—and will continue to play—a significant role in rising damage associated with TCs in the CONUS. Any increase in landfalling TC frequency or intensity (e.g., Knutson et al. 2010; Walsh et al. 2015) would expectedly combine with these socioeconomic and demographic factors to cause even greater losses.

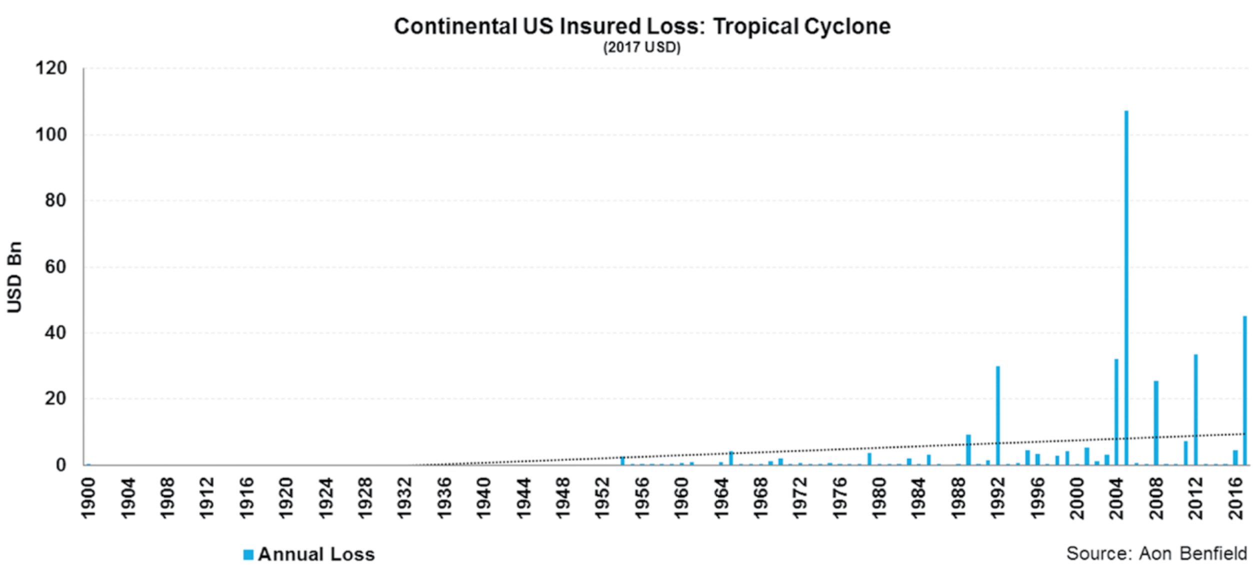

Fig. 13. CONUS total inflation-adjusted insured losses from TC landfalls (1900–2017). The dotted line represents the linear trend over the period. The *p* value for the linear trend is <0.01, indicating that the trend is significant.

Table 2. NFIP policies in place by U.S. region, the percentage of total NFIP policies in each U.S. region, the TIV of NFIP policies by U.S. region, and the percentage of TIV of NFIP policies by U.S. region.

Region	Policies per region	NFIP policies (%)	TIV per region (billion of dollars)	TIV (%)
Atlantic	1,231,707	25.0	310	25.2
Coastal west	310,757	6.3	86	7.0
Gulf Coast	2,925,909	59.4	737	59.9
Midwest	210,513	4.3	42	3.4
Noncoastal south	80,969	1.6	17	1.3
West	160,696	3.3	38	3.1
Other U.S. territories	6,918	0.1	1	0.1
Total	4,927,469	100	1,023	100

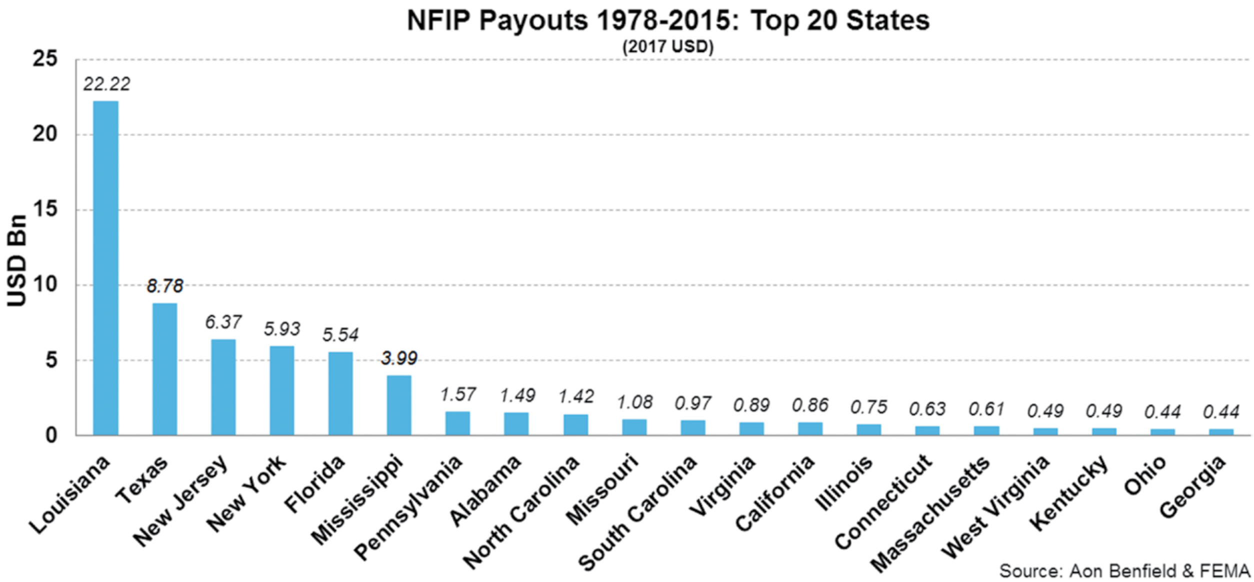

Fig. 15. Top 20 states for NFIP payouts (1978–2015; inflation adjusted to 2017 dollars).

DISCUSSION AND CONCLUSIONS. We have investigated trends in CONUS hurricane activity since 1900 and found no significant trends in landfalling hurricanes, major hurricanes, or normalized damage consistent with what has been found in previous studies. CONUS landfalling hurricane activity is, however, influenced by El Niño–Southern Oscillation on the interannual time scale and by the Atlantic multidecadal oscillation on the multidecadal time scale.

Despite a lack of trend in observed CONUS landfalling hurricane activity since 1900, large increases in inflation-adjusted hurricane-related damage have been observed, especially since the middle part of the twentieth century. We demonstrate that this increase in damage is strongly due to societal factors, namely, increases in population and wealth along the U.S. Gulf and East Coasts.

These findings have practical significance. Prior to the very active and costly 2017 season, the CONUS enjoyed an 11-yr major-hurricane drought (Hall and Hereid 2015; Hart et al. 2016), and during this period there were sizable growth patterns in coastal population, vulnerable coastal exposures, housing size, and nominal wealth in the most hurricane-prone areas of the country.

When the major-hurricane drought came to an end in 2017, Texas and Florida recorded aggregated economic damage losses in excess of $125 billion. In total, economic damage in CONUS during the 2017 season was among the costliest ever recorded on a nominal, inflation-adjusted, and normalized basis. It is further expected that future catastrophe losses resulting from landfalling storms will be even more financially significant for local, state, and federal government agencies, and the insurance industry if proper steps are not taken to reduce the current vulnerabilities of property and other exposures. The conclusion of greater future losses stands regardless of any changes in future hurricane frequency or intensity associated with changes in the climate behavior of hurricanes. Even if the frequency of future hurricanes were to lessen, even one storm in an otherwise quiet year can result in unprecedented damage (e.g., Hurricane Andrew in 1992).

Losses from future hurricanes have significant potential to dwarf those of the past based on societal change alone. Event losses will be even greater with potential increases in storm intensity (Knutson et al. 2010; Walsh et al. 2015) as well as flood-related impacts associated with an accelerated rate of sea level rise (Mousavi et al. 2011) and/or increased amounts of rainfall (Emanuel 2017). This highlights the continued importance of modernized and consistent building codes across hurricane-prone states, updated flood maps, and improved coastal and inland infrastructure given assumed impacts in the future.

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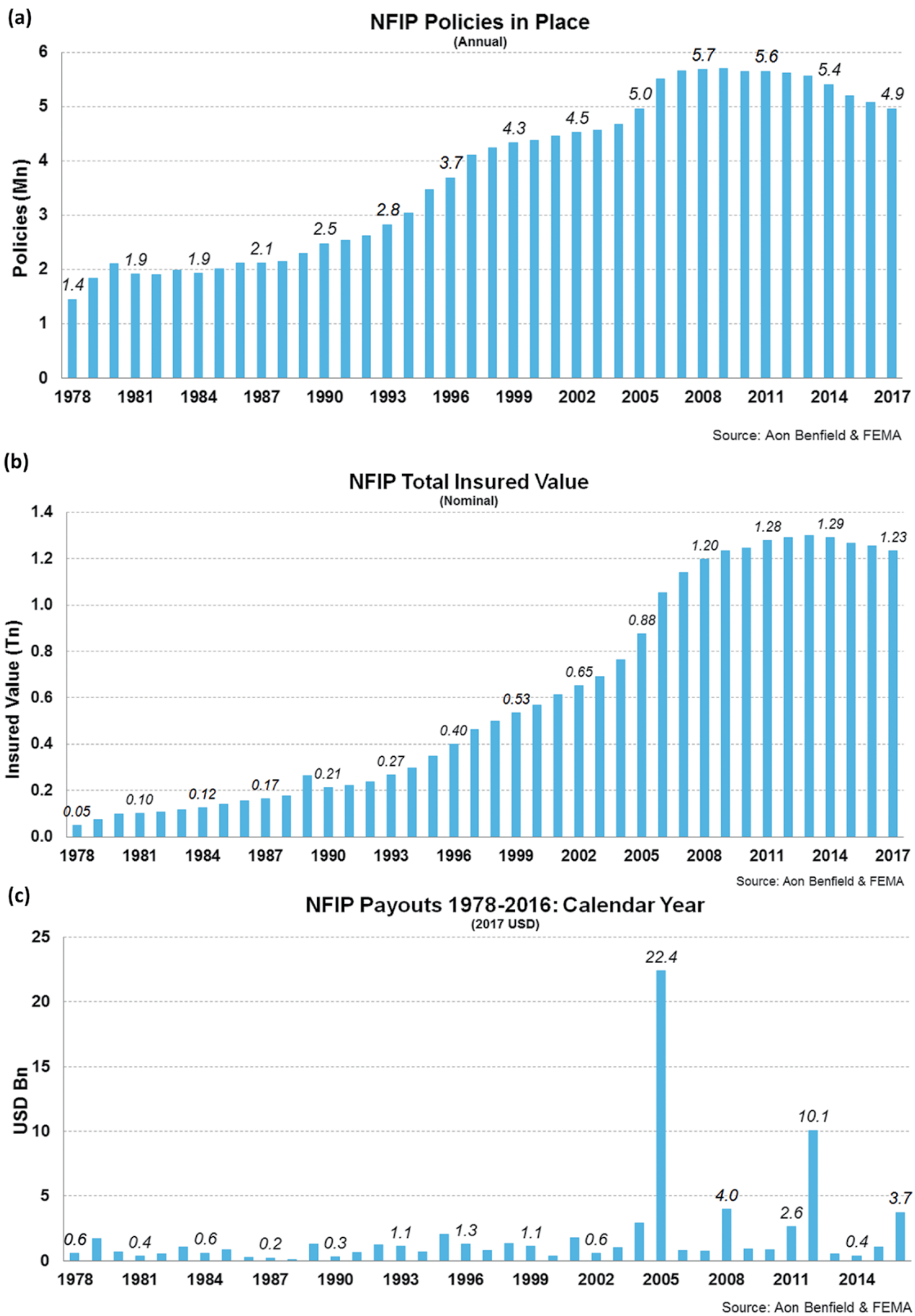

Fig. 14. (a) Annual NFIP policies in place (1978–2017), (b) total insured value of NFIP coverage (nominal values, 1978–2017), and (c) calendar year NFIP payouts from 1978 to 2016 (2017 dollars).