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Changes in tornado risk and societal vulnerability leading to greater tornado impact potential

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Tornado risk, as determined by the occurrence of atmospheric conditions that support tornado incidence, has exhibited robust spatial trends in the United States Southern Plains and Mid-South during recent decades. The consequences of these risk changes have not been fully explored, especially in conjunction with growing societal vulnerability. Herein, we assess how changes in risk and vulnerability over the last 40 years have collectively and individually altered tornado-housing impact potential. Results indicate that escalating vulnerability and exposure have outweighed the effects of spatially changing risk. However, the combination of increasing risk and exposure has led to a threefold increase in Mid-South housing exposure since 1980. Though Southern Plains tornado risk has decreased since 1980, amplifying exposure has led to more than a 50% increase in mean annual tornado-housing impact potential across the region. Stakeholders should use these findings to develop more holistic mitigation and resilience-building strategies that consider a dynamically changing tornado disaster landscape.

Severe convective storms—those capable of creating perils such as non-tornadic damaging wind, large hail, and tornadoes—are responsible for approximately half of all United States (US) billion-dollar weather disasters since 1980[1]. The annual number of billion-dollar, severe convective storm-affiliated disasters has increased rapidly over the last two decades and combined annual losses have escalated by more than 1 billion USD (inflation-adjusted) every year[1]. Tornadoes present the greatest threat to life compared to other severe convective storm hazards, causing an average of more than 75 fatalities per year over the last 30 years[2]. Consequently, there is an ever-increasing need for research that evaluates how tornado-society impacts—as measured in this study by the potential number of housing units (HU) exposed to tornadic winds—have historically changed from both spatial and temporal perspectives. Our research addresses this dearth by providing a more holistic assessment of how a changing environment and society have *individually* and *jointly* influenced tornado-HU impact potential over the last 40 years.

Prior research that has investigated spatiotemporal changes in tornado-society relationships can be split into two groups: (1) those focused on climate change-driven alterations to atmospheric conditions known to influence severe weather and tornado production, intensity, and other hazard characteristics[3–14] and (2) those concentrated on human-driven changes to the underlying societal and built-environment landscape that are subject to tornado impacts[15–25].

Studies examining the relationships between atmospheric conditions and tornado occurrence have mostly assessed historical tornado observations and/or atmospheric condition-derived indices that serve as a proxy for possible tornado events[26–29]. Although research employing tornado observations permits more detailed analyses of tornado incidence and damage path characteristics, these data are often subject to biases given event information is collected through public reporting and post-event damage surveys conducted by National Weather Service (NWS) forecasters and, on rare occasion, structural engineers[30–33]. One such atmospheric measure that has been used to combat these shortcomings is the significant tornado parameter (STP)[34]. A recent study noted that annual accumulated diurnal maximum STP is a statistically significant (p-value ≤ 0.05) covariate to tornado incidence, explaining 44% of the variance in annual tornado reports across the conterminous US from 1979 to 2017[27]. Robust trends in the number of days supportive of tornadoes was uncovered using this method, indicating that many locations in the lower Mississippi Valley or Mid-South region have witnessed an increase of more than 2 days per decade supportive of tornadoes since 1980[27].

Research assessing changes in climatological tornado risk (i.e., the probability of a tornado occurring in space and time[35]) only provides a partial answer to the question of why there is a growing tornado loss trend. Societal factors such as vulnerability, exposure, and adaptive capacity also play key roles in determining tornado impact frequency and severity[15,36–43].

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Vulnerability is commonly defined as the potential for a person or community to suffer harm from a hazard and encompasses the concepts of exposure and adaptive capacity. Exposure is defined as people, property, assets, and/or systems present in geographies that are subject to potential losses, while adaptive capacity relates to the ability of an individual, community, or system to cope or adapt to hazard conditions[37,44]. Several prior studies have examined how changing societal vulnerability and/or exposure influences tornado impacts, finding that rapidly increasing vulnerability and exposure is leading to more frequent and greater impacts on society[18,20,22]. This escalating hazard exposure issue has been termed the expanding bull's-eye effect, which describes the relationship between built-environment growth—often referred to as urban and suburban sprawl—and more frequent and greater magnitude hazard impacts[18,45]. This type of research often relies on secondary datasets such as the US Census enumerations and land use/land cover estimates spanning multiple decades to describe how societal factors such as the number of people, homes, and other built-environment entities are growing and, ultimately, leading to greater hazard exposure over time[23]. Other researchers have used spatiotemporal data that represent the underlying population or community to assess how changes in social vulnerability metrics (e.g., age, race, ethnicity, household income, and educational attainment) have led to greater distress during and after tornadoes affect communities[38,40,43,46].

Additional research over the last two decades has used spatially explicit tornado impact modeling to estimate potential damage to exposed societal entities (i.e., homes, people, and critical infrastructure[18,22]). These studies often use climatological risk and societal exposure data to simulate hazard events atop exposed geographies, revealing the importance of built-environment growth and changing atmospheric conditions on societal impact probabilities. Most notably, research using these methods in conjunction with tornado hazards has illustrated that societal impact probabilities and magnitudes are dynamic and controlled by fundamental tornado disaster constituents of risk and exposure[20,21].

Our study builds on prior work by highlighting US counties and regions where both climate change variability-driven alterations in tornado risk and societal growth-driven changes to vulnerability and exposure have collectively led to greater tornado-society impact potential. We also determine which tornado disaster constituent—risk or exposure—has been the primary driver of changes to societal impacts (as measured by tornado-HU impacts) over the last 40 years, especially in regions that have historically experienced the greatest change in tornado activity over time. We employ data from a recent study that assessed historical changes in tornado environments using spatiotemporal representations of annual accumulated daily maximum STP[27]. These data permit the determination of how favorable tornado environments have changed in US county administrative boundaries from 1980 to 2020. Again, in this study, we equate climatological tornado risk to the favorable tornado environment frequency data aggregated to counties to avoid any potential reporting or post-event damage survey biases often found in tornado event data[27]. County-level Census vulnerability enumerations for the years 1980 and 2020 are also examined to determine where and how societal vulnerability and exposure have historically changed across the US.

Lastly, we use the Tornado Impact Monte Carlo (TorMC) model[47], climatological tornado risk data, and a fine-scale HU density dataset (i.e., Spatially Explicit Regional Growth Model (SERGoM)-Integrated Climate Land Use Scenario v1 (ICLUSv1)[48,49] to conduct potential tornado-HU impact simulations. These simulations follow prior research techniques[23], updating and improving knowledge about the relative *individual* and *combined* effects of changing tornado risk and societal exposure on tornado-HU impact frequency and severity. Overall, our research aims to provide a more thorough understanding of how tornado-HU impact potential has been historically shaped by the combination of dynamically changing environmental and societal landscapes.

Results

Changing tornado risk and population

The Mid-South region has experienced a notable increase in tornado risk over the last 40 years when using accumulated annual STP as a proxy for tornado incidence (Fig. 1A; Table 1). There has also been a robust decrease in climatological tornado risk across the Southern Plains during the same timeframe. The Mid-South's amplifying trend is attributed to increasing low-level storm-relative helicity juxtaposed with greater instability[27]. Conversely, a long-term increase in convective inhibition is primarily responsible for the associated decrease in tornado risk in the Southern Plains[50,51].

When aggregating STP-derived tornado risk changes to county boundaries, 8 of the top 10 ranked counties that have experienced an increase in tornado activity are in Mississippi (Fig. 2A, B; Table 1). Simultaneously, the top 10 counties that have experienced decreasing tornado risk are in central and southern Texas. Five counties in the US—all residing in Mississippi—have had their mean annual number of tornado days increase by more than 3.5 days per decade since 1980. Lafayette County, Mississippi, had the greatest increase in tornado risk compared to all other counties, with a mean decadal change of +4.1 tornado-supportive days. Grimes County, Texas, is the only US county that experienced a decrease in the number of tornado-supportive days greater than 2.5 tornado days per decade. These results are in line with prior research that investigated historical changes in tornado frequency[26–28].

Eastern US counties associated with large population centers experienced the greatest increase in total population from 1980 to 2020 (Fig. 1B; Table 2). However, population has declined over time in some urban counties such as Allegheny County, PA (Pittsburgh), Cook County, IL (Chicago, IL), Cuyahoga County, OH (Cleveland), Erie County, NY (Buffalo), and Wayne County, MI (Detroit), while the suburban and exurban counties adjacent to these urban-core counties simultaneously witnessed substantial population growth.

We further assessed changes in tornado exposure by comparing county population density in 1980 and 2020 (Fig. 1; Panel C). Only six counties in the study area have experienced a decrease in population density since 1980: Forest County, PA, Hamilton County, NY, Daggett County, UT, Harding County, NM, Keweenaw County, MI, and Terrell County, TX. Counties associated with cities such as Boston, MA, New York City, NY, Philadelphia, PA, and Washington, D.C., contained the greatest increase in population density over the 40-year study period.

Approximately 59.8% (1203 of 2013) of counties examined in this study witnessed both an increase in tornado days and population for the 1980–2020 period (Fig. 1; Panel D). Only 4.1% (82 of 2013) of counties experienced a decrease in both tornado risk and population. Approximately 7.5% (150 of 2013) of counties have observed an increase in population but a decrease in tornado risk, while 28.6% (578 of 2013) of counties had a decrease in population and an increase in tornado risk. These results suggest that changing societal exposure has offset some of the possible climate change-driven shifts to tornado risk over the last four decades. The inverse of this relationship is also true for counties that had a decrease in population and an increase in tornado risk over time.

The mean annual number of tornadoes increased 2.7 days per decade on average for counties in the 95th percentile and greater for tornado risk changes (i.e., Mid-South region). The population increased by 9816 persons per county or 18.9 persons per km^2 on average (mean) in these same counties for the 1980–2020 period. Conversely, the mean annual number of tornado days decreased by 1.2 tornadoes per decade in Southern Plains counties (i.e., counties within the 5th percentile of tornado risk changes). However, the total population in these counties rapidly increased over time, escalating by an average (mean) of 81,361 people or 51 people per km^2 per county.

Nearly 88% (134 of 153) of counties in the 95th percentile and greater in tornado risk changes are in Alabama, Arkansas, Mississippi, and Tennessee. The top 10 counties in the Mid-South have all experienced an increase in their total population of greater than 45,000 people over the 40-year period (Fig. 2C, D; Table 2). Madison County, AL, had the largest population growth, adding over 27,000 people per decade. The total population increased by more than 100,000 people in counties such as Shelby, TN (Memphis, TN), Washington, AR (Fayetteville, AR), Johnston, NC (Raleigh, NC suburban area), and DeSoto, MS (Memphis, TN suburban area). These counties represent those

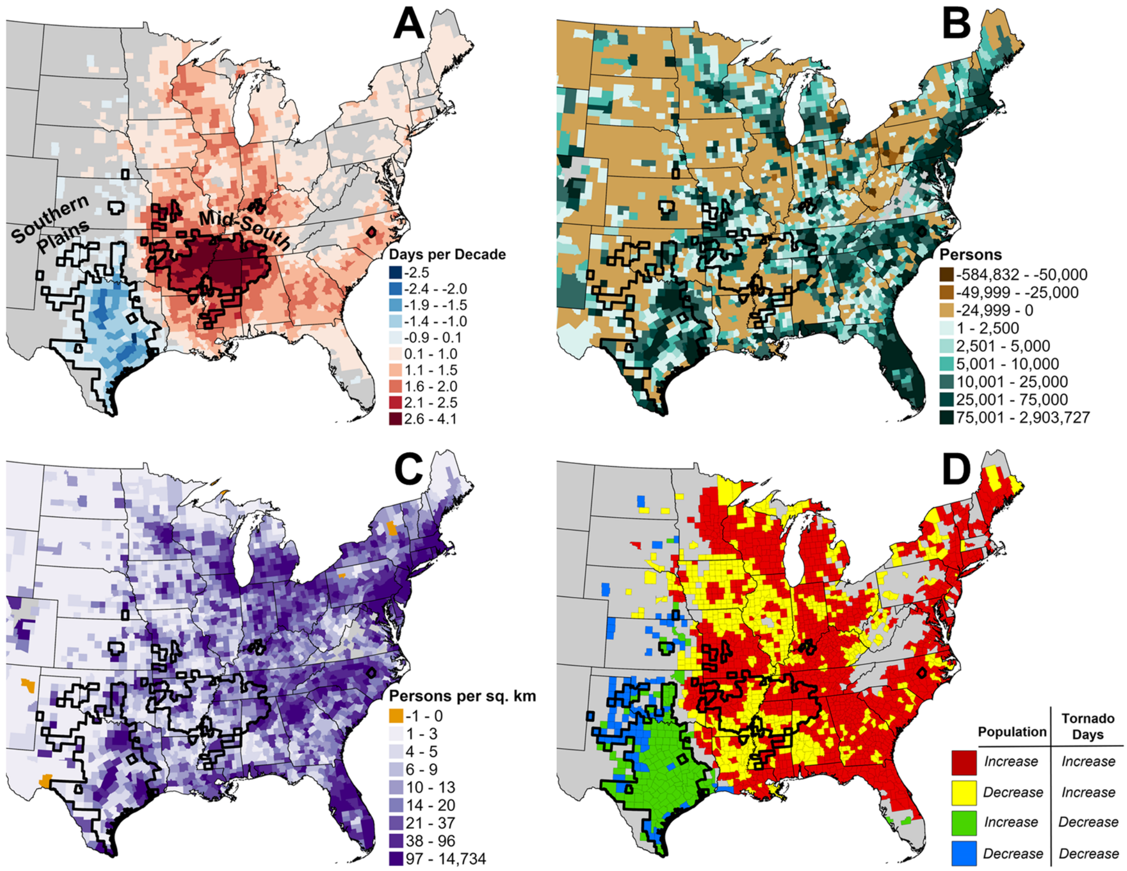

Fig. 1 | Tornado risk and societal exposure changes. County-level change (1980–2020) in the **A** favorable number of tornado days per decade as measured by the annual accumulation of significant tornado parameter (STP). Bold (black) outlined counties denote those that are within the 95th (Mid-South) or 5th (Southern Plain) percentile ranking for changes in tornado days from 1980 to 2020. Counties with no change in decadal tornado days or those removed from analyses are colored gray. Also provided are county-level absolute changes in **B** the number of persons and **C** population density (persons per km^2) from 1980 to 2020. Panel **D** highlights the county-level combinations of increasing or decreasing tornado days paired with increasing or decreasing population from 1980 to 2020.

that experienced both a robust increase in tornado activity as well as considerable population growth since 1980.

Not all counties in the Mid-South have witnessed their total population increase. For instance, the total population in rural eastern Arkansas and western Mississippi counties decreased by more than 7000 people per county since 1980, yet tornado risk has simultaneously increased in these areas. Washington County, MS witnessed the decrease in population (−27,272) over the period, followed by Jefferson County, AR (−22,595), and Mississippi County, AR (−18,121).

Table 1 | Top 10 ranking for counties that have experienced the greatest increase in tornado days per decade from 1980 to 2020

Rank	Tornado day change per decade	County	State
1 (3048)	4.1 (−2.5)	Lafayette (Grimes)	Mississippi (Texas)
2 (3047)	3.6 (−2.4)	Marshall (Comanche)	Mississippi (Texas)
3 (3046)	3.5 (−2.4)	Benton (Erath)	Mississippi (Texas)
4 (3045)	3.5 (−2.3)	Tate (Austin)	Mississippi (Texas)
5 (3044)	3.5 (−2.3)	Pontotoc (Hamilton)	Mississippi (Texas)
6 (3043)	3.4 (−2.2)	Chester (Palo Pinto)	Tennessee (Texas)
7 (3042)	3.4 (−2.1)	Union (Colorado)	Mississippi (Texas)
8 (3041)	3.3 (−2.1)	Crittenden (Lavaca)	Arkansas (Texas)
9 (3040)	3.3 (−2.1)	Alcorn (Waller)	Mississippi (Texas)
10 (3039)	3.3 (−2.0)	Lee (Calhoun)	Mississippi (Texas)

Parentheticals indicate those counties that had the greatest decrease in tornado days for the same period. Cf. Fig. 2A, B.

Tornado risk has decreased the most since 1980 in the Southern Plains region (i.e., 5th percentile in tornado risk change; Table 3). Over 85% (137 of 159) of the counties in the Southern Plains are in Texas. The population has swelled by more than 1MM people since 1980 in the Texas counties of Harris (Houston, TX), Tarrant (Fort Worth, TX), and Dallas (Dallas, TX). Counties where tornado risk and population have decreased the most over time are primarily located in Texas. Specifically, Gray County Texas (Pampa, TX) is where this region's population decline was greatest, losing more than 4323 people over the four decades. Population also decreased by more than 750 people per decade in Southern Plains counties such as Dawson, TX (Lamesa, TX), and Wilbarger, TX (Vernon, TX). Together, these findings illustrate where tornado exposure has been reduced due to decreasing tornado risk and a declining population.

Changing tornado risk coupled with changes in societal vulnerability

Assessing changes in societal vulnerability in counties that have experienced notable increases in tornado risk provides further insight into the dynamically evolving relationship between risk and vulnerability (Fig. 3; Table 3). Only 5 of 17 metrics denoted an improvement in vulnerability across the US from 1980 to 2020. These variables include poverty (−3.4%), unemployed persons (−0.5%), persons under the age of 18 (−7.6%), persons under the age of five (−1.8%), percentage of persons that are female (−0.7%), and the

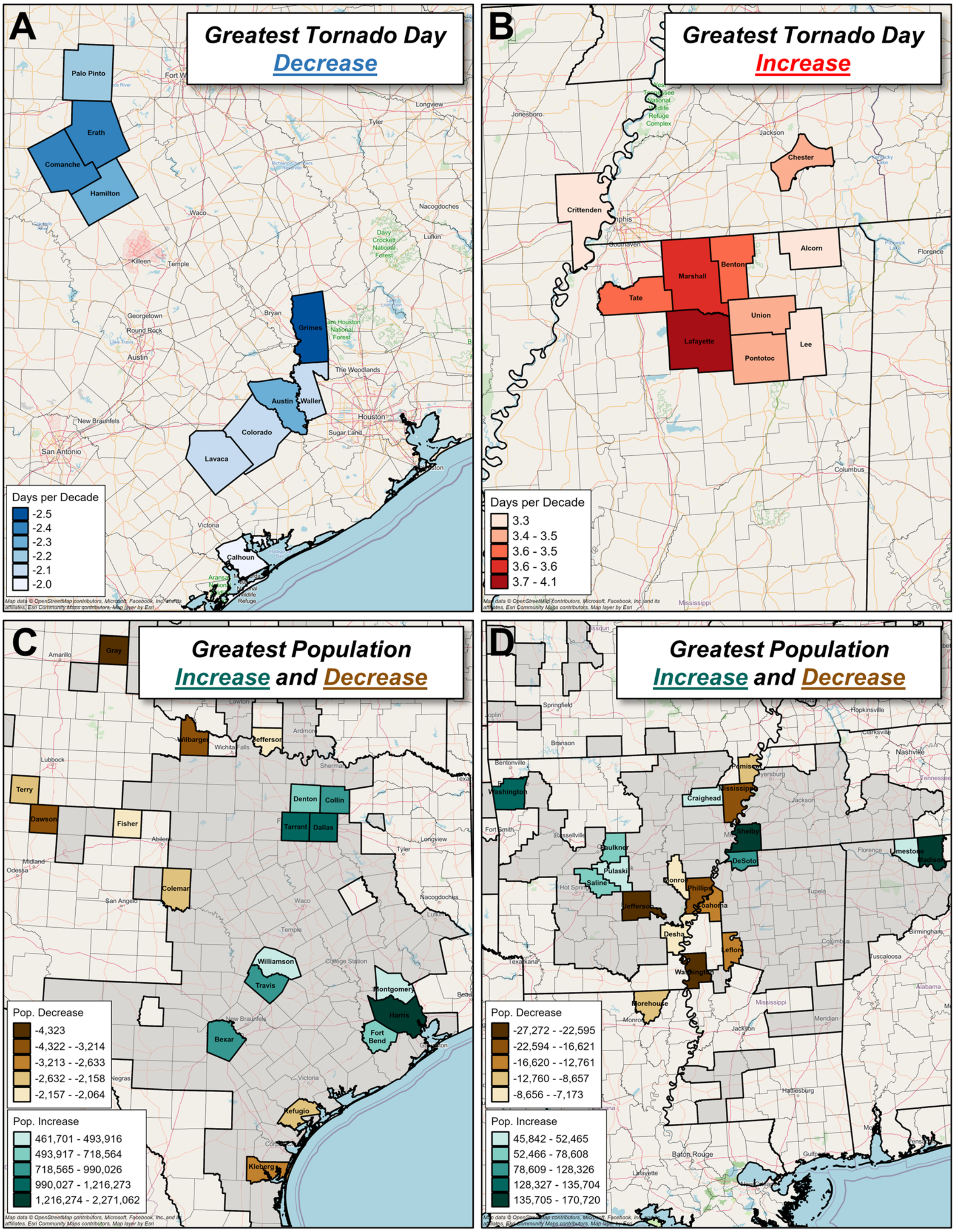

Fig. 2 | Counties with the greatest change in tornado risk and societal exposure. Top 10 county-level rankings for greatest **A** decrease and **B** increase in mean tornado days per decade from 1980 to 2020. Panel **C** and **D** represent the top 10 county-level rankings within the 5th percentile in tornado day changes region and 95th percentile in tornado day changes region. The transparent gray area of map represents the 5th percentile in tornado day changes region (Panel **C**) and the 95th percentile in tornado day changes region (Panel **D**). Gage County, Nebraska (Panel **C**) and Johnston County, NC (Panel **D**) are not shown in their respective maps as they are too far outside of the region to be mapped in conjunction with the other counties. Cf. Tables 1 and 2.

percentage of persons who did not graduate high school (−37.7%). The number of persons with a high school diploma increased the most over the 40-year study period followed by the percentage the US population under the age of 18. These findings support prior research that has illustrated that US high school educational attainment has increased dramatically over the last half century[52]. Further, US birth rates are at record lows in recent years, leading to fewer young people (e.g., less than 5 years of age)[53].

Many other metrics assessed in this work demonstrate an increasing vulnerability trend. The percentage of homes that are considered manufactured has increased most compared to all other vulnerability measures, escalating 12.3% in the last 40 years. This increasing percentage has occurred despite the number of newly constructed and shipped manufactured homes decreasing over the last decade[54]. Other vulnerability measures that have increased since 1980 include persons needing public assistance (+2.6%),

Table 2 | Changes in population from 1980 to 2020 for counties that are within the 95th (Mid-South) and 5th (Southern Plains) percentile for changes in tornado days per decade from 1980 to 2020

Rank	Mid-south region Population change	Mid-south region County, State	Southern plains region Population change	Southern plains region County, state
1 (153)	170,720 (−27,272)	Madison, AL (Washington, MS)	2,271,062 (−4323)	Harris, TX (Gray, TX)
2 (152)	159,498 (−22,595)	Shelby, TN (Jefferson, AR)	1,216,273 (−3335)	Tarrant, TX (Dawson, TX)
3 (151)	135,704 (−18,121)	Washington, AR (Mississippi, AR)	1,066,244 (−3214)	Dallas, TX (Wilbarger, TX)
4 (150)	132,709 (−16,621)	Johnston, NC (Phillips, AR)	990,026 (−2908)	Bexar, TX (Gage, NE)
5 (149)	128,326 (−14,233)	DeSoto, MS (Coahoma, MS)	861,462 (−2633)	Collin, TX (Kleberg, TX)
6 (148)	78,608 (−12,761)	Faulkner, AR (Leflore, MS)	831,311 (−2274)	Travis, TX (Refugio, TX)
7 (147)	67,829 (−9614)	Saline, AR (Morehouse, LA)	718,564 (−2173)	Denton, TX (Terry, TX)
8 (146)	52,465 (−8657)	Pulaski, AR (Pemiscot, MO)	660,046 (−2158)	Fort Bend, TX (Coleman, TX)
9 (145)	50,916 (−8222)	Limestone, AL (Desha, AR)	493,916 (−2099)	Williamson, TX (Jefferson, OK)
10 (144)	45,842 (−7173)	Craighead, AR (Monroe, AR)	461,701 (−2064)	Montgomery, TX (Fisher, TX)

The top 10 county-level ranking for highest and lowest population change over the study period is provided. Values and text in parentheses represent the bottom 10 ranking for county-level population changes. Cf. Fig. 2C, D.

Table 3 | Vulnerability metrics and absolute changes in the mean percentage, percentile ranking, and differences in vulnerability metrics from 1980 to 2020 for counties that are within the 95th (i.e., Mid-South) and 5th (i.e., Southern Plain) percentile for changes in tornado days per decade from 1980 to 2020

Category	Metric	1980 Mean %	1980 Mean percentile ranking	2020 Mean %	2020 Mean percentile ranking	Differences Mean % difference	Differences Mean percentile ranking difference
Socio-economic	Poverty	21.8 (16.5)	0.76 (0.57)	18.4 (13.7)	0.73 (0.49)	−3.4 (−2.9)	−0.030 (−0.077)
	Unemployed	3.2 (1.5)	0.61 (0.16)	2.7 (2.2)	0.59 (0.47)	−0.5 (0.7)	−0.019 (0.310)
	Public Assistance	13.8 (8.2)	0.81 (0.52)	16.4 (12.3)	0.67 (0.47)	2.6 (4.1)	−0.134 (−0.048)
Housing	Manufactured Homes	9.3 (8.1)	0.52 (0.43)	21.5 (18.0)	0.66 (0.57)	12.3 (9.9)	0.141 (0.145)
	Renters	26.4 (27.0)	0.48 (0.50)	29.4 (27.9)	0.55 (0.49)	3.0 (0.9)	0.073 (−0.011)
Age	Aged 65+	14.1 (15.6)	0.59 (0.63)	18.5 (18.3)	0.45 (0.44)	4.4 (2.8)	−0.135 (−0.183)
	Aged 17 or Younger	30.3 (28.5)	0.57 (0.42)	22.7 (23.4)	0.57 (0.64)	−7.6 (−5.1)	0.005 (0.217)
	Aged 4 or Younger	7.7 (7.6)	0.52 (0.47)	5.9 (6.2)	0.57 (0.61)	−1.8 (−1.4)	0.046 (0.132)
Race and Ethnicity	Non-white	21.4 (14.1)	0.67 (0.67)	30.0 (31.2)	0.62 (0.69)	8.6 (17.0)	−0.048 (0.028)
	Black	20.6 (7.1)	0.72 (0.59)	22.7 (6.7)	0.72 (0.54)	2.1 (−0.4)	−0.009 (−0.046)
	Hispanic	0.1 (5.2)	0.27 (0.88)	3.9 (29.3)	0.36 (0.87)	3.8 (24.1)	0.093 (−0.009)
Migration	Migrants	0.2 (1.3)	0.30 (0.76)	0.6 (1.7)	0.35 (0.63)	0.4 (0.4)	0.056 (−0.132)
Language	Poor English	1.3 (15.9)	0.19 (0.79)	1.5 (6.4)	0.36 (0.79)	0.1 (−9.5)	0.173 (0.003)
Disability	Disability	7.8 (5.7)	0.80 (0.46)	9.8 (7.3)	0.76 (0.48)	2.0 (1.5)	−0.037 (0.015)
Sex	Female	51.5 (50.9)	0.68 (0.54)	50.9 (49.4)	0.67 (0.44)	−0.7 (−1.5)	−0.010 (−0.103)
	Female Head of Household	6.8 (4.8)	0.65 (0.42)	14.2 (11.7)	0.71 (0.58)	7.4 (6.9)	0.061 (0.152)
Education	No High School Diploma	51.9 (46.6)	0.77 (0.65)	14.1 (14.2)	0.70 (0.65)	−37.7 (−32.5)	−0.065 (0.006)
Overall	**All**	−(−)	**0.71 (0.66)**	− (−)	**0.70 (0.68)**	− (−)	**−0.01 (−0.02)**

Values in parentheses represent mean vulnerability measures for Southern Plains counties.

renters (+3.0%), persons 65 years of age and older (+4.4%), minority populations (+8.6%), Hispanic populations (+3.8%), and female head of households (+7.4%). Of these amplifying vulnerability metrics, the minority population percentage has increased most given the increased international migration of Asian, Latino, or Hispanic populations over the last few decades[55]. The percentage of female heads of households has also increased substantially, with this finding being attributed to lower marriage rates and a larger percentage of females purchasing homes[56].

Equally weighting all 17 vulnerability measures into an overall county-level societal vulnerability metric indicates that counties, where tornado risk increased the most over time, are in the 70th percentile and greater for societal vulnerability compared to the US mean (50th percentile). Thus, the overall vulnerability in counties where tornado risk has increased over time are 20% more vulnerable on average in 2020 compared to all other US counties. There was very little change in the overall vulnerability percentile ranking from 1980 through 2020 for counties in the Mid-South, suggesting that there has not been an improvement in resilience in the most tornado fatality-prone region of the US[15,20]. Individual vulnerability metrics such as manufactured housing, minority population, etc., illustrate that critical individual household or population vulnerability measures may be rapidly

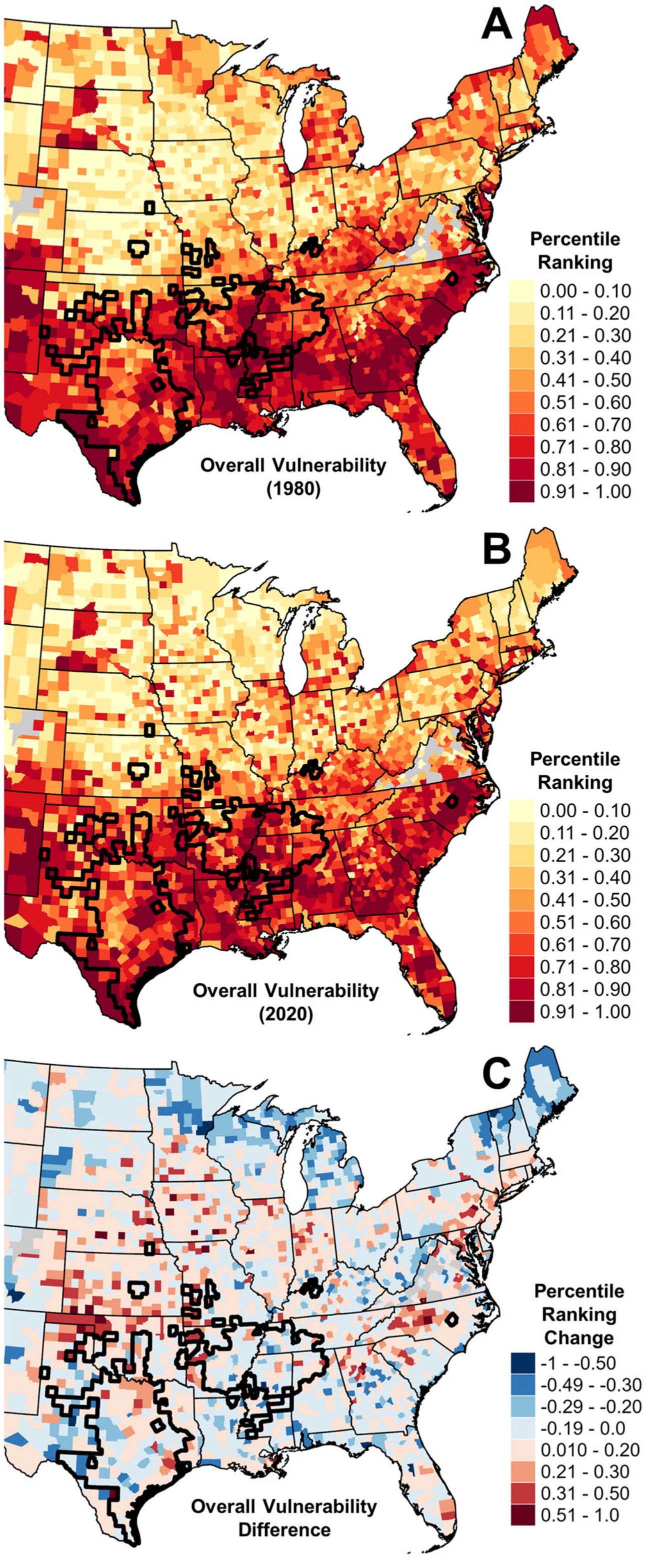

Fig. 3 | Changes in county-level societal vulnerability. County-level overall vulnerability percentile ranking for **A** 1980 and **B** 2020. Panel **C** illustrates the change county-level percentile ranking from 1980 to 2020. Bold (black) outlined counties denote those that are within the 95th (Mid-South) or 5th (Southern Plains) percentile ranking for changes in tornado days from 1980 to 2020.

increasing in areas where tornado risk—again, as measured by favorable tornado environment frequency—is also growing.

Counties that have experienced the greatest decline in tornado risk over time would normally result in decreasing tornado-HU impact potential. However, many Southern Plains counties have experienced an increase in societal vulnerability and exposure since 1980 (Fig. 3; Table 3). Specifically, 7 of 17 (41.2%) vulnerability measures in the Southern Plains illustrate decreasing vulnerability over time. These include poverty (−2.9%), percentage of the population under the age of 18 (−5.1%), persons less than 5 years old (−1.4%), black population (−0.4%), persons with poor English (−9.5%), female population (−1.5%), and those with no high school diploma (−32.5%). Increases in vulnerability are evident across 10 Southern Plains vulnerability measures, with the percentage of non-white population increasing most in the region at over 24%. Again, this is largely attributed to strong international migration from Hispanic or Latino countries from which many persons seek employment in agricultural settings in the Great Plains[57–59].

Other increasing vulnerability measures such as the non-white population percentage (+17%), manufactured home percentage (+9.9%), persons on public assistance (+4.1%), persons over 65 years old (+2.8%), and percentage of homes with a female head of household (+6.9%) all suggest escalating societal vulnerability in the Southern Plains. However, the overall vulnerability mean percentile ranking change (−0.02) does indicate that Southern Plains vulnerability has been neutral or decreasing slightly over time. Factors such as the percentage of the total persons that do not speak English well and/or living in manufactured homes are likely more important considering their ties to severe weather threat messaging[58,60] and sheltering issues[41,61–64].

Pragmatic tornado-housing impact simulations

Tornado-housing impact simulations provide context into which changing factor—risk or exposure—has been driving historical tornado-society impact probability. Overall, the mean annual tornado-HU impact potential east of the Continental Divide has increased by more than 80% (+9000 HUs) since 1980 (Fig. 4E; Table 4). The 90th percentile and greater probabilities represent those years where there were several large tornado outbreaks and/or many of the tornadoes traversed high-density, urban, and suburban areas such as Atlanta, GA, Chicago, IL, Dallas-Fort Worth, TX, etc. The variability (standard deviation) in annual EF1+ tornado-HU impact potential also increased by 46.1% over the 40-year period. East of the Continental Divide, the 90th percentile and greater annual tornado-HU impact probability increased by over 15,000 HUs, or 78.0%, since 1980. The 95th and 99th percentile probabilities also illustrate the same trend, with the 99th percentile escalating more than 24,000 HUs, or 65.1%, over four decades.

Scaling analyses down to the Mid-South and Southern Plains regions where risk has increased (95th percentile; Mid-South) or decreased (5th percentile; Southern Plains) over the last 40 years permits a more refined, region-based understanding of how US tornado-HU impact potential may be evolving over time (Fig. 4F; Table 4). The Mid-South's mean annual EF1+ tornado-HU impact potential has more than tripled over the last four decades. Simultaneously, the interannual variability in Mid-South tornado-HU impact potential doubled. Mid-South's 90th through 99th percentile tornado-HU impacts also increased over 100% since 1980, with 90th percentile values inflating by approximately 160%.

Tornado-HU impact potential in the Southern Plains also increased over the last few decades; albeit comparatively less than the Mid-South. This result was expected, given tornado risk in the Southern Plain has decreased over the last 40 years (Fig. 1A). Nevertheless, escalating exposure in the region led to an approximate 60% increase in mean tornado-HU impact potential. Associated interannual variability in tornado-HU impact probabilities swelled over the same period, rising by more than 1000 HUs, or 73.0%. Southern Plains' 90th percentile and greater annual impact probabilities have all increased more than 1200 HUs, or 57%, with 99th percentile impacts increasing most at nearly 5000 HUs, or 79.2%.

Comparing changes in tornado-HU impact potential for the Mid-South and Southern Plains shows that Mid-South tornado-HU impact potential has increased notably more than the Southern Plains (Fig. 4F; Table 4). This result is attributed to both the increasing tornado risk and built-environment growth the Mid-South has experienced over the last four

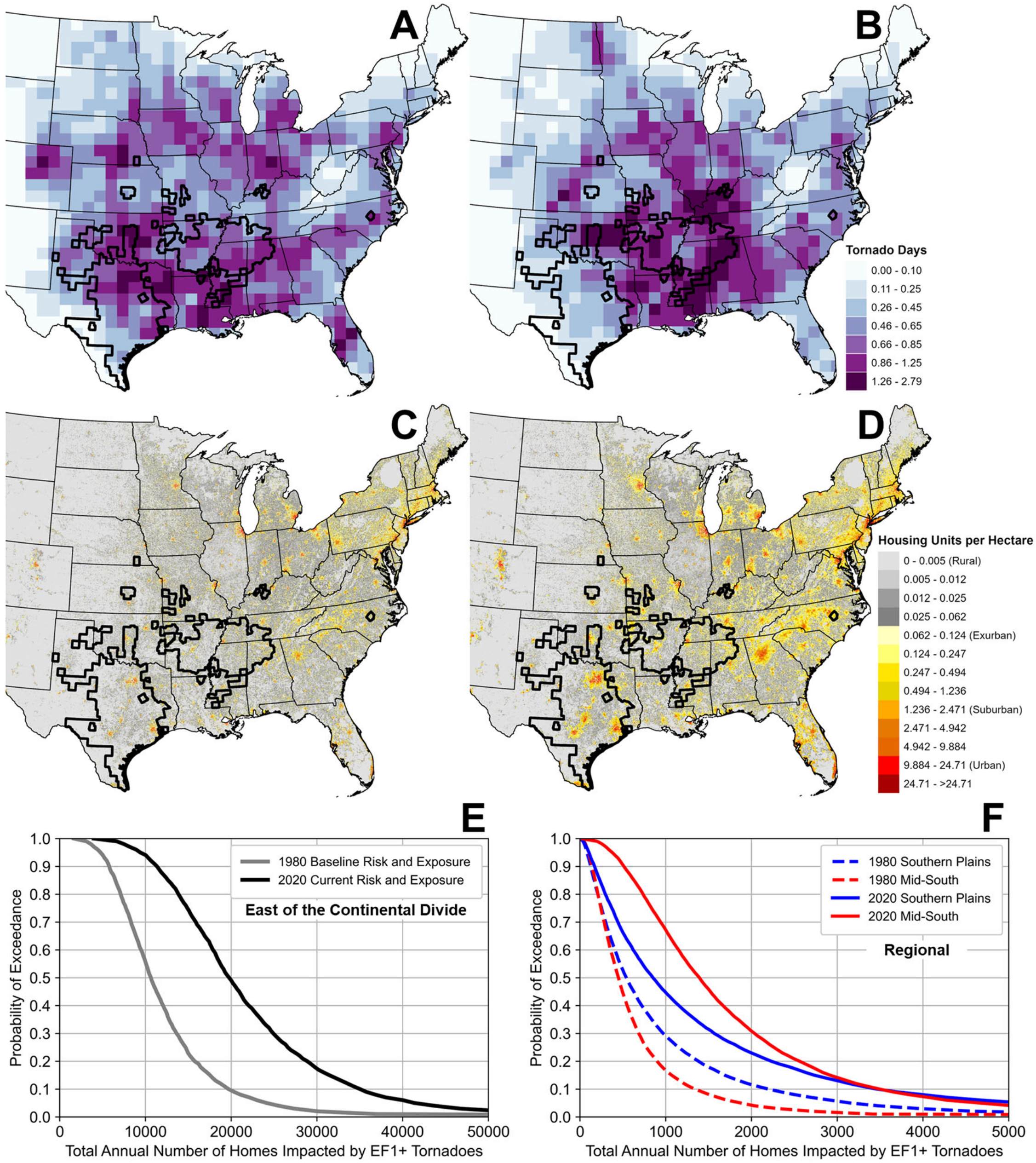

Fig. 4 | Changes in tornado-housing unit impact potential. The 25-year mean annual EF1+ tornado days from **A** from 1973 to 1997 and **B** 1998–2021 on an 80-km grid is provided along with housing unit (HU) density maps on a 100-m grid for the years of **C** 1980 and **D** 2020. Bold (black) outlined counties denote those that are within the 95th (Mid-South) or 5th (Southern Plains) percentile ranking for changes in tornado days from 1980 to 2020. The probability of exceedance (POE) curves for the combination of 1980 risk and exposure (gray line) and 2020 risk and exposure (black line) for regions east of the Continental Divide are provided (**E**). Panel **F** provides POE curves for the Southern Plains (blue lines) and the Mid-South (red lines) regions for the years 1980 (dashed line) and 2020 (solid lines).

decades. Although tornado risk across the Southern Plains has declined since 1980, rapidly escalating built-environment exposure (i.e., suburban and exurban growth in metropolitan areas such as Austin, Dallas-Fort Worth, and Houston, TX) has led to increasing tornado-HU impact potential over time.

Experimental control tornado-housing impact simulations

The results above illustrate that the area east of the Continental Divide has generally experienced increasing tornado-HU impact potential over time, even for regions where there has been a decrease in tornado risk (e.g., Southern Plains). These results, however, do not describe the *relative* importance of changing risk and exposure on tornado-HU impact potential. As such, we use a set of experimental control simulations to illustrate how the two fundamental disaster constituents of risk and exposure are individually and collectively influencing tornado-HU impact potential (Fig. 5A; Table 4). Results from solely allowing tornado risk to change and holding HU exposure constant in areas east of the Continental Divide suggest that the changes in tornado risk have had little influence on changing tornado-HU impact potential. Conversely, allowing exposure to change over time while holding any spatial changes to tornado risk constant illustrates that built-environment growth has been the primary driver for alterations to tornado-HU impact potential. There is very little difference between the historical simulation and changing risk-constant exposure scenario and the current and changing exposure-constant risk scenario when comparing pragmatic historical simulation impact statistics to the experimental risk and exposure control impact statistics east of the Continental Divide (Fig. 5A).

Table 4 | Annual total EF1+ tornado-housing unit (HU) impact descriptive statistics (median, mean, standard deviation (SD), 90th, 95th, and 99th percentiles) for areas east of the Continental Divide, the Mid-South, and Southern Plains

Region	Scenario	Simulation layers		Impact statistics					
		Risk	Exposure	Median	Mean	SD	90th	95th	99th
East of the Cont. Div.	Historical	1980	1980	10,636	12,160	7436	19,672	24,118	36,947
	Current	2020	2020	19,755	22,063	10,866	35,009	41,348	60,995
	Changing Risk	2020	1980	10,909	12,275	6252	19,924	23,808	34,480
	Changing Exposure	1980	2020	19,650	22,084	12,448	35,430	41,811	60,604
Mid-South	Historical	1980	1980	448	646	728	1340	1875	3414
	Current	2020	2020	1392	1809	1585	3493	4657	7796
	Changing Risk	2020	1980	728	990	967	1948	2614	4672
	Changing Exposure	1980	2020	855	1175	1174	2418	3277	5704
Southern Plains	Historical	1980	1980	540	964	1381	2197	3150	6310
	Current	2020	2020	849	1565	2389	3460	5180	11,306
	Changing Risk	2020	1980	309	643	1068	1501	2243	5024
	Changing Exposure	1980	2020	1477	2413	3032	5325	7412	14,772

The different combinations of changing risk and exposure in the regions are provided as simulation layers, risk and exposure.

However, because tornado risk has changed most in the Southern Plains and Mid-South, the experimental control simulation results in these regions provide more detail about how both changing risk and societal exposure affect tornado-HU impact potential at a finer spatial scale (Fig. 5B, C; Table 4). In the Mid-South, amplifying exposure has outweighed the effects of increasing tornado risk. Expected mean and median annual EF1+ tornado-HU impact probabilities are over 16% greater in the changing exposure-constant risk scenario. The largest differences between Mid-South changing exposure-constant risk and changing risk-constant exposure scenarios are found in the 95th and 99th percentile annual HU impacts, where the changing exposure-constant risk 95th and 99th percentile impacts are 22.5% and 19.9% greater, respectively, than in the changing risk-constant exposure scenario.

In the Southern Plains, experimental control simulation results are notably different than in the Mid-South. Specifically, the changing risk-constant exposure scenario's mean annual tornado-HU impacts are nearly half of the region's actual historical (1980) mean annual impact probabilities, highlighting the region's decreasing tornado risk over time. Simply, without increasing exposure, tornado-HU impact potential in the Southern Plains would have decreased over time. Conversely, the changing exposure-constant risk scenario illustrates how much worse tornado-HU impact potential could be in the Southern Plains without a historical decrease in tornado risk. Changing exposure-constant risk mean annual impact probabilities are nearly double that of the actual present-day (2020) mean annual impact measures. High-end annual impact statistics (i.e., 90th, 95th, and 99th percentiles) more clearly illustrate the importance of both risk and exposure change given 99th percentile measures for the changing exposure-constant risk are nearly three times greater than the changing risk-constant exposure scenario.

Discussion

We assessed how historical changes in climatological tornado risk, vulnerability, and exposure have individually and collectively influenced impact and disaster potential across the US. Tornado-HU impact potential is rapidly escalating over time due to increases in tornado risk, vulnerability, and exposure. However, the relative influence of each of these disaster constituents varies regionally, signifying the importance of assessing impacts at finer spatial scales. Climatological tornado risk in the Southern Plains has decreased over time while its built-environment footprint has expanded. The combination of these two factors has led to a more than 50% increase in tornado-HU impact potential in the region. This demonstrates that changing exposure is a greater contributor to the Southern Plains' increasing tornado-HU impact potential than spatially changing tornado risk.

Mid-South analyses also highlight the importance of both risk and exposure changes in controlling societal impact potential since both measures have increased over time in the region. As a result, the Mid-South experienced a threefold escalation in tornado-HU impact potential since 1980. The ramifications of these findings point to the need for further integration of societal factors in the climate change research community. For instance, several prior studies have highlighted the importance of manufactured housing in the context of tornado mortality and impacts[18,40,62,64–68]. Additionally, other recent works have suggested that climatological tornado risk and other tornado attributes such as length, width, damage rating or intensity, etc. have changed over time, especially at the regional scale[16,24,69–71]. Findings from these works may be incorporated into future studies to determine their importance in conjunction with spatially changing tornado risk on potential tornado-society impacts. In all, climate change-driven changes to risk and society-controlled changes in vulnerability should be assessed in conjunction to better understand how tornado impacts and disasters have and may potentially change over time. This statement also holds true for research investigating climate change influences on deadly hazards such as flooding, temperature extremes, tropical cyclones, etc.

Exposure is only a single component of vulnerability. Other measures related to society or the built environment, such as socioeconomics, housing type, race, ethnicity, age, etc., can have notable influence and control on tornado disaster frequency and severity[37,72]. Thus, coupling increasing exposure and risk with escalating social vulnerability points to the possibility of not just greater tornado-HU impact potential but also increasing impacts as measured by other means (e.g., indirect impacts) and disaster potential. Disasters are ultimately a measure of a community's ability to cope with hazard impacts and directly relate to human distress when hazard events affect society[37,38,40,42,43,72]. Nowhere is this more important than in the Mid-South, where tornado mortality is the greatest[15,40,73]. The results presented herein suggest that this issue is worsening over time.

Lastly, findings from this study highlight the importance of interdisciplinary research aimed at reducing the impact of hazards on society. Stakeholders and policymakers can use these findings to improve weather hazard mitigation activities and plans at the local and regional scales. For example, continued focus on the improvement of building codes, more strict enforcement of these building codes, retrofitting of existing vulnerable structures, and providing sheltering options—especially for highly exposed and vulnerable populations—will reduce financial losses and improve survivability when the next tornado event occurs.

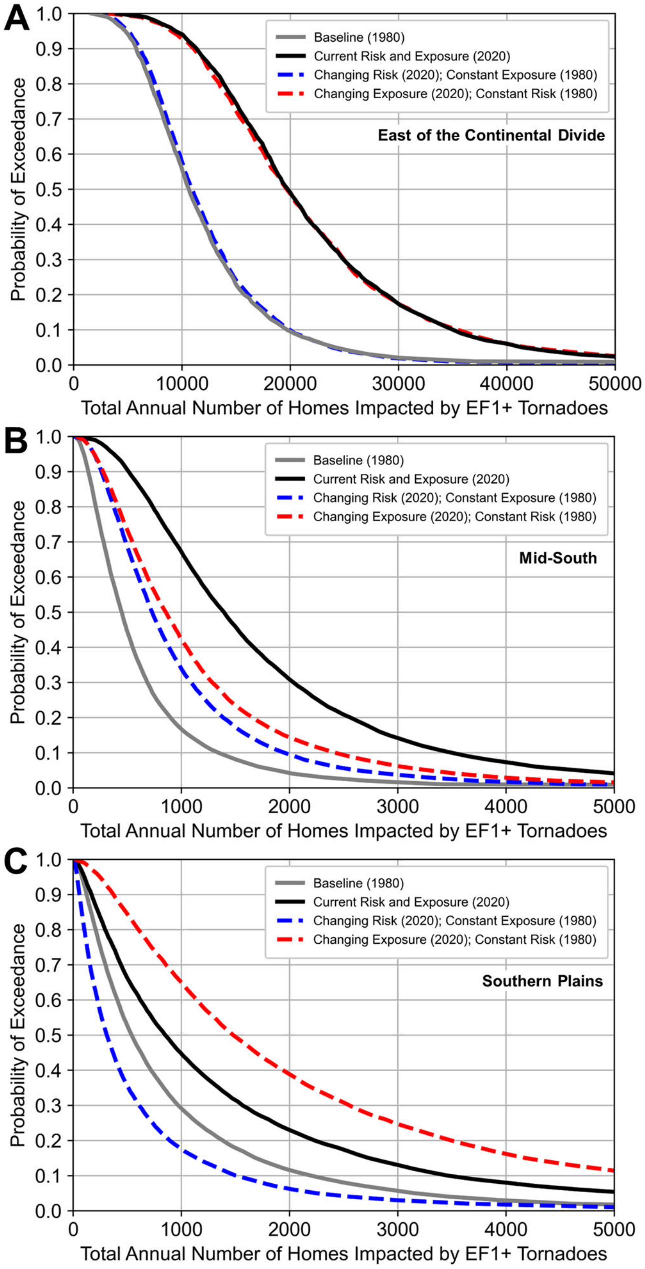

Fig. 5 | Experimental tornado-housing unit impact simulations. Probability of exceedance (POE) curves for the total number of homes affected by EF1+ tornadoes for three regions: **A** east of the Continental Divide, **B** 95th (Mid-South), and **C** 5th (Southern Plains) percentile ranking for changes in tornado days from 1980 to 2020 regions. Baseline (1980 risk and 1980 exposure; gray lines) and current (2020 risk and 2020 exposure; black lines) are provided for the three regions. Dashed blue lines represent solely changing tornado risk and constant exposure from 1980 to 2020. Dashed red lines signify solely changing exposure and constant risk housing impact probabilities from 1980 to 2020.

Methods

Tornado risk data generation

Methods are split into three primary sections that outline our process for examining historical changes in (1) climatological tornado risk, (2) societal vulnerability and exposure, and (3) tornado-housing unit (HU) impact potential. First, we follow the methods described in a prior study[27] by generating historical county-level representations of tornado risk from 1980 through 2020. Specifically, North American Regional Reanalysis (NARR)[74] data were used to generate representations of the annual accumulated daily maximum significant tornado parameter (STP; https://rda.ucar.edu/datasets/ds608.0/; Eq. 1) across the US.

$$\mathrm{STP} = \frac{\mathrm{SBCAPE}}{1500}\,\mathrm{x}\,\frac{2000 - \mathrm{SBLCL}}{1000}\,\mathrm{x}\,\frac{\mathrm{SRH01}}{150}\,\mathrm{x}\,\frac{\mathrm{BWD06}}{20} \tag{1}$$

STP is a unitless metric that combines measures of surface-based convective available potential energy (SBCAPE), surface-based lifting condensation level (SBLCL), 0–1-km storm-relative helicity (SRH01), and 0–6-km bulk wind difference (BWD06). Values were calculated at the native 3-hourly NARR temporal interval. NARR-derived STP values were vertically interpolated from isobaric levels to calculate BWD06 and spatially masked where unfavorable convective inhibition (<-50 J kg^{-1}) was present. An annual accumulated STP measure was then calculated by summing all STP daily (1200–1200 UTC) maximums over a given year on the native 32-km Lambert Conformal NARR grid. Prior work that assessed monthly regressions between the STP metric and historical tornado observations found that annual accumulated maximum STP explains 44% of the variance in annual tornado counts compared to tornado reports from the Storm Prediction Center's database[27]. These efforts established that STP can be used as an environmental proxy for tornado occurrences while also controlling the reporting bias often present in historical tornado report data[30–33].

This prior research also assessed the trend in STP on the NARR grid using a Theil-Sen slope estimator coupled with Kendall's τ statistic to determine any spatial or temporal changes in tornado risk[27]. Their results indicate that there has been an increase in favorable tornado environments across the Midwest and Lower Mississippi Valley and a decrease in the Southern Plains since 1980. We recommend readers examine the methods and findings from this prior work for a more detailed explanation of how changes in tornado environments across the US were determined. Pertaining to the research outlined in this study, daily maximum STP values accumulated annually from 1980–2020 were proportioned into county administrative boundaries to facilitate a spatiotemporal comparison between county-level STP and societal vulnerability measures.

Societal exposure and vulnerability data generation

For societal vulnerability change analyses, we employ US Census Bureau data for the years 1980 (Supplemental Fig. 1) and 2020 (Supplemental Fig. 2). Specifically, county-level Census enumerations related to socioeconomic and demographic characteristics, population, and housing were used to approximate underlying population magnitude and societal vulnerability. Variables such as total population, HU, households, age, race, ethnicity, sex, income per capita, public assistance, education, housing type, and household size were examined. Previous studies have discussed the importance of these variables when assessing society vulnerability[36,37,43]; specific societal measures used in this study and the reasons for their inclusion are provided (Supplemental Table 1). Each vulnerability metric was normalized by percentages of total county population or households to control for different size counties and total county population, HUs, and households. Counties, where administrative boundaries changed from the 1980 to the 2020 Census, were excluded from analyses and only those societal variables that existed in both the 1980 and 2020 Censuses were considered. Although Census enumerations smaller than county-scale are preferred when assessing these measures in relation to tornado damage paths, Census tracts and smaller are not available for a large portion of the US before 1990[18]. Lastly, it should be noted that many 2020 Census variables may suffer from slight overcounting or undercounting at the state scale[75].

We also follow methods outlined in prior research by equally weighting each of the 17 vulnerability measures based on their percentile ranking to generate an overall vulnerability metric[40,43,76,77]. Differences between the county-level 1980 and 2020 vulnerability measures are also calculated by measuring the change in percentile ranking for each individual vulnerability variable and the overall vulnerability metric (Supplemental Fig. 3).

Tornado impact Monte Carlo (TorMC) model simulations

The Tornado Impact Monte Carlo (TorMC) model was the primary tool used in conjunction with historical tornado risk and societal exposure data to assess tornado-HU impact potential[50]. Simulations comprising 2500 years of Enhanced Fujita scale 1 and greater (EF1+) tornado damage footprints were generated with the TorMC to reveal the individual and combined influence of changing tornado risk and societal exposure on impacts over the last 40 years. Several simulation lengths (i.e., 1000-year, 2500-year, 5000-year, and 10,000-year) were explored, and the 2500-year simulation length was the ideal combination given model runtime, accuracy, and impact statistic convergence. EF1+ tornado paths were chosen to represent tornado risk because their annual counts over time have been relatively stable compared to all (EF0+) tornado counts[20,78].

More specifically, the TorMC is a spatially explicit model that uses climatological information such as tornado incidence, damage magnitude or maximum damage rating, path lengths, widths, bearings, etc., to generate synthetic tornado paths across a user-defined geographic region of interest. The simulated paths are then intersected with an underlying exposure or cost surface that represents exposed entities (e.g., persons, homes). Spatially Explicit Regional Growth Model (SERGoM)[48] and Integrated Climate Land-Use Scenario version 1 (ICLUSv1)[49] model were employed in this study to represent the underlying exposed built environment. The SERGoM model provides fine-scale decadal HU density estimates across the US from 1940–2000 at the 100-m gridded resolution. SERGoM employs inputs of protected land areas, water, road density, Census enumerations, developable lands, etc., to spatially allocate the total number of HUs in a county to fine-scale grids using dasymetric techniques[79]. The SERGoM and ICLUSv1 modeling methods are functionally identical, but the SERGoM solely provides decadal gridded HU estimates from 1940 to 2000.

The SERGoM model is the backbone of the ICLUSv1 model, but instead of using historical county-level HU enumerations to allocate HUs into fine-scale grids, the ICLUSv1 model employs county-level HU growth rates projected from the year 2000 and onward to estimate decadal, fine-scale HU density from 2010 to 2100[79]. HU growth rates in the ICLUSv1 model are controlled by Special Report Emission Scenarios (SRES) climate change storylines that consider both economic and environmental factors that influence population and HU growth rates. For example, the ICLUSv1 A2 SRES scenario is focused on more regional economic development, where HU growth rapidly accelerates from the year 2050 onward. Specific to our methods and analyses, we use the ICLUSv1 A1 SRES model output to represent 2020 HU density—and, therefore, societal exposure—given the total number of HUs in all ICLUSv1 grids most closely match that of the 2020 Census HU totals in our study regions[79,80]. We assessed this accuracy by summing the total ICLUSv1 SRES A1 HUs within the US and comparing this value to the 2020 Census HU enumerations. The benefit of using the SERGoM and ICLUS HU data over Census tract or larger HU enumerations is its gridded respresentation[48] (i.e., Census tract spatial boundaries change over time). Aside from geospatial resolution, another critical limitation to using Census tract or smaller data enumerations besides spatial scale is the limited availability prior to 1990 for many counties across the U.S[80]. To the best of our knowledge, there are no other publicly available exposure datasets that provide gridded representations of housing or similar built-environment variables across the US at fine spatial scales (~100 m).

A more detailed and thorough explanation of the TorMC model steps, biases, and verification are presented in prior work[47]. We follow prior research that has employed the TorMC by presenting the results in the form of probability exceedance curves and descriptive statistics that highlight mean, median, standard deviation (SD), 90th, 95th, and 99th percentile annually accumulated HU impact probabilities[22,23].

Several 2500-year simulations were conducted across three primary study regions or domains: (1) east of the Continental Divide, where most tornadoes in the US occur (2) counties within the 95th percentile of changes in tornado days from 1980 to 2020 (i.e., Mid-South), and (3) counties within the 5th percentile of changes in tornado days from 1980 to 2020 (i.e., Southern Plains). The tornado-HU impact simulations were conducted to reveal the relative individual and combined influence of escalating tornado risk and exposure in each region.

All simulations use three pieces of information: (1) historical tornado observations from the Storm Prediction Center's database, (2) spatial weighting surface that determines the probability of a tornado path being generated in a given US region, and (3) a cost surface that determines how many exposed entities (i.e., HUs) were affected per simulated tornado path. The first group of pragmatic simulations employs two 80 km × 80 km grids representing mean annual tornado days for the 25-year periods of 1973–1997 and 1998–2021. These risk layers were created to represent tornado risk prior to and after the noted changes in regional trends in tornado incidence from the Southern Plains to the Mid-South and present-day tornado risk. Although we are unable to directly employ the STP-derived tornado day proxy data in the TorMC simulations because much of the historical STP analysis period pre-dates the satellite era (i.e., pre-1980s), these tornado observation periods most closely match results from prior environmental proxy research[27,78]. Ultimately, the baseline and current gridded tornado risk surfaces served as the spatial weighting surfaces for synthetic EF1+ tornado placement across the US in the TorMC simulations. The number of tornadoes generated in each simulation was not altered from 1980 to 2020 simulations because no studies have uncovered a temporal change in the mean annual number of EF1+ observed tornado events[81].

Experimental control TorMC simulations were created for each region to isolate the contributions of an increasing exposure or risk. Specifically, two simulations per region were conducted: (1) permitting tornado risk to regionally change as found in prior proxy research[27] while holding exposure constant, and (2) permitting HU exposure to change from 1980 to 2020 while holding tornado risk constant. Together, the differences in POE curves and impact descriptive statistics—relative to the realistic scenarios where historical risk is matched with historical exposure or current risk is matched with current exposure—permit us to determine the relative importance of changing tornado risk and societal exposure on tornado-HU impact potential. We move beyond prior work by incorporating reanalysis-derived findings from work focused on uncovering historical changes in tornado risk and consider how both spatial and annual tornado count changes influence tornado-society impact probabilities.

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Author contributions
S.M.S. designed research, conducted primary analyses, prepared figures and tables, and wrote the paper. V.A.G. provided risk data, assisted in research design and writing, and provided paper edits. W.S.A. assisted in research design, writing, and paper edits. A.N.W. prepared the vulnerability data for analysis.

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