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Changes in the US hurricane disaster landscape: the relationship between risk and exposure

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Abstract This research appraises how residential built environment growth influences coastal exposure and how this component of societal vulnerability contributes to tropical cyclone impact and disaster potential. Historical housing unit data and future demographic projections from a high-resolution, spatial allocation model illustrate that the area within 50 km of the US Atlantic and Gulf Coastlines has the greatest housing unit density of any physiographic region in the USA, with residential development in this region outpacing non-coastal areas. Tropical cyclone exposure for six at-risk metropolitan statistical areas (MSAs) along the US Atlantic and Gulf Coasts are assessed. All six MSAs evaluated are distinct in their development character, yet all experienced significant growth from 1940 through the contemporary period; projections from the model under various socioeconomic pathways reveal that this growth is anticipated to continue during the twenty-first century. Using a worst-case scenario framework, the historical and future residential data for the six MSAs are intersected with synthetic hurricane wind swaths generated from contemporary landfalling events. The New York City MSA contains the greatest residential built environment exposure, but Miami is the most rapidly changing MSA and has the greatest potential for hurricane disaster occurrence based on the juxtaposition of climatological risk and exposure. A disaster potential metric illustrates that all six MSAs will experience significant increases in disaster probability during the twenty-first century. This analysis facilitates a detailed spatiotemporal assessment of US coastal region vulnerability, providing decision makers with information that may be used to evaluate the potential for tropical cyclone disasters, mitigate tropical cyclone hazard impacts, and build community resilience for these and other hazards in the face of environmental and societal change.

Keywords Hurricane · Tropical cyclone · Coastal exposure · Vulnerability

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1 Introduction

There has been a notable upward trend in US tropical cyclone losses during the past half century (Pielke 2007; Pielke et al. 2008; Burton 2010; Mendelsohn et al. 2012). While major hurricanes are climatologically rare, they accounted for 85% of the total US tropical cyclone damage from 1900 through 2005 (Pielke et al. 2008). Pielke (2007) suggests that losses from US tropical cyclones are expected to double every 10 years; a rate that implies that losses in 2050 will be 15 times greater than those in the 2000s. Societal factors, such as population and affiliated built environment growth, are likely responsible for the trends found in tropical cyclone losses (Pielke et al. 2008; Miller et al. 2008; Bouwer 2011), and at least at this point, these losses do not appear to be based on changes in the frequency or intensity of the hazard (Changnon et al. 2000; Cutter and Emrich 2005; Pielke et al. 2005, 2008; Borden et al. 2007; Pielke 2007; Changnon 2008; Burton 2010; Bouwer 2011, 2013; Mendelsohn et al. 2012; Weinkle et al. 2012; Ashley et al. 2014; Noy 2016).

Trends in population magnitude and density indicate increasing development across the USA, especially along the coasts (Wilson and Fischetti 2010). For instance, the US coastal population increased from 47 million in 1960 to 87 million in 2008, which exceeds the population change for non-coastline counties by 20% (Wilson and Fischetti 2010). To accommodate the population growth, there has been a corresponding increase in the number of housing units along the coastline, with coastal counties increasing collectively their residential development by roughly 300% during the same 48-year period. In conjunction with projected population growth, the residential built environment is projected to continue to swell in the future. By 2040, the US population is expected to reach 400 million, with more than 60% of the population located in the nation's ten "mega-regions" (Nelson and Lang 2007a, b), three of which are located along the Gulf and Atlantic Coasts. As population increases, cities enlarge outward to allow room for growth, in turn, expanding the area's overall developed footprint (Hall and Ashley 2008). US urban and suburban regions are expected to experience a population influx, increasing their populations between 19 and 23% by 2100, while also expanding their developed footprint (Bierwagen et al. 2010). Growth of the built environment of a city increases the risk of a geophysical hazard impact and disaster potential (Ashley et al. 2014; Strader and Ashley 2015). The conceptual disaster framework known as the "expanding bull's-eye effect" suggests that—regardless of potential changing storm characteristics—increasing and expanding built environment leads to more "targets" for hazards to impact. Employing this concept to tropical cyclones, it is likely that the vulnerability of coastal counties will escalate over time, which will increase the likelihood of future tropical cyclone disasters. This begs the question: What impact will tropical cyclones have on coastal exposure in the future and, in turn, how will the tropical cyclone disaster landscape change? This is an important inquiry since both tropical cyclone risk and exposure to the hazard are likely to shift—and potentially increase—in a warming world.

The research suggests that development across the US Atlantic and Gulf Coasts will increase human and built environment exposure (measured, in our case, by housing units) to tropical cyclones, and, consequently, inflate their vulnerability to disasters now and in the future. This study uses residential built environment output from a fine-scale, spatial allocation model to investigate how coastal exposure to tropical cyclones has changed since the mid-20th century and how it is projected to evolve through 2100. Synthetic hurricane models are developed based on historical storm attributes, permitting an empirically grounded approach to evaluate future disaster "what if" scenarios (Clarke

2005). The modeling of potential “worst-case” scenarios conveys the idea of a possible disaster occurring and promotes preparation for a future extreme event. The synthetics are employed to simulate possible hurricane impacts across a spatially diverse risk landscape. Previous studies have exemplified the benefits of hazard synthetics in assessing potential disasters to the human-built environment, primarily for the tornado hazard (Wurman et al. 2007; Hall and Ashley 2008; Paulikas and Ashley 2011; Ashley et al. 2014; Strader et al. 2014). Hurricane synthetics have been used to evaluate simulated lifecycle and intensity through historical storm data (Casson and Coles 2000; Vickery et al. 2000; Emanuel 2006; Emanuel et al. 2006; Hall and Jewson 2007; Hallegatte 2007; Rumpf et al. 2007, 2009; Yonekura and Hall 2011; Nakamura et al. 2015; Ellis et al. 2015, 2016). Other studies have simulated hurricanes by creating hurricanes with multiple pathways and assessing worst-case scenarios (Scheitlin et al. 2011). While previous synthetic studies focused on simulating storm lifecycles and track projections, there is a dearth of research that focuses on the simulated impact of storms on the built environment. Finally, a simple disaster metric is developed using exposure and climatological risk to assess the potential for tropical cyclone disaster over time for the investigated regions. Tropical cyclones are natural phenomena that can develop into disasters if they interact with human and physical environment systems (Mileti 1999; Abramovitz 2001; Reilly 2009). Increasing the number of HUs along and near the coastline places more potential “targets” in the path of a tropical cyclone; however, without a climatological risk of tropical cyclone hazard, there is no disaster potential. Further insight into tropical cyclone disaster potential can be gained by combining climatological risk and coastal exposure into a single metric. The goal of the work is to deliver a methodology and set of results that may be used by catastrophe analysts, emergency managers, and policy makers to evaluate how their portfolio and/or community may be affected by future tropical cyclone events. The information may be used by these groups to reduce vulnerabilities and build resilience in the face of both environmental and societal change.

2 Data and methods

The study area includes coastal metropolitan statistical areas (MSAs) of the USA that have historically been impacted by tropical cyclones that form and traverse the North Atlantic Basin, focusing specifically on areas with extensive development. The study uses six MSAs as cases of assessment, including: New York City-Newark-Jersey City (New York City), Charleston-North Charleston (Charleston), Miami-Fort Lauderdale-West Palm Beach (Miami), Tampa-St. Petersburg-Clearwater (Tampa), New Orleans-Metairie (New Orleans), and Houston-The Woodlands-Sugar Land (Houston) (Fig. 1).

2.1 Hurricane data

The National Hurricane Center (NHC) provides best-track storm analysis data (HURDAT2) that includes attributes of historical storms from their genesis to dissipation. The archive includes all observed tropical systems (depressions, post tropical cyclones, named storms, and hurricanes) from 1851 to 2016 and provides the basic attributes for each storm—i.e., location, maximum sustained wind speed, and minimum pressure—every six hours, as well as special timestamps upon landfall or during other important storm life events. From 2004 to 2016, the dataset includes wind radii of the storm for each quadrant

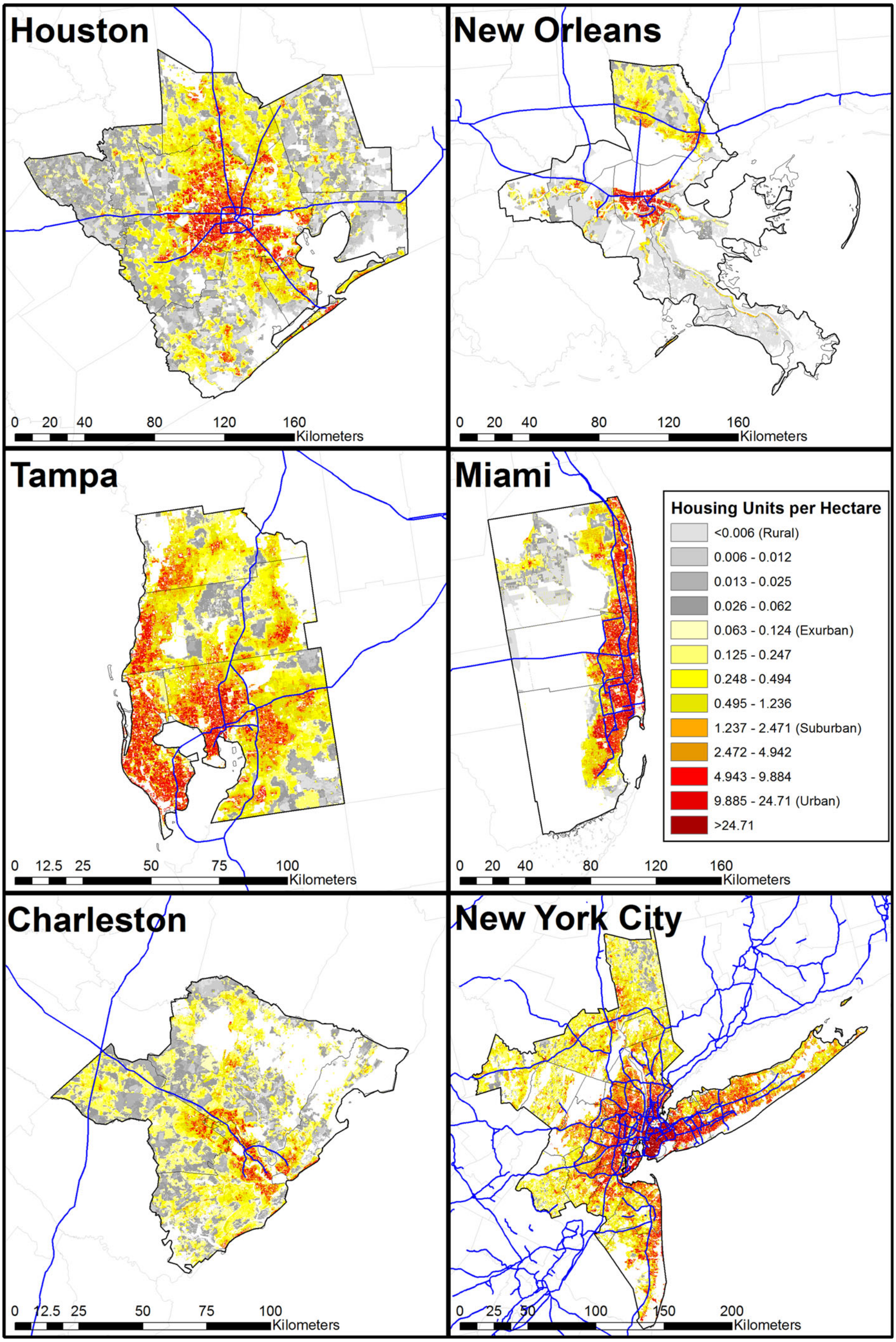


Fig. 1 Six MSAs investigated and their housing unit density and land use distribution for 2010 base case. The US interstate system is represented by blue lines. Confer with Fig. 2 for MSA locations in the eastern USA

throughout its lifetime. The wind radii show the extent of the wind speeds at 17.5 m s^{-1} (34 knots; tropical cyclone classification), 25.7 m s^{-1} (50 knots), and 32.9 m s^{-1} (64 knots; Category 1 hurricane classification). Since HURDAT2 only provides radii at three wind speeds, the extended best-track data provided by Demuth et al. (2006) is used in conjunction with the HURDAT2 radii. The extended best track includes additional storm parameters supplementing HURDAT2, such as the radius of the maximum wind at each timestamp. This hypothetical framework will be used as a basis for simulating both historical and future hurricane impacts.

2.2 Housing unit data

The US Environmental Protection Agency's (EPA) Integrated Climate and Land-Use Scenarios (ICLUS) project used a demographic and spatial allocation model to examine population growth scenarios (Bierwagen et al. 2010). The ICLUS scenarios for the USA consist of population, housing density, and impervious surface estimates. The spatial allocation model employed in ICLUS is the Spatially Explicit Regional Growth Model, or SERGoM, which relates historical development trends to predict future growth of population and housing units (HUs) (cf. Theobald 2005). ICLUS employed four "baseline," or "reference," scenarios from the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emission Scenarios (SRES; US EPA 2009; Bierwagen et al. 2010); the SRES project differences in future greenhouse gas concentrations, land use, and describe other societal development and socioeconomic trajectories. Specifically, there are binary storylines along two axes in which the SRES describes population growth in the model: economic versus environmentally driven development (A-B) and global versus regional development (1–2). The matrix produces scenarios in which the future HU density layer will behave: A1, A2, B1, and B2. A1 represents low population growth but rapid economic development, encouraging flexible migration (U.S. EPA 2009; Bierwagen et al. 2010). The A2 scenario assumes the highest fertility and the highest mortality of the SRES storylines, resulting in steadily increasing economic growth. The B1 storyline is similar to A1, except B1 focuses on environmentally sustainable economic growth. B2 focuses on local environmental and economic issues, and illustrates a regionally oriented landscape. Additionally, there is a "base case" scenario where all the influencing parameters (fertility, mortality, and migration) are set to "medium" (U.S. EPA 2009). Scenario A2 has the highest projected increase in population at 164% from 2010 to 2100 for the contiguous USA, while scenario B1 has the lowest at 60%. Each scenario includes HU density data that are allocated at a 100-m resolution with a semi-decadal temporal resolution from 1940 to 2100. With the housing density projections, future population scenarios are used to assess potential residential exposure within a spatiotemporal framework.

2.3 Methods

To address the research questions, we initially create buffers along the Gulf and Atlantic coasts at 50-km increments up to 200-km inland to assess the historical and future residential development. Next, the land use character of the six MSAs is assessed. Using criteria developed by Theobald (2005), four different land use classifications are employed in this study, including: rural (<0.062 HU per hectare), exurban (0.062–1.236 HU per hectare), suburban (1.236–9.884 HU per hectare), and urban (>9.884 HU per hectare).

HURDAT2 does not provide radii data prior to 2004; therefore, storms that made landfall from 2004 through 2014 along the US coastline (Table 1) are compiled to construct two hurricane synthetics: an "all" synthetic and a "major" synthetic. The "all" synthetic comprises all the landfalling storms on the Gulf and East Coasts for the 11-year period, while the "major" synthetic comprises only the major (Category 3+) landfalling storms. The "all landfalling" synthetic contains three wind swaths: 17.5, 25.7, and 32.9 m s^{-1} (Category 1). The "major" synthetic contains the same three wind swaths and an additional major swath (50 m s^{-1} swath herein) of 50 m s^{-1} or greater wind speed (Category 3 or greater). To construct the synthetics, the mean radii wind swaths for each landfalling storm is extracted for each quadrant. The area of the mean swath (A_{swath}) is calculated by Eq. 1,

Table 1 Observed hurricanes used for creating the "all" synthetic

Name	Year	Category	Max sustained winds (ms^{-1})	Minimum Pressure (mb)	Landfall location(s) (state)
Charley*	2004	4	66.82	941	SW Florida
Frances	2004	2	46.26	960	Florida
Gaston	2004	1	33.41	985	South Carolina
Ivan*	2004	3	53.97	946	Alabama; Florida
Jeanne*	2004	3	53.97	950	Florida
Cindy	2005	1	33.41	991	Louisiana
Dennis*	2005	3	53.97	946	Florida; Louisiana
Katrina*	2005	3	56.54	920	Florida; Louisiana
Rita*	2005	3	51.4	937	Florida; Texas
Wilma*	2005	3	53.97	950	Florida
Humberto	2007	1	41.12	985	Texas
Dolly	2008	2	38.55	967	Texas
Gustav	2008	2	46.26	954	Louisiana
Ike	2008	1	48.83	950	Texas
Irene	2011	1	38.55	952	North Carolina
Isaac	2012	1	35.98	967	Louisiana
Sandy	2012	1	35.98	945	New York
Arthur	2014	2	43.69	973	North Carolina
Percent of total					
Cat 1	Cat 2		Cat 3	Cat 4	Cat 5
38.9%	22.2%		33.3%	5.6%	0%

Hurricane strikes on the mainland United States (1851–2010; Blake and Gibney 2011)

Cat 1	Cat 2	Cat 3	Cat 4	Cat 5
113	75	75	18	3
Percent of total				
39.7%	26.4%	26.4%	6.3%	1%

* The storms employed in constructing the "major" synthetic

$$A_{\mathrm{swath}} = \frac{\pi}{4}\sum_{i=1}^{4} r_i^2 \tag{1}$$

where r_1 is the radius in the northeast quadrant, r_2 is the radius in the southeast quadrant, r_3 is the radius in the southwest quadrant, and r_4 is the radius in the northwest quadrant. A_{swath} is used to find the radius of the synthetic swath (R_{synth}) by Eq. 2.

$$r_{\mathrm{synth}} = \sqrt{\frac{A_{\mathrm{swath}}}{\pi}} \tag{2}$$

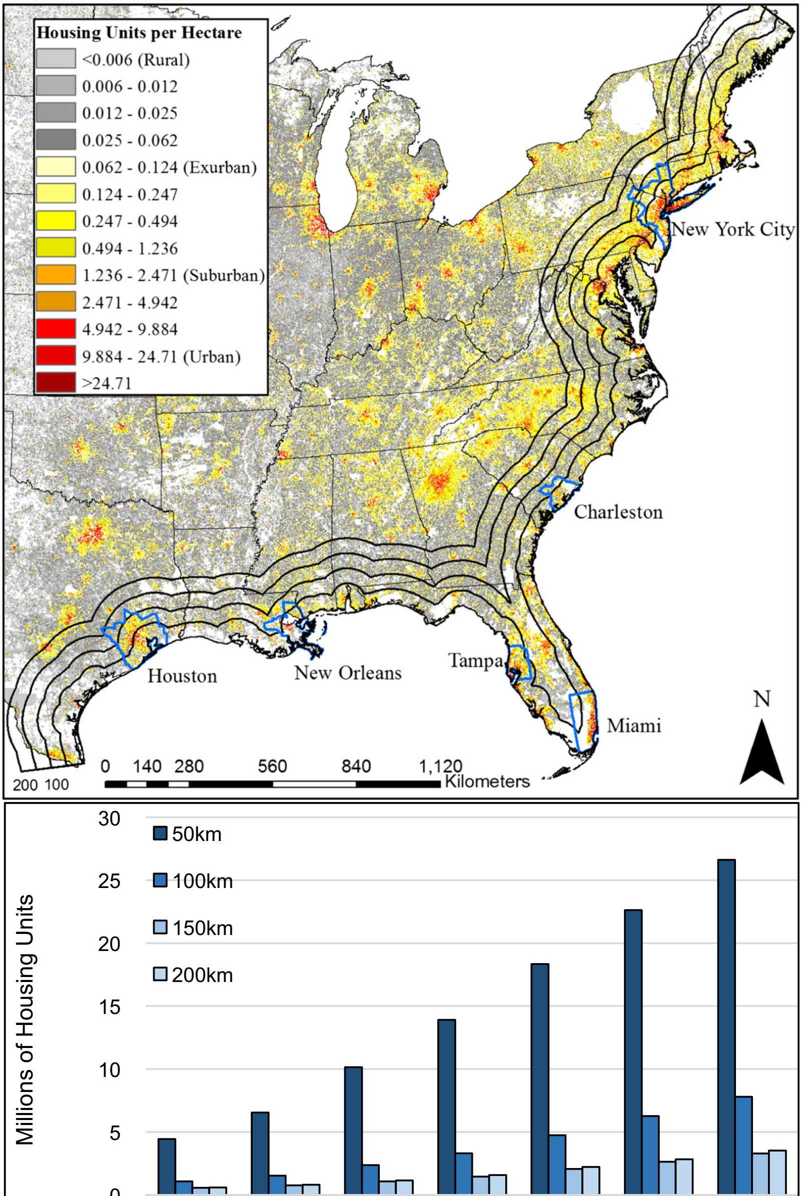
The result is a storm synthetic that has a uniform wind radius over all quadrants. This method is applied to the 6-hr and landfall timestamps provided by HURDAT2, creating a smooth wind swath from 24 h prior to landfall through dissipation. The hurricane synthetics were placed over the developed core of each MSA to assess "worst-case" scenarios (Fig. 5; Clarke 2005). The angle of the synthetic's landfall was determined by examining previous hurricanes and how they made landfall near each corresponding MSA. In most cases, landfall was orthogonal to the coastline for each MSA, except for Tampa. Tampa's location along the eastern Gulf Coast suggests that an orthogonal landfall would be improbable; therefore, the hurricane synthetic was placed over Tampa in likeness to Hurricane Charley in 2004. As was illustrated by 2016's Hurricane Matthew, orthogonal landfall does not always occur; however, for the purposes herein, orthogonal or near-orthogonal intersections with the coastline provide a basis for assessment and comparison. A limitation of the storm synthetics having a uniform wind radius is the asymmetry affect. The combination of the storm's forward momentum and the counterclockwise rotation can enhance the wind speeds in the northeast quadrant (relative to motion) of the storm. Conversely, the southwest quadrant may be less intense than the synthetic indicates. Including dissipation in the study provides an analysis on the tropical cyclone impacts on both coastal and inland counties. The storm synthetics are used for different locations along the coast, but do not change in size and shape. This is a limitation since Atlantic Ocean hurricanes are on average larger than Gulf of Mexico hurricanes (Vickery and Wadhera 2008).

The ICLUS output included HU raster files that illustrate the number of HU within one hectare for each of the five SRES scenarios semi-decennially for the period of analysis. The number of HUs impacted by year and scenario were extracted for each MSA through *ArcGIS*. This method works similarly for the hurricane synthetics and is used to extract the number of HUs that were affected theoretically by the storm's wind swath, providing a standard metric for analysis and comparison.

3 Results and discussion

3.1 Coastline and inland growth

In 2010, about 40% of the US population lived in coastal counties, which suggests that a large proportion of the US housing stock is at risk of coastal hazards (National Ocean Service 2014). To assess the character of HU density and how its growth has evolved near the coastline, buffers were placed at 50-km increments, starting on the coastline and applied inland iteratively thereafter. The number of HU decreases inland nearly exponentially, which is similar to the coastal growth pattern elsewhere around the globe (Fig. 2;



	1940	1950	1960	1970	1980	1990	2000
50km	4.44	6.55	10.14	13.90	18.33	22.62	26.61
100km	1.08	1.52	2.37	3.30	4.74	6.26	7.80
150km	0.57	0.76	1.07	1.46	2.06	2.64	3.29
200km	0.60	0.81	1.16	1.58	2.22	2.83	3.52

Fig. 2 50, 100, 150, and 200 km buffer regions and the land use distribution for 2010 base case (*top*), and the number of housing units from 1940 to 2000 within each of the four different buffer regions defined from the top panel (*bottom*). Each MSA is outlined in *blue*

Nicholls and Small 2002). The number of HUs located within 50 km is about twice the number of HU within the other three analyzed buffer zones (i.e., 50–200 km inland), combined. In 2000, the HU density for the contiguous U.S., outside of the 200-km region, was approximately 11 HU km^{-2}, while the HU density for the 200-km region was approximately 40 HU km^{-2} and the HU density for the 50-km buffer zone was approximately 78 HU km^{-2}. The HU density and subsequent growth in that density near the coastline is aligning more people and their property with the risks from tropical cyclone hazards—including hurricane induced storm surge and winds—which could cause more frequent and higher magnitude disasters in the future. Ultimately, these buffer results reveal that HU growth is greatest, and exposure is the highest, in the areas that typically experience the most extreme tropical cyclone hazard risk and affiliated hazards.

The 50-km buffer region was examined further by investigating the land use classification over time to provide detail on the character of the human-built environment. In 1940, 80% of the developable land in the 50-km buffer region was classified as rural, but, by 2000, only 46% of the region was rural (Fig. 3). The decrease in rural land use is largely due to the increased conversion of developable rural land to more densely populated exurban and suburban morphologies Suburban and urban grew nearly 20 million HUs collectively from 1940 to 2000 within the 50-km buffer region, while exurban increased 2.2 million. The absolute changes in HUs for suburban and urban (high density) exceeds that of exurban, indicating that the greatest potential for catastrophic impact are in the suburban and urban regions (Ashley et al. 2014; Ashley and Strader 2016). The change in HU density and its expanding footprint are important factors when understanding exposure and its contribution to disasters. Future projections indicate that HUs are expected to continue growing, further increasing exposure to tropical cyclones and associated hazards.

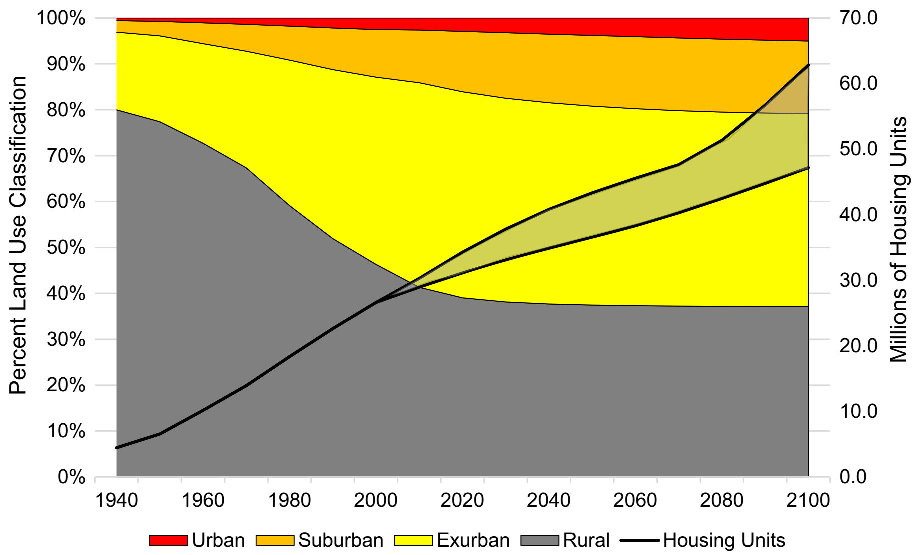


Fig. 3 Percentage of rural, exurban, suburban, and urban land use (*shaded*) for the 50-km buffer region from 1940 to 2100, where 2010 to 2100 is projected under the A1 storyline. The thick, black line represents the total number of housing units within the 50-km buffer region in millions up to 2000 and then splits to represent the envelope of maximum and minimum number of housing units within the region based on the SRES storylines

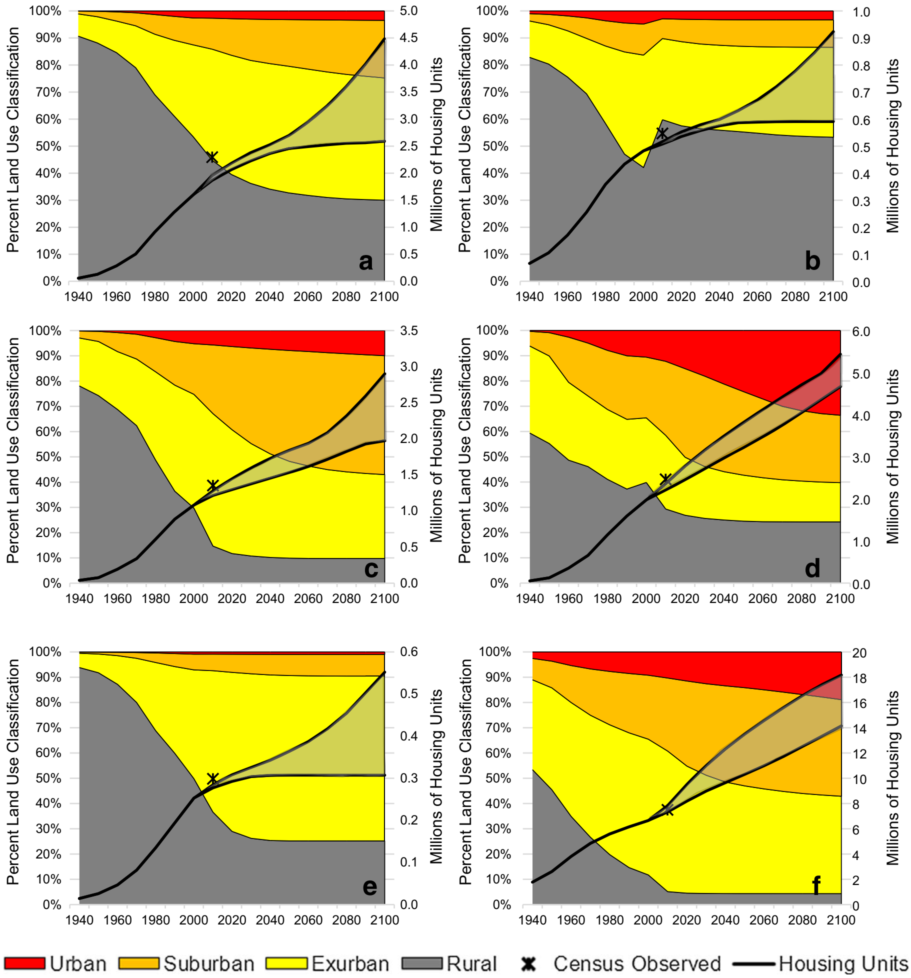


Fig. 4 Percentage of rural, exurban, suburban, and urban land use for **a** Houston, **b** New Orleans, **c** Tampa, **d** Miami, **e** Charleston, and **f** New York City from 1940 to 2100, where 2010 to 2100 is projected under the A1 storyline. The *thick black line* represents the total number of housing units within the MSA in millions, and the *shaded region* after the *thick black line* splits represents the projected number of housing units based on SRES storylines. The *asterisk* represents the number of census observed housing units for 2010

By 2100, the number of HUs in the 50-km buffer region is projected to rise by approximately 22.2 million HUs, a 73% increase from 2010 under the A1 projection. Further, rural and exurban land use morphologies are projected to decline by −10 and −6%, respectively, within the 50-km buffer region from 2010 to 2100. The 50-km region remains mostly exurban up to 2100; however, urban is projected to grow by 92%, indicating future expansion of high-density regions. Additionally, the number of HUs within urban regions is projected to increase by 32.4 million HUs, or 100%, under the A1 projection by the end of the century, further increasing the HU density along the coastline. Since disasters are partially a product of a hazard interacting with the built environment, this study defines the macroscale (or coastal region), worst-case scenario as the projection with the largest number of HU in a defined coastal buffer that could be impacted by

Table 2 Number of housing units reported by the 2010 Census for each MSA, as well as the number of housing units for each scenario

	Population estimate 2010	Census reported housing units 2010	ICLUS scenario housing unit counts				
			A1	A2	B1	B2	Base
Houston	5,920,416	2,295,018	**1,956,710**	1,867,605	1,942,435	1,889,436	1,895,453
New Orleans	1,189,866	546,694	**516,931**	507,610	515,042	508,575	509,303
Tampa	2,783,243	1,353,158	**1,280,680**	1,217,681	1,258,159	1,215,663	1,225,169
Miami	5,564,635	2,464,429	**2,359,252**	2,212,090	2,349,312	2,232,323	2,236,486
Charleston	664,607	298,542	**284,618**	277,541	280,542	277,111	278,821
New York City	19,567,410	7,496,069	7,851,616	7,264,103	7,841,788	7,317,603	**7,324,936**

The scenario that most aligns with the 2010 Census counts is highlighted in bold tropical hazards at any given time (Clarke 2005). It is unknown exactly how the coastal built environment will grow in the future and how it will align with the projections; however, the scenario data permits at least an exploration of tangible possibilities. Since development and density are not uniform across the coastline, the six high-risk MSAs along the coast are examined to further understand the built environment change now and in the future.

3.2 MSA exposure

To assess historical and projected changes in HU growth and developmental characteristics along the at-risk coastline, six coastal MSAs were investigated, including: Houston, New Orleans, Tampa, Miami, Charleston, and New York City. MSA geographic boundaries were defined by the Office of Management and Budget's 2013 delineations (OMB 2013), with MSAs assessed in this research based on the metropolitan region's size, propensity for historical tropical cyclone impacts, potential for catastrophic events under worst-case scenarios, and their facilitation of robust measures of disaster potential for the US coastline. The MSAs are unique in HU composition and land use character, indicating that each MSA is exposed differently than the other MSAs.

The 2010 ICLUS HU projections are validated with 2010 US Census data to assess how close the modeled projections are to census reports for the same enumerations (Fig. 4). The US Census provides HU counts for each MSA; however, since MSAs change over time, the Census HU counts for the MSAs were not used. Instead, the number of HUs within the counties in each study area was summed to provide a total HU count for the MSA. When discussing individual projections, A1 is used herein to explore historical (2010) and future projections for each MSA because of how closely the projections aligned to the US census counts (Table 2).

All MSAs experienced substantial growth between 1940 and 2010 (Fig. 4) and are projected to increase for the remainder of the twenty-first century; however, they are all unique in their growth patterns and magnitudes. From 1940 to 2010, the number of HUs in New York City increased about 6 million HUs, or 341%. Comparatively, Miami gained a relatively lower 2.3 million HUs, but experienced 4526% growth. The number of HUs in Charleston increased about 270,000, or 1871%, from 1940 to 2010. From 1940 to 2010, Miami densified most rapidly, shifting from 3.88 to 179.5 HU km^{-2}. New Orleans exhibited a discontinuous pattern from 2000 to 2010; recall that the projected land use classification begins in 2010, indicating there is disconnect between the historical and projected data. It is possible that the destructive nature of Hurricane Katrina in 2005 may have been the cause of the land use shift, thus altering how the built environment will grow now and in the future (Vigdor 2008).

From 2010 to 2100, HUs grow in a quasi-linear fashion in every MSA, with an increase in HU across all scenarios. Overall, the fanning pattern could exhibit greater variability in HU growth, while the narrow pattern indicates that the scenario input parameters do not greatly alter the projections. Miami is projected to increase in HUs between 109 and 146% from 2010 to 2100. Conversely, the number of HUs in Houston is projected to increase between 33 and 140%, a large range for potential HU growth under the various societal pathways modeled. The number of HUs is difficult to predict, especially for the MSAs with a large variability in the model. This challenge exists for all models as their output are not perfect. Based on the percent change of HU and density change, Miami is the most rapidly changing MSA in this study and is projected to experience more growth within urban morphology than the other land use classifications. Miami is expected to experience the

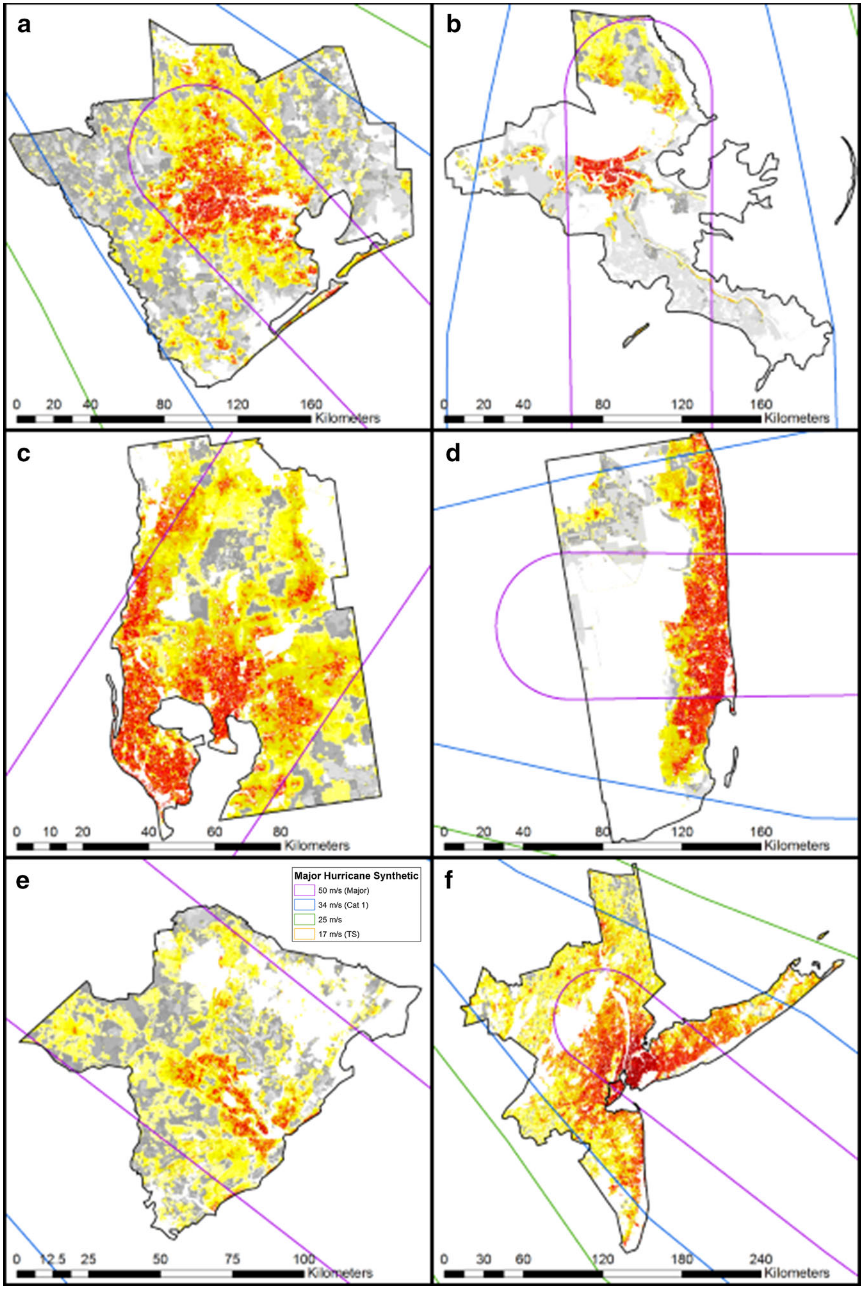


Fig. 5 Major Storm superimposed on the A1 2010 projection for **a** Houston, **b** New Orleans, **c** Tampa, **d** Miami, **e** Charleston, and **f** New York City. The All Storm is overlaid on the MSAs similarly, but without the major swath (50 m s^{-1}) represented by the *pink line*. The *green*, *yellow*, and *green lines* represent the 17 m s^{-1}, 25 m s^{-1}, and 34 m s^{-1} (Category 1) wind swaths, respectively. The housing units per acre are represented in the same way as Fig. 1. Note that the MSAs are not the same scale in this figure, and the same synthetic is used for all MSAs

greatest change in density—nearly +9700%—from 1940 to 2100. The number of HUs within Miami is projected to range between 4.8 and 5.5 million by 2100. New York has more HUs than Miami, but Miami's disaster potential landscape is changing far more rapidly than the other MSAs, indicating that it may be difficult to adapt to potential hurricane and other geophysical hazards (Adger et al. 2003; Cutter et al. 2003; Borden et al. 2007; Satterthwaite 2007; Hauer et al. 2016) now and in the future.

Every MSA has decreased in rural area and rural-classified HUs from 1940 to 2000 and is projected to continue decreasing from 2010 to 2100 for all scenarios. Much of the growth within the MSAs has been in the exurban and suburban morphologies at the expense of rural, especially in the Tampa, Charleston, and New York City MSAs (Fig. 4). These locations had a negative change in rural character from 1940 to 2010, indicating that the rural landscape is developing into a higher-density zone in these MSAs. In 1940, all the MSAs were mostly rural, including New York City; by 2010, Tampa, Charleston, and New York City were mostly suburban. Houston and New Orleans remained mostly rural in the historical 70-year period, but experienced rapid suburban and urban development. Miami is nearly split evenly between rural, exurban, and suburban, with urban the smallest morphology by proportion; however, Miami experienced 13,747% increase of the number of HU within urban classification from 1940 to 2010. The percentage of urban within Miami has grown from 0.3 to 12.2%, resulting in an urban footprint about 140 times larger than that of 1940. Due to the Everglades Wildlife Management Area and National Park west of the Miami MSA, the expansion of development may be limited, or halted; however, the MSA will likely densify and become largely suburban and urban over time. While exurban and suburban growth varies per MSA, all MSAs exhibit an increase in urban development. By 2100, Miami will be the only MSA in this study to be more than 30% urban for all projections. All MSAs continue growth into the twenty-first century—especially in urban areas—indicating that the potential for disaster from tropical cyclones, and other hydrometeorological and geophysical hazards, will continue to increase.

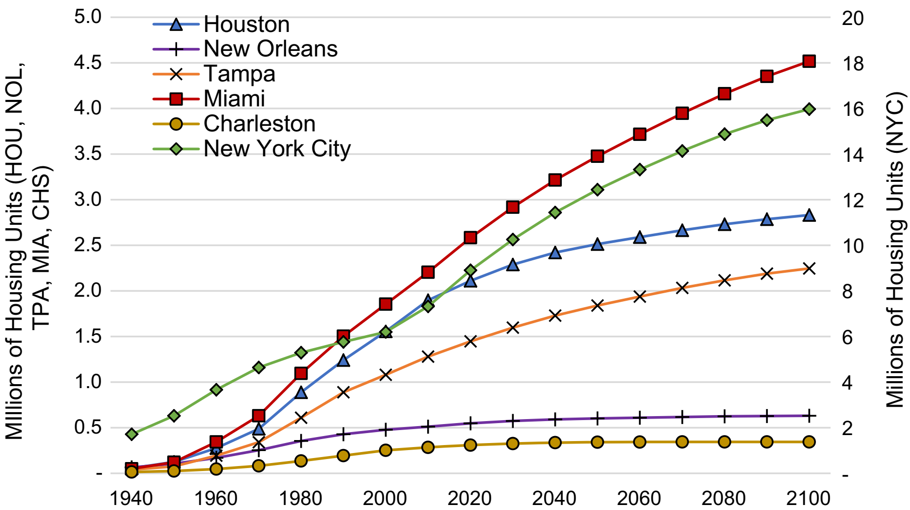


Fig. 6 Total number of housing units impacted by the Cat 1 swath of the All Storm for all MSAs from 1940 to 2100, where 2010 to 2100 is projected under A1

Table 3 Total number of housing units impacted by the Cat 1 swath of the All Storm for all MSAs in 2010, 2050, and 2100, projected under A1, and the percent change in housing units from 2010 to 2100

	2010	2050	2100	2010 to 2100 Percent Change
Houston	1,898,477	2,512,569	2,833,144	49%
New Orleans	511,899	601,665	631,660	23%
Tampa	1,280,680	1,840,493	2,246,761	75%
Miami	2,204,788	3,476,090	4,518,062	105%
Charleston	284,618	341,260	344,487	21%
New York City	7,324,997	12,439,396	15,973,848	118%

3.3 Hurricane scenarios

In this study, the use of hurricane scenarios does not include the structural integrity of the underlying HUs within the storm swath. Simply, the scenarios examine the potential number of HU impacted by a hurricane synthetic's wind swath. Although the impact of the hurricane will vary per HU, the central focus is to illustrate the residential disaster potential and how the development footprint changes the disaster potential over time. There are two hurricane synthetics that were created for this study: an "all landfalling" synthetic and a "major" synthetic. The "all landfalling" synthetic contains three wind swaths: 17.5, 25.7, and 32.9 m s^{-1} (Category 1). The "major" synthetic (Fig. 5) contains the same three wind swaths and an additional major swath (50 m s^{-1} swath herein) of 50 m s^{-1} or greater wind speed (Category 3 or greater).

For Houston under the A1 projection, the number of HUs within the "all" synthetic (hereafter All Storm) is projected to increase from 1.9 million to 2.9 million, or 53%, from 2010 to 2100 (Fig. 6; Table 3). About 95% of the exposure growth will be within the Category 1 swath, but tropical storm winds can be damaging as well. In addition, other disastrous impacts can arise from less-intense, landfalling tropical storms, such as heavy rainfall and flooding (e.g., Tropical Storm Allison in 2001). In Miami, the number of HUs within the Category 1 wind swath is projected to increase by 104.9% from 2010 to 2100. The absolute number of HUs with the Category 1 wind swath is projected to be ten times larger than the number of HU with the 25 m s^{-1} wind swath. By 2100, 90% of the HU in Miami will reside within the Category 1 wind swath. Overall, the number of HUs within the All Storm synthetic is projected to increase from 2.3 to 4.9 million, or 112%, from 2010 to 2100 under the A1 scenario. It is unknown what the underlying impacts will be, given the different variables of a hurricane.

Overall, the impact of a Category 1 storm is projected to increase based on the rising exposure within all the MSAs. From 1940 to 2100, the number of HUs impacted by the entire All Storm synthetic increases from 51,000 to 5,000,000, or 9695%. Although New York City has the highest number of HUs impacted by the All Storm synthetic, the MSA changed the least in terms of HUs potentially impacted—or, about 845%—of the MSAs from 1940 to 2100. The Houston, Tampa, Miami, and New York City MSAs are projected to have over 2 million HUs impacted by the All Storm synthetic by 2100. These analyses illustrate that the growing exposure within the MSAs will continue to amplify disaster potential.

The major synthetic (Major Storm hereafter) scenario under the A2 projection—i.e., the "worst-case"—produced the largest disaster potential for the MSAs studied from 2010 to

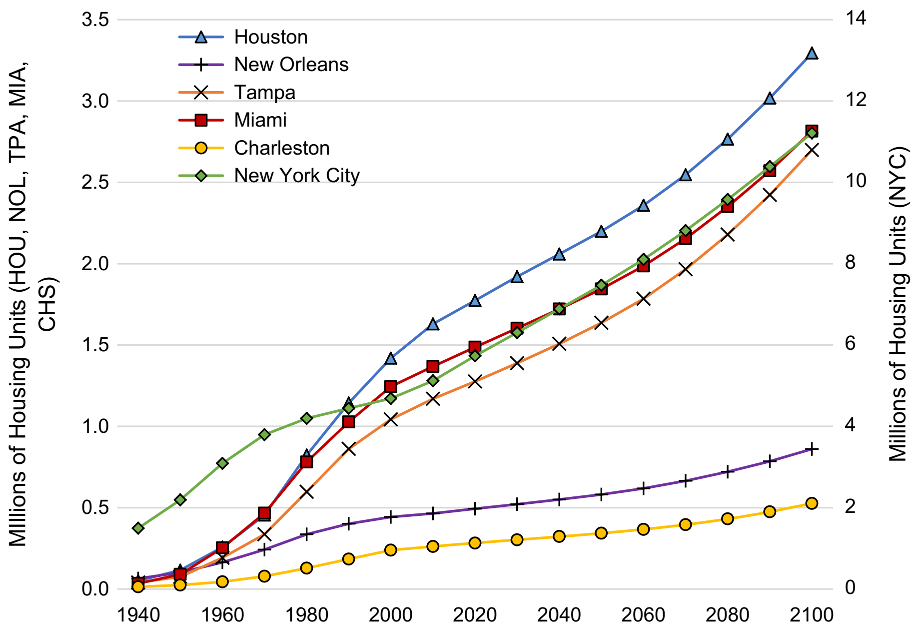


Fig. 7 Total number of housing units impacted by the major swath of the Major Storm for all MSAs from 1940 to 2100, where 2010 to 2100 is projected under A2

2100 (Fig. 7). For all MSAs, A2 has the largest increase in the projections for the four swaths that characterize the Major Storm synthetic. For New Orleans and Charleston, the number of HUs impacted by the 50-m s^{-1} swath rises from 2010 to 2100 instead of remaining constant as A1 projects. The Houston, Miami, and Tampa MSA cores are growing rapidly; however, locations around the core are growing much faster, resulting in a sprawl morphology. Houston, Miami, and Tampa exhibit faster growth in the Category 1 swath than the 50-m s^{-1} swath; however, the number of HUs within the 50-m s^{-1} swath is much larger and increases by at least 100% from 2010 to 2100. This results in the number of HUs within the 50-m s^{-1} swath spreading into the Category 1 wind swath, illustrating further the expanding bull's-eye effect (Ashley et al. 2014; Strader and Ashley 2015). The 50-m s^{-1} swath in New York City is projected to experience a faster rate of growth than the other swaths and contain at least three times more HUs than that of the Category 1 swath. If a major hurricane affects New York City, the damage could be catastrophic, especially since New York City does not experience hurricanes as often as other locations along the coast (Pielke 1997; Mileti 1999; Blake and Gibney 2011; Cangialosi and Berg 2012). The Great New England Hurricane in 1938 made landfall at Long Island, New York as a Category 3 event (Spignesi 2002) and provides a perspective on the possibility of a high-end case occurring in this MSA. There were more than 600 deaths, over 1700 injuries, and approximately 23,000 structures damaged in this hurricane. The number of buildings impacted was relatively low compared to the potential built environment damage tallies if a similar storm were to occur again in the modern era. If a storm like the Great New England Hurricane occurred again today, it would be one of the greatest disasters in US history in terms of HU impacts alone (Spignesi 2002). All of the MSAs are completely encompassed within the All Storm and Major Storm synthetics, indicating that any growth

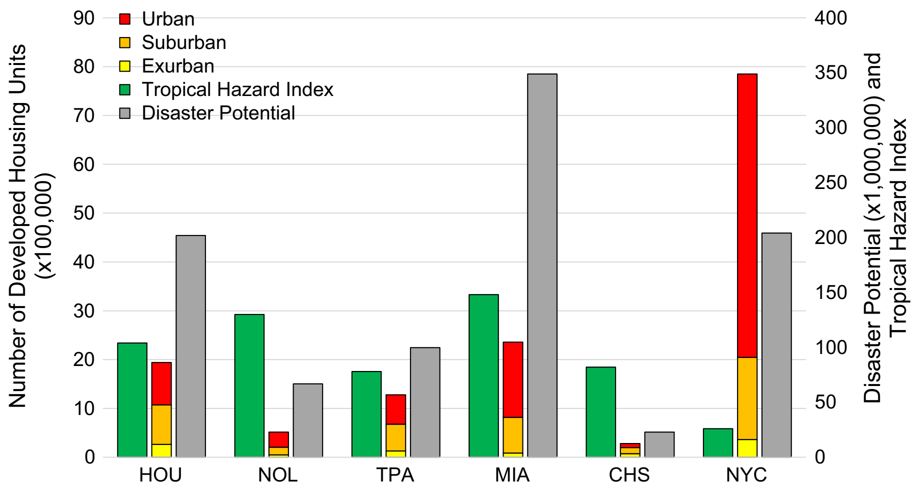


Fig. 8 Tropical Hazard Index (*green*; from Keim et al. 2007), the number of housing units in 2010 by land use (where *yellow* is exurban, *orange* is suburban, and *red* is urban), and a combined disaster potential (*gray*), which is calculated by multiplying the number of housing units (i.e., residential exposure) by the Tropical Hazards Index (i.e., risk) in each MSA

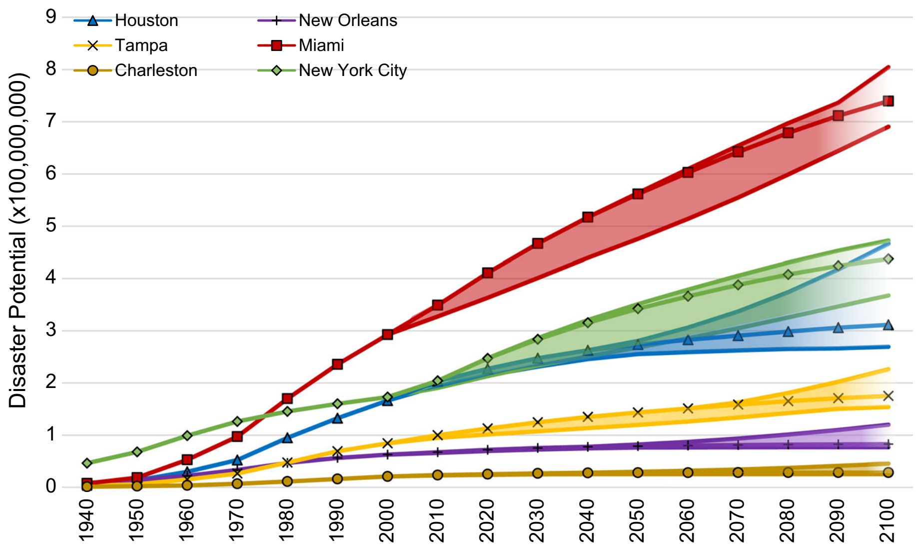


Fig. 9 Change in disaster potential from 1940 to 2100, where the upper bound is the highest potential of housing unit projections, the lower bound is the lowest potential of the projections, and the marked line is the A1 projection

that the MSAs experience in the future would be impacted by both theoretical storms. All MSAs illustrate the amplification of exposure, an important predictor of disaster consequences.

3.4 Disaster potential

We generate a metric that assesses disaster potential of an MSA by calculating the product of the theoretical HU exposure and the tropical cyclone climatological risk of an MSA. The climatological risk is defined by the Tropical Hazard Index (THI; Keim et al. 2007), which is derived from the intensity and frequency of landfalling storms from 1901 to 2005. In this index, a tropical storm strike is awarded two points, a Category 1 to 2 is awarded four points, and a Category 3 or greater is awarded eight points. The THI provides a simple geographical index that may be used to denote the risk of the Atlantic and Gulf Coastlines to tropical cyclones. The number of HUs that were within an MSAs developed footprint (exurban, suburban, and urban) are summed and used as the exposure constituent in disaster potential calculation. Each MSAs developed exposure value is multiplied by the MSA's THI to derive the disaster potential metric for the area over time (Fig. 8). Naturally, there are a considerable number of caveats in using this disaster metric. For instance, the calculation does not assess the plethora of social, physical, and non-residential, built environment vulnerabilities and capacities that can either magnify or attenuate disaster potential. Additionally, each MSA has distinct physical characteristics (e.g., differences in bathymetry, bay and estuary system, hazard reduction infrastructure) that could greatly modify the disaster potential. Additionally, there may be variability in risk change across time and space that could affect the results. The goal here is to deliver a broad view to disaster potential, providing a basis for additional future interrogation of other important disaster constituent variables.

In 1940, the New York City MSA had the highest disaster potential because of its high exposure at the time compared to the other MSAs (Fig. 9). By 1980, the Miami MSA surpassed New York City and became the MSA with the highest disaster potential, primarily due to Miami's elevated tropical cyclone risk combining with the area's rapid exposure growth. Miami's disaster potential has intensified more rapidly than the other MSAs; it is expected to see a hundredfold increase in disaster potential from 1940 to 2100. New York City has the second greatest disaster potential through 2100 because of the large number of HUs within the developed footprint of the MSA. New York City's tropical cyclone risk was the lowest of the MSAs, indicating that the disaster potential of the MSA is largely driven by exposure. However, as Hurricane Sandy and the Great New England Hurricane illustrate, a low risk does not equate to zero risk. The Houston and Tampa MSAs experience a substantial disaster potential increase, growing by 5522 and 5739%, respectively. Compared to the other MSAs, New York City had the smallest change and is projected to experience an 853% growth in disaster potential from 1940 to 2100. The Charleston MSA has a higher climatological tropical cyclone risk than the New York City MSA and Tampa MSA, but has the fewest number of developed HUs. Since Charleston has relatively low exposure, the disaster potential is smaller than the other MSAs. Thus, all MSAs are projected to experience an increase in disaster potential over time, and that potential is largely driven by the exposure of residential development. Overall, there is a statistically significant ($t = 2.68$; $p = 0.04$) increase in the disaster potential from 1940 to 2100 for all MSAs. The analysis provides evidence that the disaster potential will continue to increase in the future and that the next landfalling hurricane may be far more disastrous than the USA has experienced to date.

4 Research constraints

As with any research, there are constraints to the data and methodologies employed. For instance, in this study, there are several caveats associated with extracting data from HURDAT2. First, the wind radii data “best-tracked” is only available beginning in 2004, which provided a limited sample to employ in hurricane synthetic creation—18 landfalling storms, of which seven were considered major. The number of landfalling hurricanes from 2004 to 2014 provided sufficient data to construct a synthetic hurricane, but may not be fully representative of landfalling hurricane potential. Additionally, compared to alternative wind swath data from, for example, H*Wind and QuikScat, HURDAT2 underestimates the operational wind radii, which, in turn, underestimates the wind radii used for the hurricane synthetics (Moyer et al. 2007). Further, “best-track” radii are based on a “survey” approach, and these data do not include other observational datasets, such as Doppler radar (Landsea and Franklin 2013). Overall, the database is incomplete and limited, but efforts are being made to re-analyze and expand the dataset (Landsea and Franklin 2013). Another caveat of this research is that, for some storms, surge and rainfall could be the most damaging part of the storm rather than the assessed “wind” component herein.

The five ICLUS scenarios provide snapshots of potential residential and land use growth in the twenty-first century; however, these deterministic scenarios are not the only possible futures in a large spectrum of societal and environmental possibilities. It is likely that residential growth will deviate from the predicted ICLUS scenarios. There are model inputs and assumptions that can modify the overall projection of each scenario. For instance, the spatial allocation model assumes that growth rates and patterns will be like those of recent years (1990s to 2000; US EPA 2009). The model begins with an initial population at year t and develops a new population based on demographic transition for year $t + 1$. It is important to recognize that ICLUS data are employed to *estimate* the potential impact of hurricanes if HU trends continue to grow, and *not provide* a single deterministic solution or expectation. Rather than employing the residential built environment impacts calculated in this study as absolutes, the data should be used to explore evolution in land use and the relative importance of exposure change to the disaster landscape.

This study examined solely residential exposure theoretically impacted by a landfalling hurricane. There are many vulnerability factors beyond residential exposure that can amplify or attenuate disaster consequences. For instance, future research should assess additional socioeconomic vulnerabilities of MSAs, including variables such as age, race, poverty. Though many of these variables are now collected by the Census Bureau, the enumerations often change from one census to the next, making spatiotemporal comparisons—which was a hallmark of this study—difficult. Research has revealed that communities with high proportions of, for instance, minorities and elderly are particularly vulnerable to disaster impacts (Cutter et al. 2003, 2007; Flanagan et al. 2011). Race and ethnicity poses potential language and cultural barriers that can affect how a person copes with disaster (Cutter et al. 2003). The elderly tends to have greater mobility constraints that can affect abilities to react to an impending disaster. Other particularly vulnerable populations include those of low income status, women and children, and those of high social dependence (Cutter et al. 2003).

Understanding how vulnerable segments of the population have changed, and will possibly change in the future, will provide a better estimate potential tropical cyclone disaster impacts. Additionally, identifying the type of residential unit, as well as its age, alters the fundamental exposure and vulnerability constituent investigated in this study. For example, mobile homes are far more vulnerable than timber frame build homes because they cannot withstand high winds, whether hurricane, thunderstorm, or non-thunderstorm induced (Cutter et al. 2003; Donner 2007). Also, assessing how building codes are implemented and enforced at the local level would promote a greater understanding of the true vulnerability of the built environment (Simmons and Sutter 2008). If building codes are not applied or enforced, a residential unit is more likely to be constructed inadequately and, therefore, more probable to sustain structure failure affiliated with hurricanes and other wind hazards (Burby 2006; Tansel and Sizirici 2011). Destruction to other critical infrastructure—such as bridges, hospitals, or power plants—can influence a disaster as well and should be considered in future disaster potential assessment. Ultimately, this research provided a broad understanding of both historical and future exposure changes for the residential built environment at threat to a hurricane disaster. A more sophisticated, and arguably more complex, research model incorporating additional variables—storm attributes such as rainfall rate and surge measurements; a full census of the built environment and integrity of that environment; important socioeconomic and demographic factors—would promote a more robust disaster potential assessment.

5 Discussion and conclusion

This study provided an assessment of historical and future exposure to tropical cyclones in the USA and evidence that the change in the residential built environment continues to alter the disaster landscape. At the regional level, residential density within 50 km of the coastline was greater than the rest of the contiguous USA, and this highly vulnerable region is expected to continue to experience substantial future exposure growth. Spatiotemporal trends of residential exposure in six at-risk MSAs along the Atlantic and Gulf Coasts were also assessed, revealing how disaster potential has evolved and is projected to change in these areas over a 160-year period. Results revealed immense growth in housing and land use—both historically and in future projections through 2100—within all MSAs studied. Each MSA has unique growth rates and patterns, but all MSAs experienced statistically significant growth in housing exposure from 1940 to 2010. The number of HUs in New York City increased the most of the MSAs, but Miami had the greatest percent change in HUs during the period. The sustained residential growth uncovered is expected to further expose coastal regions to tropical cyclones and their affiliated hazards.

The increasing tropical cyclone disaster potential varies across time and space; generally, MSAs in the lower latitudes are at a greater risk of tropical cyclone hazards than areas more poleward (Brettschneider 2008; Keim et al. 2007; Blake and Gibney 2011; Czajkowski et al. 2011; Cangialosi and Berg 2012). The frequent occurrence of hurricane landfalls and the rapid growth of the MSA increase the risk of disaster now and in the future. Due to the juxtaposition of exposure, its growth, and the highest landfall risk of any MSA along the Atlantic and Gulf Coasts (Kiem et al. 2007), Miami currently has the highest disaster potential of the MSAs investigated and is projected to have the highest disaster potential in the future; however, hurricanes can make landfall anywhere along the Atlantic and Gulf Coasts. The possibility of more intense hurricanes in a warming world (Knutson et al. 2010; Nordhaus 2010; IPCC 2012; Wong et al. 2014; NAS 2016; Walsh et al. 2016), in conjunction with rapidly increasing exposure along the coastline, will create higher magnitude tropical cyclone disasters than the USA has ever experienced (Pielke 1997; Mileti 1999).

While wind swaths were the tropical storm hazard used to explore impact potential, most tropical cyclone hazards include storm surge and flooding. In addition, studies reveal that sea level rise will have potentially disastrous consequences in the future (Pielke et al. 2008, Maloney and Preston 2014; Hay et al. 2015; Carson et al. 2016; Hauer et al. 2016). The already substantial storm surge hazard associated with landfalling hurricanes will amplify as the elevated sea will combine with storm-induced surges to create greater coastal flooding and catastrophic wave action in the future. With the global mean sea level projected to rise more than 1.5 meters by 2100 (DeConto and Pollard 2016), storm surge amplification due to sea level rise will induce a greater threat to all coastal locations, including those that were once thought to be safe from surge impacts (Rowley et al. 2007; Hauer et al. 2016). Low-lying areas, which characterize all the MSAs investigated in this study, are becoming more exposed to tropical inundation as sea level rises, which is increasing the likelihood of disaster when a tropical cyclone event occurs.

As the built environment footprint continues to swell in areas exposed to possible tropical storm hazards, the threat of US hurricane disaster increases. If, for example, the US coast lacked people and their assets, a landfalling hurricane would not pose a significant threat to local, regional, and national socioeconomic systems. The coast has experienced an influx of people because of the area's idyllic features, despite the potential for hurricane impacts. Additionally, people typically only plan for the immediate future, overestimate their capability of recovering from a disaster, and heavily rely on emergency relief (Mileti 1999). The government subsidizes disaster relief, flood insurance, and coastal infrastructure improvements through tax dollars, providing a "back up plan" for those living in risk-prone areas (Steinburg 2000; Sutter 2007).

Minimizing loss of life and costs is a general goal of US hurricane policy (Pielke 1997), but it is important to consider actions that reduce vulnerability, and therefore, reduce disaster potential. There have been proposals to reduce US vulnerability, including: changes in land use (Cutter et al. 2007); adjustments in federal disaster assistance and mitigation policies; improvements to hurricane forecasting; and new evacuation strategies (Pielke 1997). On average, every $1 used for mitigation strategies can prevent $7 in disaster recovery costs (Abramovitz 2001). Retrofitting structures is an effective mitigation method that allows buildings to be reinforced and become more hazard-resistant (Smith 2013). Communicating effectively tropical cyclone disaster risk to residents in these areas will promote a more informed, risk-averse populace that may be more motivated to employ hazard mitigation and adaptation strategies. By understanding the effects of hazards and working together, society can reduce the consequences of future disasters (Abramovitz 2001).

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