Assessment of NWS County Warning Area Tornado Risk, Exposure, and Vulnerability

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ABSTRACT: This study investigates the interrelationships between National Weather Service (NWS) county warning area (CWA) tornado risk, exposure, and societal vulnerability. CWA climatological tornado risk is determined using historical tornado event data, and exposure and vulnerability are assessed by employing present-day population, housing, socioeconomic, and demographic metrics. In addition, tornado watches, warnings, warning lead times, false alarm warnings, and unwarned tornado reports are examined in relation to CWA risk, exposure, and vulnerability. Results indicate that southeastern U.S. CWAs are more susceptible to tornado impacts because of their greater tornado frequencies and larger damage footprints intersecting more vulnerable populations (e.g., poverty and manufactured homes). Midwest CWAs experience fewer tornadoes relative to Southeast and southern plains CWAs but encompass faster tornado translational speeds and greater population densities where higher concentrations of vulnerable individuals often reside. Northern plains CWAs contain longer-tracked tornadoes on average and larger percentages of vulnerable elderly and rural persons. Southern plains CWAs experience the highest tornado frequencies in general and contain larger percentages of minority Latinx populations. Many of the most socially vulnerable CWAs have shorter warning lead times and greater percentages of false alarm warnings and unwarned tornadoes. Study findings provide NWS forecasters with an improved understanding of the relationships between tornado risk, exposure, vulnerability, and warning outcomes within their respective CWAs. Findings may also assist NWS Weather Forecast Offices and the Warning Decision Training Division with developing training materials aimed at increasing NWS forecaster knowledge of how tornado risk, exposure, and vulnerability factors influence local tornado disaster potential.

KEYWORDS: Tornadoes; Operational forecasting; Emergency preparedness; Risk assessment; Societal impacts

1. Introduction and background

The National Weather Service (NWS) attempts to reduce tornado casualties and losses by issuing tornado watches and warnings prior to tornado events. The goal of these products is to provide the public with critical, life-saving information about potential tornado threats. Tornado watches contain key details related to the underlying severe weather forecast and associated environmental conditions, while tornado warnings deliver storm-related details that outline approximate tornado timing, location, translational speed, and intensity. Both tornado watch and warning information is directly communicated to the general public and local officials through a variety of means [i.e., National Oceanic and Atmospheric Administration (NOAA) Weather Radio (NWR), wireless emergency alerts (WEA), outdoor sirens, TV meteorologist broadcasts, social media posts, etc.]. As such, tornado watches and warnings serve as calls to action for potentially exposed populations, while also alerting emergency managers and first responders of possible upcoming impacts on communities.

Tornado watch and warning attributes are mostly dependent on the region's underlying tornado climatology. Simultaneously, tornado characteristics (e.g., frequency and severity) are controlled by the ongoing atmospheric conditions or severe weather ingredients (Johns and Doswell 1992; McNulty 1995; Doswell et al. 2005). As a result, tornado watch and warning metrics vary substantially from one NWS weather forecast office (WFO) county warning area (CWA) to another. Given the primary reasoning behind the issuance of tornado watches and warnings is to alert populations about a possible or ongoing tornadoes that may impact society, the types, character, and number of people and assets (e.g., exposure and vulnerability) potentially in the path of a tornado also plays a vital role during the severe weather forecasting and nowcasting process.

The hazards and disaster science community defines risk and vulnerability in many different ways (e.g., Cutter 1996; Department of Homeland Security 2010; Morss et al. 2011; Paul 2011; IPCC 2012). To remain consistent with prior research that has investigated tornado threats and societal impacts (e.g., Brooks et al. 2003; Dixon et al. 2011; Coleman and Dixon 2014; Ashley and Strader 2016; Strader and Ashley 2018), this study utilizes the basic *climatological* definition of *risk* that equates to the probability of a tornado occurring in space and time (Paul 2011). Moreover, *vulnerability* in this study is defined as the susceptibility of a person or system to experience harm from a tornado event, and *exposure* encompasses measures of people, assets, or characteristics of the natural and/or built environment that position a system to be affected by a tornado (Morss et al. 2011; IPCC 2012).

For this particular research, a CWA's tornado disaster potential is a product of climatological tornado risk measures

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(i.e., annual tornado path frequency, mean damage footprint area, etc.), built environment and population exposure, and societal vulnerability. While we do not directly examine tornado disasters[1] within this study, elevated measures of tornado risk, exposure, and vulnerability are assumed to lead to increased tornado impacts and greater odds or probability of disaster with CWAs. Given the variability in both tornado risk and societal vulnerability across geographic space, this research examines how these factors interact to create a variety of potential disaster scenarios for tornado-prone CWAs. Specifically, this research seeks to answer the following questions: Which CWAs contain the greatest (lowest) climatological tornado risk? Which CWAs should be most (least) concerned about societal exposure and vulnerability? Where are tornado warning frequencies, outcomes (i.e., false alarms, unwarned tornadoes or missed events), and shorter warning lead times of greatest concern relative to tornado risk, exposure, and vulnerability? How does the combination of risk, exposure, and vulnerability influence potential tornado impacts and severity within CWAs? Last, how might this information be used by NWS forecasters, Integrated Warning Teams (IWT), and the Warning Decision Training Division (WDTD) to improve forecaster knowledge, mitigation strategies, and community resilience-building efforts?

a. *Climatological tornado risk, exposure, and vulnerability assessments*

Several previous studies have examined climatological tornado risk using a variety of methodologies and techniques (e.g., Brooks and Doswell 2002; Brooks et al. 2003; Simmons and Sutter 2011; Dixon et al. 2011; Coleman and Dixon 2014; Ashley and Strader 2016; Elsner et al. 2016; Krocak and Brooks 2018; Strader and Ashley 2018). Many of these investigations have focused on the intersection of tornadoes and societal vulnerability to better understand how tornado disasters unfold and fatalities take place across a variety of spatiotemporal domains (Cutter et al. 2003; Ashley 2007; Simmons and Sutter 2008, 2009, 2011; Coleman and Dixon 2014; Ashley and Strader 2016; Strader et al. 2017; Strader and Ashley 2018). Although previous research has assessed tornado characteristics such as frequency, magnitude, seasonality, and daily timing that are most likely to influence tornado impacts at the county and larger scales (e.g., Dixon et al. 2011; Simmons and Sutter 2011), these variables have yet to be aggregated and examined together at the CWA scale for WFOs in tornado-prone areas.

In addition to research that has examined climatological tornado risk, many studies have also concentrated on exposure and vulnerability elements of tornado impacts and losses (Cutter et al. 2003; Ashley 2007; Sutter and Simmons 2010; Emrich and Cutter 2011; Dixon and Moore 2012; Ash 2017; Strader and Ashley 2018; Strader et al. 2019; Fricker 2020). These examinations frequently concentrate on specific population, socioeconomic, demographic, and housing characteristics related to population counts, household income, race, gender, age, education, housing density, housing type (e.g., permanent or mobile or manufactured home), and other factors that strongly influence exposure, vulnerability, and tornado impact severity and frequency (Cutter et al. 2003; Table 1). For example, socioeconomically disadvantaged individuals are disproportionately affected by tornadoes compared to those populations with stronger financial and social safety nets (e.g., higher income, health, home, and vehicle insurance, higher educational attainment; Peacock et al. 1997; Cutter et al. 2003; Fothergill and Peek 2004; Morrow 2008). Individuals who fall into these more vulnerable socioeconomic categories are also less likely to have insurance, making the replacement of their materials lost in a tornado much more difficult and expensive (Tierney 2006). Unemployed persons may also not have health benefits that help share the cost of medical care after a tornado strikes (Brodie et al. 2006). Additionally, those without a high school diploma may have more trouble understanding tornado watch, warning, and recovery information, which may lead to them not taking proper shelter (Cutter et al. 2003; Ash 2017; Ash et al. 2020).

Research examining social vulnerability and tornadoes has also indicated that elderly populations may not be able to adequately protect themselves from a tornado because they are less mobile than younger populations (Morrow 1999). Young persons aged less than five years old also may not have the ability to protect themselves because they lack key resources, education, experience, knowledge, and/or rely on others to assist them when taking protective action (Cutter et al. 2003). Disabled populations also frequently rely on others, leading to their increased vulnerability during tornado warning situations (Phillips and Hewett 2005). These factors are also exacerbated during tornado situations when the burden of childcare or disabled person care falls on one parent (i.e., single-parent head of household; Flanagan et al. 2011). Minority populations and/or those that speak English ''less than well'' face cultural and language barriers that may lead to them not taking correct protective action when tornado threats arise (Peacock et al. 1997; Cutter et al. 2006; Elder et al. 2007; Strader and Ashley 2018).

Societal factors such as multiple-unit structures, crowding, and those living in group quarters influence hazard vulnerability because they result in increased exposure to a tornado and cause evacuation difficulties before and after a tornado event (Cutter et al. 2003; Flanagan et al. 2011). For example, individuals residing in high-rise apartments may have difficulty evacuating their buildings when a tornado strikes due to a limited number of exit stairwells, cramped quarters, and a lack of evacuation order once they reach the street below (Flanagan et al. 2011). Moreover, these factors are often tied to personal wealth, such that those in poverty tend to live in multiple-unit structures or group quarters where crowding is more common (Flanagan et al. 2011).

One vulnerability factor that has been examined in great detail are mobile/manufactured homes and their residents (e.g., Ashley 2007; Ashley et al. 2008; Schmidlin et al. 2009;

[1] *Disasters* occur when hazard events interact with vulnerable sectors of society, leaving a community unable to function normally or recover without external support (IPCC 2012).

TABLE 1. Summary of potential tornado disaster climatological risk, exposure, and vulnerability factors employed in this study. Associated variables, measures, and expected influence on potential tornado impacts are also noted.

Variable	Metric	Influence on potential impacts
	Climatological risk	
Tornado	Frequency and density for all paths and fatal paths; fatalities per capita; pathlength; width; theoretical damage footprint; translational speed	Likelihood of tornado occurrence and specific path characteristics (e.g., Brooks et al. 2003; Brooks 2004b; Ashley and Strader 2016)
Watches	Frequency and density for all watches	Potential tornado threat frequency (e.g., Dean 2006)
Warnings	Frequency and density for all tornado warnings, positive lead time warnings, and false alarm warnings; average warning lead time	Potential tornado threat frequencies as they relate to all warnings, those with a positive lead time enabling residents to seek shelter, and those warnings that resulted in false alarms that may breed distrust in the NWS and warning process (e.g., Harrison and Karstens 2017; Lim et al. 2019)
Reports	Frequency and density of all reports and unwarned reports	Potential tornado threats that occur without warning, leading to greater impacts (e.g., Brotzge and Erickson 2010)
	Exposure	
Population	Count	The higher the population exposure is, the greater the impact is (e.g., Ashley and Strader 2016; Strader and Ashley 2018)
Housing units	Count and percentage of homes in rural, exurban, suburban, and urban housing density	The higher the housing exposure is, the greater the impact is (e.g., Ashley et al. 2014; Strader et al. 2017)
Households	Count	The higher the housing exposure is, the greater the impact is (e.g., Ashley et al. 2014; Strader et al. 2017).
	Vulnerability	
Below poverty	Percentage of population	Less ability to withstand impacts and losses; lower resilience; fewer financial and social safety nets (e.g., Peacock et al. 1997; Fothergill and Peek 2004)
Unemployed	Percentage of population	
Income	Per capita	
No high school diploma	Percentage of population	Relationship to income and economic constraints; understanding of watch and warning information (e.g., Cutter et al. 2000)
≥65 age	Percentage of population	Less mobile; not self-reliant (e.g., Phillips and Hewett 2005)
≤17 age	Percentage of population	
Disabled	Percentage of population	
Single-parent household	Percentage of population	Limited financial resources; economic, social, and family responsibilities (e.g., Morrow 1999; Cutter et al. 2009)
Minority	Percentage of population	Cultural barriers (e.g., Peacock et al. 1997; Cutter et al. 2006)
Speaks English "less than well"	Percentage of population	Cultural and language barriers (e.g., Peguero 2006)
Multiunit structures	Percentage of homes	Overcrowding and evacuation difficulties (e.g., Cutter et al. 2003; Flanagan et al. 2011)
Mobile/manufactured homes	Percentage of homes	Lower construction standard; more likely to be destroyed in hazard; farther away from critical resources (e.g., Cutter et al. 2003; Ashley 2007; Simmons and Sutter 2011; Strader and Ashley 2018)
Crowding	Percentage of homes	Overcrowding and evacuation difficulties (e.g., Cutter et al. 2003; Flanagan et al. 2011)
No vehicle	Percentage of homes	Lack of ability to reach sheltering or medical assistance (e.g., Flanagan et al. 2011; Strader et al. 2019)
Group quarters	Percentage of homes	Overcrowding and evacuation difficulties (e.g., Cutter et al. 2003; Flanagan et al. 2011)

TABLE 2. Tornado warning performance contingency table outlining potential tornado event outcomes (adapted from Lim et al. 2019). An asterisk indicates that it may result in a positive tornado warning lead time (min).

		Tornado event observed or confirmed report	
		Yes	No
Tornado warning issued	Yes	Warned tornado* ("hit"; true positive)	False alarm warning ("false alarm"; false positive)
	No	Unwarned tornado ("missed event"; false negative)	No tornado ("null event"; true negative)

Chaney and Weaver 2010; Sutter and Simmons 2010; Strader and Ashley 2018; Strader et al. 2019, 2020). Research assessing tornadoes in relation to these structures has illustrated that poor structural quality in conjunction with other socially vulnerable characteristics (e.g., poverty) leads to greater odds of tornado deaths (Ashley 2007; Ash 2017; Strader and Ashley 2018; Ash et al. 2020). Most of this prior research has concentrated on the Southeast where it has been found that mobile/manufactured homes are the circumstance of death for most tornado-related fatalities (Strader and Ashley 2018).

Overall, tornado vulnerability studies have identified several important physical and social variables that can drastically affect the severity of tornado impacts. Thus, stakeholders invested in reducing tornado disaster impacts (i.e., NWS forecasters, emergency managers, law enforcement, local government, residents, etc.) should be informed of the juxtaposition of pertinent vulnerability measures and climatological tornado risk. This in turn, allows WFOs, IWTs, and the WDTD to develop and implement tornado education, mitigation, and community resilience strategies that are aimed at specifically addressing the interrelationships between tornado risk, exposure, and vulnerability.

b. *Tornado watches and warning outcomes*

Tornado watches are issued by the Storm Prediction Center (SPC) up to several hours prior to a severe weather event and are utilized to communicate upcoming potential severe weather and tornado threats for relatively large geographic areas (i.e., multiple CWAs). Tornado warnings are issued in real-time at the storm scale when local WFO NWS forecasters deduce that a tornado is imminent based on environmental conditions, radar data, ground truth information (e.g., public or official report), and/or forecaster experience (Trainor et al. 2015). Consequently, the warning process leads to four possible tornado event and warning outcomes that are described by a warning performance contingency table (Doswell and Flueck 1989; Doswell et al. 1990; Brooks 2004a; Trainor et al. 2015; Lim et al. 2019; Table 2).

The most common tornado warning process outcome is the true negative or null event case where *no* tornado was reported, and *no* tornado warning was issued. This type of event is considered a success in the tornado warning process and commonly occurs with nonsevere thunderstorms or those severe storms that do not produce tornadoes. Another tornado warning outcome results when a tornado warning *is* issued, and a tornado *does* occur (i.e., "hit"). This true positive outcome is associated with warnings that provide a lead time (i.e., approximate time it takes for the tornado to reach a person's location) for populations within a warning polygon. In general, studies have found that longer tornado warning lead times may reduce tornado fatalities (e.g., Brooks 2004a; Simmons and Sutter 2008; Brotzge and Erickson 2009, 2010; Brotzge et al. 2011; Hoekstra et al. 2011; Brooks and Correia 2018). False negative tornado warning outcome cases (i.e., unwarned tornadoes or "missed" events) occur when a tornado *is* reported, and *no* tornado warning was issued by the time of tornadogenesis (Brotzge and Erickson 2010). Research examining unwarned tornado events found that approximately 25% of tornadoes from 2000 to 2004 fall into this category, with most rated as weak tornadoes that do not result in fatalities (Brotzge and Erickson 2010). Unfortunately, a negative result of unwarned tornadoes is that they may breed public distrust in the NWS and warning process if populations are affected (Lim et al. 2019). The final possible warning outcome is associated with false alarm tornado warnings (i.e., tornado warnings issued when no tornado occurred or was reported). These "unverified" tornado warnings represent nearly 75% of all warnings across the entire United States and are considered an unfavorable outcome in the tornado warning process (Brotzge et al. 2011; Lim et al. 2019).

There have been a few studies (e.g., Brotzge and Erickson 2010; Brotzge et al. 2011) that have examined regional trends in tornado warning outcomes such as unwarned tornadoes and false alarms. These examinations have found that of tornado-prone regions (i.e., east of the Continental Divide), the percentage of tornadoes that occurred without warning is highest in the Midwest and Southeast (Brotzge and Erickson 2010). Prior research has also illustrated that the percentage of false alarm warnings is typically greater in the Southeast and Midwest (Brotzge et al. 2011).

2. Methods

To assess how tornadoes, watches, and warnings interact with and relate to societal exposure and vulnerability at the CWA scale, we examined 53 individual CWAs east of the Continental Divide where tornadoes are most frequent (Fig. 1b). CWAs were grouped into larger geographic regions based on shared climatological, exposure, and vulnerability characteristics [northern plains (NP), central plains (SP), Midwest (MW), and Southeast (SE); Fig. 1a]. We first developed a tornado climatology for each CWA using a variety of tornado risk metrics (Table 3). The SPC Severe Weather GIS (SVRGIS) tornado database was our primary source for historical tornado event information from 1950 to 2018 (SPC 2020). Metrics such as tornado count (fatal and nonfatal events), density (tornadoes per km^2), length (km), maximum tornado width (m), and

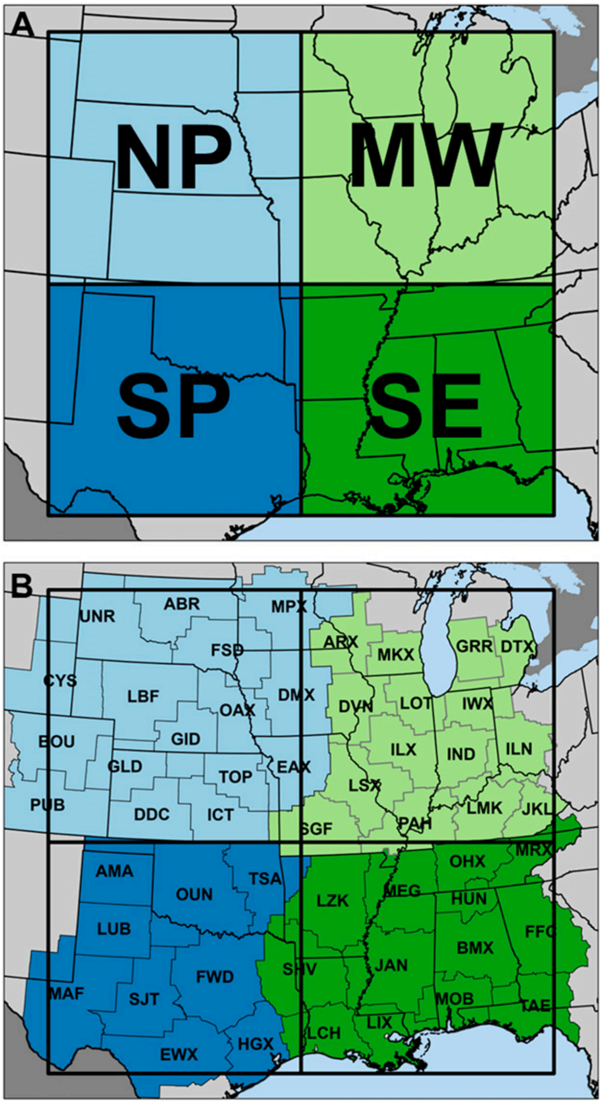

FIG. 1. (a) Regional Midwest (MW), northern plains (NP), southern plains (SP), and Southeast (SE) study domains. (b) Locations of the CWAs, colored to indicate the regional domain to which they belong.

theoretical footprint (length × maximum width; km^2) were examined within each of the 53 CWAs using the SPC SVRGIS database. Similar to prior research (Brooks et al. 2003; Brooks 2004b; Ashley 2007; Dixon et al. 2011; Ashley and Strader 2016) and the reinsurance catastrophe modeling sector (e.g., Grossi 2005), all CWA tornado climatology measures were normalized to produce the mean counts, mean annual counts, and/or mean annual densities to allow for the direct comparison of tornado risk measures across differing spatial domains (i.e., CWAs). Also using prior research methodologies (e.g., Agee and Childs 2014; Brooks et al. 2014; Tippett et al. 2015; Ashley and Strader 2016), this study controls for any potential temporal changes in U.S. tornado counts, pathlengths, widths, etc. For instance, we removed Fujita scale/enhanced Fujita scale 0 (F0/EF0)[2] tornadoes from this study since the annual frequency of these weak events has increased over time due to nonmeteorological factors (e.g., Verbout et al. 2006; Anderson et al. 2007; Potvin et al. 2019). Given reported tornado width changed from mean path width to maximum path width by 1995 (Brooks 2004b), maximum tornado width and theoretical footprints were calculated using SVRGIS data from 1995 to 2018. In addition to SVRGIS-derived climatological risk metrics, tornado translational speeds were determined from National Centers for Environmental Information (NCEI) Storm Data from 1997 to 2018 since it is the only publicly available tornado dataset to contain both starting and ending times (NCEI 2020). In all, CWA tornado risk metrics are ordered from highest to lowest value to highlight the 80th- and 90th-percentile rankings.

To place the CWA tornado climatological analyses in the context of societal exposure, housing density data from the Spatial Explicit Regional Growth Model (Theobald 2005) was employed. This dataset represents rural (>40 acres per housing unit), exurban (2–40 acres per housing unit), suburban (0.25–1.9 acres per housing unit), or urban (<0.25 acres per housing unit) housing density classes at 100-m gridded spatial resolution for the conterminous United States. Using this dataset, the percentage area of each housing density classification was calculated for all WFOs and ranked to reveal the predominant housing density within CWAs.

This study also employs tornado watch, warning, and report data from the Iowa Environmental Mesonet (IEM) NWS Storm-Based Warning Verification data archive to assess CWA tornado risk via the relationship between tornado event outcomes, watches, and storm-based warnings. Although tornado watches and warnings were available prior to 2007, storm-based tornado warnings were not implemented nationwide until 2007 (Harrison and Karstens 2017). Thus, we limited our watch and warning analyses to solely storm-based warnings from 2007 to 2019. Tornado report and warning outcomes were also separated into three categories based on the previously discussed tornado warning or report outcomes, warnings with a positive lead time, false alarm warnings, and unwarned reports or missed events (Table 3). Watch, warning, and report metrics for all CWAs were also normalized to the mean and mean annual levels, ranked, and compared. It should be noted that this study does not consider the causes or reasons for the warning or report type (e.g., severe weather environment, storm morphology, and seasonality); rather, study results are focused on identifying how tornado warning and report outcomes relate to the underlying CWA tornado climatologies.

Exposure and social vulnerability characteristics within each CWA were also examined. Social vulnerability data were

[2] The F scale was updated to the EF scale in 2007 after research meteorologists, engineers, NWS forecasters, and the National Severe Storms Laboratory addressed critical wind speed–structural damage issues that were apparent in the original damage rating scale (Wind Science and Engineering Center 2006; Edwards et al. 2013).

TABLE 3. Tornado watch and warning counts, mean annual counts, and percent of all warnings or reports for the study domain from 2007 to 2019. Warning and report types are also distinguished.

	Count	Mean annual count	Percent warnings or reports (%)
Watches	7223	556	—
All warnings	37 163	2859	—
All reports	22 460	1728	—
Positive lead time warnings	7746	596	20.8% (all warnings)
False alarm warnings	28 923	2225	77.8% (all warnings)
Unwarned reports	7448	573	33.2% (all reports)

acquired from the Center for Disease Control's social vulnerability index (SVI; Flanagan et al. 2011; Wolkin et al. 2015; Flanagan et al. 2018). The SVI dataset comprises 15 population, economic, household, and housing unit variables that are grouped into four primary categories or themes: 1) socioeconomic status, 2) household composition and disability, 3) minority status and language, and 4) housing type and transportation. The 15 SVI variables cover a range of topics including income, education, employment, age, minority status, language, housing unit character, and household or family structure at the county scale (Center for Disease Control/Agency for Toxic Substances and Disease Registry 2020). For this study, we utilize the most recently available county-level SVI layer that was generated from the 5-yr average American Community Survey (ACS) data from 2014 to 2018. Each county SVI enumeration was assigned to the associated CWA based on location. All county-level SVI measures were then averaged within each CWA to provide mean normalized approximations for each of the 15 individual variables and four primary vulnerability themes. Again, similar to the tornado climatological, watch, and warning analysis methodologies, we rank each CWA based on the individual SVI components so that comparisons among CWAs can be made. Although the tables within this research highlight the 80th and 90th percentile for tornado risk variables, housing density, warning/report outcomes, and vulnerability measures, the online supplemental tables that accompany this paper contain these statistics for all CWAs within the larger tornado-prone domain (Tables S1–S9). Raw and quality controlled data are also available to interested users by contacting the primary author of this study.

Although more comprehensive social vulnerability indices exist [e.g., the identically named social vulnerability index (SoVI) of Cutter et al. (2003)], the SVI was selected because it is publicly available and provides a more simplified and digestible overview of social vulnerability while also allowing for the examination of key individual vulnerability index components. Prior research has shown that many end users (e.g., NWS forecasters and emergency managers) prefer receiving simple and straightforward information when tornado threats arise because there is a tendency for forecasters to get overwhelmed or inundated with the amount of information that must be assimilated in a short time period (Hoffman et al. 2017). Thus, the 15 SVI variables composing four primary themes and an overall vulnerability score allows for both detailed and holistic assessments of social vulnerability within CWA by focusing on the vulnerability metrics that are most critical to tornado-societal impacts.

3. Results

a. *Tornado climatology and risk measures*

As expected, CWAs in the SP and SE regions experience the greatest overall annual EF1+ tornado path frequencies, with OUN containing the highest mean number of tornadoes per year with 22 on average (Table 4; Fig. 2a). This result is in agreement with previous literature that has highlighted the central plains and southeastern United States as the most tornado-prone regions in the world (Brooks et al. 2003; Dixon et al. 2011; Gensini and Ashley 2011; Ashley and Strader 2016; Gensini and Brooks 2018). CWAs such as JAN, MEG, OUN, SHV are within both the 80th-percentile mean annual nonfatal and fatal tornado frequency rankings. The SE region CWAs of BMX, JAN, LZK, and MEG all experience an average of one fatal tornado path per year. After normalizing tornado county by CWA area, one-half of CWAs in the 80th-percentile EF1+ path density ranking reside in the SE region. Conversely, 2 of 5 CWAs in the 90th-percentile tornado density ranking are located in the SP domain (TSA and OUN). Because HUN's CWA area is the smallest of all CWAs examined in this study (24 050 km^2) and encompasses a relatively large mean number of EF1+ tornado paths per year (6), it has the greatest overall mean annual tornado density with 2.4 paths per 10 000 km^2. All CWAs in the 80th-percentile EF1+ path density ranking are expected to experience greater than 1.5 paths per 10 000 km^2 per year on average.

For mean annual fatal EF1+ tornado densities, those in the SE region are ranked higher relative to CWAs in the MW, NP, and SP regions (Table 4). In fact, the top seven CWAs in terms of mean annual fatal tornado path density are all located within the SE region. Results for CWA mean annual EF1+ tornado fatalities per capita (per 1 000 000 people) are mixed and do not highlight CWAs in one particular tornado-prone region. Although the SE domain encompasses four CWAs ranked in the top 10 of mean annual fatalities per capita, the remaining six CWAs in the 80th percentile are located in the SP, MW, and NP regions. Nevertheless, HUN is the highest-ranked CWA for mean annual fatalities per capita with nearly 45 fatalities per 1 000 000 people per year. All 80th-percentile-ranked CWAs are expected to experience greater than 27 fatalities per capita per year.

TABLE 4. Mean annual and mean 80th- and 90th-percentile (PCTL) EF1+ tornado CWA attribute rankings. Parentheses indicate specific tornado attribute values. Subscript acronyms denote the parent CWA region.

Rank	Mean (annual)					Mean			
	Path frequency	Path density (per 10^4 km^2)	Fatal path frequency	Fatal path density (per 10^4 km^2)	Fatalities per capita (per 10^6 people)	Pathlength (km)	Path width (m)	Path footprint (km^2)	Translational speed (m s^{-1})
1	OUN$_{SP}$ (21.72)	HUN$_{SE}$ (2.40)	MEG$_{SE}$ (1.28)	HUN$_{SE}$ (0.25)	HUN$_{SE}$ (44.99)	GID$_{NP}$ (16.19)	TSA$_{SP}$ (421.16)	BMX$_{SE}$ (12.53)	MRX$_{SE}$ (22.11)
2	JAN$_{SE}$ (18.55)	JAN$_{SE}$ (2.02)	LZK$_{SE}$ (1.14)	MEG$_{SE}$ (0.16)	JAN$_{SE}$ (34.45)	ICT$_{NP}$ (16.13)	DDC$_{NP}$ (394.59)	DDC$_{NP}$ (9.55)	SGF$_{MW}$ (20.05)
3	SHV$_{SE}$ (15.64)	TSA$_{SP}$ (1.79)	BMX$_{SE}$ (1.06)	BMX$_{SE}$ (0.14)	ICT$_{NP}$ (33.72)	HUN$_{SE}$ (15.45)	OAX$_{NP}$ (376.56)	HUN$_{SE}$ (9.4)	GRR$_{MW}$ (20.01)
4	FWD$_{SP}$ (13.62)	OUN$_{SP}$ (1.74)	JAN$_{SE}$ (1.06)	LZK$_{SE}$ (0.13)	TOP$_{NP}$ (31.12)	OAX$_{NP}$ (15.37)	BMX$_{SE}$ (363.45)	JKL$_{MW}$ (8.60)	OHX$_{SE}$ (19.90)
5 (90th PCTL)	LZK$_{SE}$ (12.87)	SHV$_{SE}$ (1.69)	OUN$_{SP}$ (0.99)	OHX$_{SE}$ (0.13)	SGF$_{MW}$ (31.03)	LBF$_{NP}$ (15.31)	OUN$_{SP}$ (354.79)	FFC$_{SE}$ (8.55)	JAN$_{SE}$ (19.81)
6	TSA$_{SP}$ (12.07)	GID$_{NP}$ (1.69)	FFC$_{SE}$ (0.88)	JAN$_{SE}$ (0.12)	LZK$_{SE}$ (29.54)	BMX$_{SE}$ (15.14)	GID$_{NP}$ (344.8)	MEG$_{SE}$ (8.49)	ILX$_{MW}$ (19.64)
7	BMX$_{SE}$ (11.55)	LCH$_{SE}$ (1.63)	MPX$_{NP}$ (0.65)	FFC$_{SE}$ (0.11)	BMX$_{SE}$ (29.11)	JAN$_{SE}$ (14.99)	GRR$_{MW}$ (337.67)	OUN$_{SP}$ (7.98)	TSA$_{SP}$ (19.51)
8	DMX$_{NP}$ (10.74)	IND$_{MW}$ (1.61)	PAH$_{MW}$ (0.62)	LOT$_{MW}$ (0.10)	GID$_{NP}$ (28.97)	TOP$_{NP}$ (14.8)	AMA$_{SP}$ (334.95)	JAN$_{SE}$ (7.96)	PAH$_{MW}$ (19.43)
9	MEG$_{SE}$ (10.25)	MKX$_{MW}$ (1.60)	SHV$_{SE}$ (0.62)	LMK$_{MW}$ (0.10)	LUB$_{SP}$ (28.71)	DDC$_{NP}$ (14.68)	LUB$_{SP}$ (327.31)	ICT$_{NP}$ (7.78)	LCH$_{SE}$ (19.40)
10 (80th PCTL)	FFC$_{SE}$ (10.19)	BMX$_{SE}$ (1.57)	HUN$_{SE}$ (0.61)	PAH$_{MW}$ (0.10)	OUN$_{SP}$ (27.25)	ARX$_{MW}$ (14.59)	JAN$_{SE}$ (320.17)	OAX$_{NP}$ (7.59)	IWX$_{MW}$ (19.35)

CWAs in the NP and SE typically experience longer-tracked tornadoes relative to all other regions (Table 4). This finding is consistent with the few studies that have examined tornado pathlength regionality (e.g., Dixon et al. 2011). EF1+ pathlengths for many NP CWAs regularly extend 15.3 km on average, while all 80th-percentile-ranked CWAs have mean pathlengths of at least 14.5 km or longer. GID and ICT (NP region) are the highest-ranked CWAs in terms of pathlength, with both containing mean EF1+ pathlengths greater than 16 km. Again, HUN is represented in the 90th-percentile rankings with a mean pathlength of 15.5 km. This mean length makes it the SE CWA with the longest average tornado pathlength, just ahead of BMX (15.1 km) and JAN (15.0 km).

The 80th-percentile rankings for CWA mean path widths vary significantly from CWA to CWA and region to region. Mean path widths for the 80th-percentile-ranked CWAs are all wider than 320 m. TSA has the greatest mean EF1+ path width with 421 m, followed by DDC (395 m) and OAX (377 m). The 80th-percentile-and-greater-ranked CWAs contain mean tornado path widths of at least 0.25 mi and wider. In addition, there are four NP CWAs and one SE CWA within the 90th-percentile mean path width ranking, with each containing mean path widths over 350 m.

Five of the top 10 CWAs ranked by mean EF1+ footprint area are in the SE region with three others residing in the NP domain. Again, this finding is supported by prior research (Dixon et al. 2011; Ashley and Strader 2016) that has indicated that not only do tornado frequencies influence tornado risk and impact potential, but associated path characteristics such as length, width, and damage footprint area are incredibly important when assessing tornado risk, especially in the southeastern United States. For example, BMX (SE region) contains the largest mean tornado footprint with 12.5 km^2. SE region CWAs such as HUN (9.4 km^2) and FFC (8.55 km^2) are also in the 90th percentile for tornado footprint area. In fact, 50% (5 out of 10) CWAs in the 80th percentile and greater for tornado footprint area are located in the Southeast region.

All but one tornado-prone CWA is not located in the SE or MW region above the 80th percentile for mean translational speed, indicating that tornado translational speeds are generally faster for CWAs east of the Mississippi River (Table 4). All 80th-percentile-ranked CWAs contain mean translational speeds of 19 m s^{-1} (36 kt; 1 kt $\approx$ 0.51 m s^{-1}) or greater. Although MRX illustrates the greatest mean tornado translational speed with 22.1 m s^{-1} (43 kt), 5 of the top 10 CWAs belong to the MW region (i.e., ILX, IWX, GRR, PAH, and SGF). It is surmised that the greater MW CWA tornado translational speeds are linked to the underlying storm morphology (i.e., more frequent quasi-linear convective system or unorganized convection) and upper-level dynamics or evolution of the parent midlatitude cyclone (Thompson et al. 2012; Ashley et al. 2019). Although this pattern was expected, these findings highlight unique patterns in tornado translational speed given research has yet to assess this tornado characteristics or risk metric from a climatological and spatial perspective, or how it may relate to exposure and vulnerability.

Within the context of tornado risk variables and the underlying exposed built environment, those CWAs associated

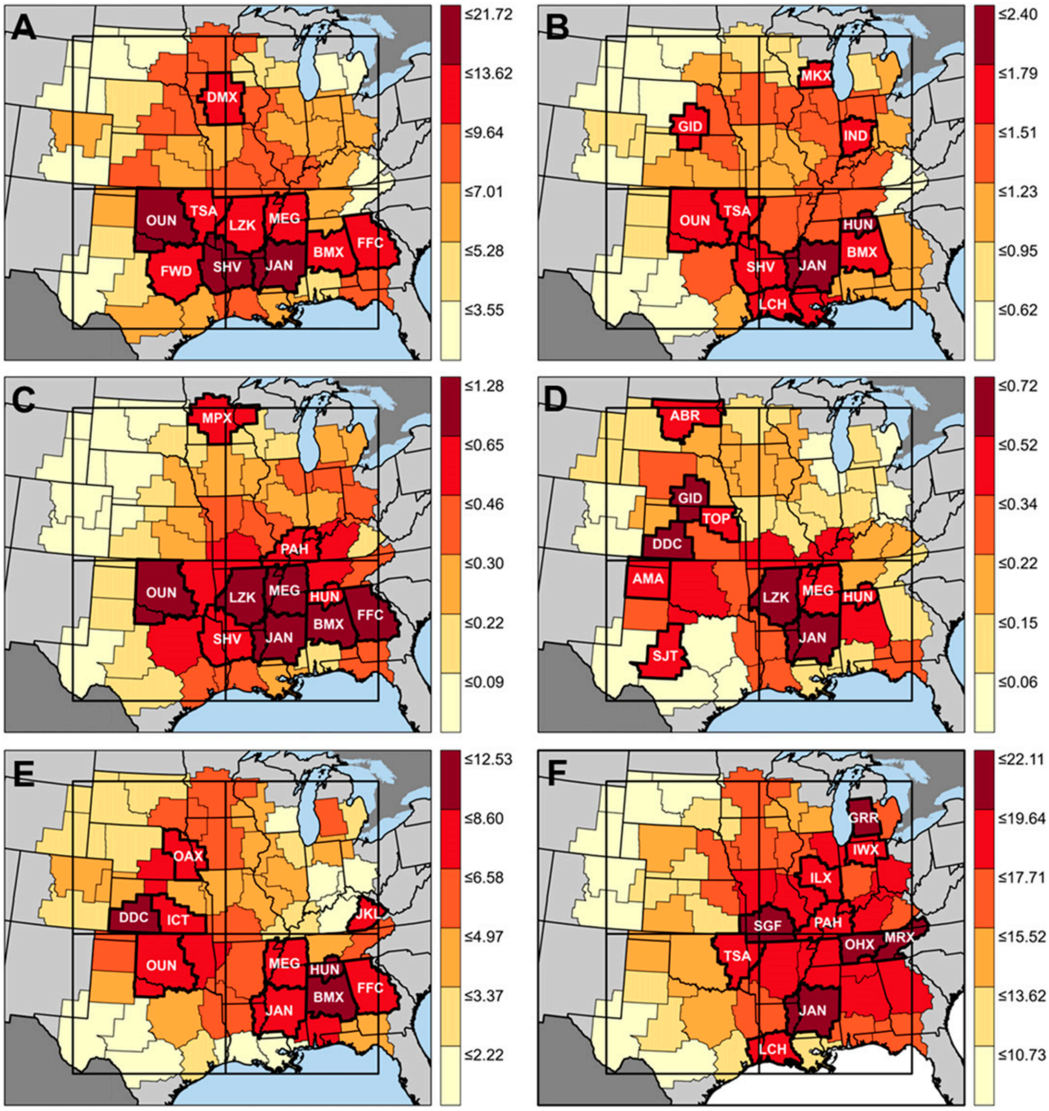

FIG. 2. CWA enumerations of EF1+ (a) mean annual tornado frequency, (b) mean annual tornado density (per 10 000 km^2), (c) mean annual fatal tornado frequency, (d) mean annual fatalities per capita (per 1 000 000 people), (e) mean theoretical damage footprint (pathlength × maximum width; km^2), and (f) mean translational speed ($m\,s^{-1}$). CWAs within the 80th percentile for each variable are thickly outlined.

with the largest population centers are LOT (Chicago, Illinois), FWD (Dallas–Fort Worth, Texas), and FFC (Atlanta, Georgia; Table 5). Each of these WFOs contain more than 8 million people and 3 million homes. A majority of CWAs in the NP regions do not encompass a large number of people and homes given they mostly intersect rural areas generally made up of agricultural or grazing land use. In fact, NP CWAs contain the greatest percentages of rural land area with CYS, GLD, LBF, and UNR all being made up of greater than 98% rural land. Those CWAs with the highest percentages of exurban housing density are located in the MW and SE regions. CWAs with larger percentages of suburban housing density are primarily located in the MW and SE regions, except for HGX (Houston, Texas). As expected, all of the higher suburban and urban percentages are associated with CWAs that encompass larger population centers such as Chicago; Detroit, Michigan; Atlanta, and so on. Together, the suburban and urban percentage housing density results highlight those CWAs that have potential for a large number of people and homes to be affected by a tornado.

Overall, CWA tornado risk analyses involving selected tornado climatology and path attributes reveal that the WFOs in the SE region should be most concerned about tornadoes affecting their CWA populations. In terms of tornado path frequencies, CWAs in the NP and SP regions should also be prepared when tornado threats arise given the overall elevated number of tornadoes that cross these CWAs. However, because most NP and SP region CWAs contain lower population

TABLE 5. CWA population, housing units, households, and percentage of the total CWA area that is rural, exurban, suburban, or urban housing density 80th- and 90th-percentile rankings. Parentheses indicate specific population and housing density attribute values. Subscript acronyms denote the parent CWA region.

	Total count (millions)			Percentage (%)			
Rank	Population	Housing units	Households	Rural	Exurban	Suburban	Urban
1	LOT_{MW} (10.1)	LOT_{MW} (4.0)	LOT_{MW} (3.7)	GLD_{NP} (99.06)	MRX_{SE} (51.27)	LOT_{MW} (9.05)	LOT_{MW} (2.40)
2	FWD_{SP} (8.8)	FWD_{SP} (3.4)	FWD_{SP} (3.0)	LBF_{NP} (98.83)	HUN_{SE} (48.05)	DTX_{MW} (8.86)	DTX_{MW} (1.76)
3	FFC_{SE} (8.1)	FFC_{SE} (3.3)	FFC_{SE} (2.9)	CYS_{NP} (98.52)	GRR_{MW} (44.08)	FFC_{SE} (7.37)	HGX_{SP} (1.17)
4	HGX_{SP} (7.4)	HGX_{SP} (2.8)	HGX_{SP} (2.5)	UNR_{NP} (98.25)	DTX_{MW} (43.44)	HGX_{SP} (5.28)	MKX_{MW} (0.91)
5 (90th PCTL)	ILN_{MW} (5.9)	DTX_{MW} (2.6)	ILN_{MW} (2.3)	MAF_{SP} (98.23)	OHX_{SE} (41.08)	ILN_{MW} (5.01)	FWD_{SP} (0.79)
6	DTX_{MW} (5.9)	ILN_{MW} (2.5)	DTX_{MW} (2.3)	AMA_{SP} (97.88)	JKL_{MW} (39.96)	MRX_{SE} (4.62)	ILN_{MW} (0.79)
7	EWX_{SP} (4.9)	MPX_{NP} (1.9)	MPX_{NP} (1.8)	DDC_{NP} (97.63)	FFC_{SE} (39.67)	MKX_{MW} (4.48)	BOU_{NP} (0.74)
8	MPX_{NP} (4.7)	EWX_{SP} (1.8)	EWX_{SP} (1.7)	ABR_{NP} (97.31)	LMK_{MW} (36.96)	IND_{MW} (3.69)	LIX_{SE} (0.68)
9	BOU_{NP} (3.9)	LSX_{MW} (1.6)	BOU_{NP} (1.4)	SJT_{SP} (97.10)	ILN_{MW} (34.85)	GRR_{MW} (3.62)	FFC_{SE} (0.59)
10 (80th PCTL)	LSX_{MW} (3.6)	BOU_{NP} (1.6)	LSX_{MW} (1.4)	LUB_{SP} (95.78)	SGF_{MW} (29.48)	LIX_{SE} (3.42)	MPX_{NP} (0.52)

and housing density (Ashley and Strader 2016; Strader et al. 2017), fatalities are much less of a concern unless a tornado intersects a large population center (e.g., Oklahoma City, Oklahoma; Dallas–Fort Worth; Omaha, Nebraska). Longer pathlengths are of greatest concern in the NP and SE CWAs, while there is no one region that stands out among the others in terms of mean path widths. Mean tornado damage footprints again point toward the SE having the greatest climatological tornado risk, with tornado translational speed being of most concern to CWAs east of the Mississippi River where built-environment development is greater (i.e., MW and SE regions; Ashley and Strader 2016). Although the greater number of SE CWAs ranked within the 80th percentile of tornado risk metrics are influenced by the 27 April 2011 tornado outbreak (Sherman-Morris and Brown 2012; Chiu et al. 2013; Knupp et al. 2014), removing this historical severe weather outbreak from analyses does not change the overall CWA trends or climatological risk patterns.

b. Tornado watch and warning measures

Annual CWA tornado watch and warning frequencies are generally highest in SE CWAs (Table 6; Figs. 3a,b). All 80th-percentile mean annual CWA tornado watch and warning frequencies are expected to contain an average (mean) of greater than 16 watches and 86 warnings per year. To provide density measures for each tornado advisory product, tornado watch and warning frequencies were also normalized by CWA area. After controlling for CWA area, the SE region still encompasses a majority of the 80th-percentile-ranked CWAs for mean annual watch and warning density. All CWAs within the 80th percentile of mean annual tornado watch density are located in the SE region except TSA with 2.6 watches per 10 000 km^2 per year. MOB encapsulates the highest overall watch density with approximately 4.2 annual watches per 10 000 km^2 per year. All 80th-percentile-ranked CWAs are expected to be intersected by at least 2.5 tornado watches per 10 000 km^2 per year.

The 80th-percentile tornado warning density rankings indicate similar patterns to mean annual watch density findings, with a majority (7) of the CWAs ranked in the top 10 belonging to the SE region. In all, tornado warning densities for CWAs in the 80th-percentile ranking are expected to experience 13 or more tornado warnings per 10 000 km^2 on average per year. HUN has the highest annual tornado warning density with nearly 28.1 warnings per 10 000 km^2 per year.

Annual tornado watch and warning frequencies are analogous to mean annual tornado path frequency and density 80th-percentile rankings (i.e., Table 4). Taking the prior tornado climatology and risk findings into account, watch and warning results highlight some of the same CWAs. For example, BMX, HUN, and JAN are in the 80th-percentile rankings for overall tornado risk, watch, and warning density. CWAs ranked above the 80th percentile in mean annual tornado watch and warning counts or densities are also more likely to experience a greater number of fatalities per year, especially in the SE region. Overall, SE CWAs not only encompass larger overall concentrations of fatal and nonfatal tornadoes but are also intersected by tornado watches and warnings more frequently. This result was in contrast to Brotzge and Erickson (2010) and Brotzge et al. (2011) where it was indicated that tornado warning counts were slightly more common in the central plains. It is presumed that this discrepancy is at least in part attributed to the differences in data period length and spatial and statistical aggregation.

Examining tornado watch and warning frequencies in relation to other tornado risk and exposure variables, higher-ranked CWAs in terms of annual watch and warning densities often have larger overall EF1+ tornado damage footprints and faster tornado translational speeds. Combining the CWA developed housing density rankings (i.e., Table 5) with the watch and warning frequency and density analyses, findings indicate that the tornado watches and warnings in MW and SE CWAs likely affect a greater number of people on average due to higher concentrations of exurban, suburban, and urban housing density. This finding is consistent with prior research focusing on tornado impacts in the southeastern United States (Ashley and Strader 2016; Strader and Ashley 2018).

c. Lead time warnings, false alarm warnings, and unwarned tornado events

The SE region CWA mean annual frequencies and densities (warnings per 10 000 km^2) for lead time warnings (LTWs), false alarm warnings (FAWs), and unwarned tornado reports

TABLE 6. Mean annual tornado watch and warning frequency and density (per 10 000 km^2) 80th- and 90th-percentile CWA rankings. Parentheses indicate specific watch and warning attribute values. Subscript acronyms denote the parent CWA region.

Rank	Watch frequency	Warning frequency	Watch density (per 10^4 km^2)	Warning density (per 10^4 km^2)
1	JAN_{SE} (26.7)	JAN_{SE} (165.2)	MOB_{SE} (4.2)	HUN_{SE} (28.1)
2	LZK_{SE} (24.5)	BMX_{SE} (130.2)	LIX_{SE} (4.0)	LIX_{SE} (22.5)
3	SHV_{SE} (22.4)	SHV_{SE} (105.6)	HUN_{SE} (3.7)	MOB_{SE} (22.3)
4	OUN_{SP} (21.2)	MOB_{SE} (104.2)	LCH_{SE} (3.0)	JAN_{SE} (18.0)
5 (90th PCTL)	MEG_{SE} (20.8)	MEG_{SE} (102.1)	JAN_{SE} (2.9)	BMX_{SE} (17.7)
6	MOB_{SE} (19.8)	LIX_{SE} (101.2)	LZK_{SE} (2.8)	OHX_{SE} (17.3)
7	BMX_{SE} (18.7)	OUN_{SP} (94.7)	MEG_{SE} (2.7)	PAH_{MW} (14.4)
8	LIX_{SE} (18.2)	LZK_{SE} (92.2)	TAE_{SE} (2.6)	SGF_{MW} (13.5)
9	TSA_{SP} (17.6)	PAH_{MW} (92.2)	TSA_{SP} (2.6)	LMK_{MW} (13.3)
10 (80th PCTL)	TAE_{SE} (16.8)	SGF_{MW} (86.8)	BMX_{SE} (2.5)	MEG_{SE} (13.0)

(UWRs) are generally higher compared to all other tornado-prone regions (Table 7; Figs. 3c,e,g). This result is consistent with prior research findings (Brotzge and Erickson 2010; Brotzge et al. 2011; Anderson-Frey et al. 2019). In terms of mean annual LTWs and FAWs, these rankings are very similar to the mean annual tornado warning (all warnings) CWA rankings (e.g., Table 6). As expected, this finding suggests that mean annual LTW, FAW, and UWR frequency and density are products of the overall tornado climatology and number of warnings issued by a CWA.

In general, CWAs in the MW region have lower LTW counts and densities. MW CWAs such as DTX (2.2 LTWs per year; 14.6% LTWs), GRR (2.0 LTWs per year; 15.8% LTWs), and JKL (3.4 LTWs per year; 11.1% LTWs) contain lower LTW frequencies and percentages of all warnings that are LTWs relative to most CWAs in the study domain. JAN (124.4 FAWs per year) and BMX (20.1 UWRs per year) are ranked the highest of all CWAs for FAW and UWR frequency. When normalizing by CWA size, HUN is the highest-ranked CWA in terms of FAW (21.5 FAWs per 10 000 km^2 per year) and UWR (3.7 UWRs per 10 000 km^2 per year) mean annual densities. Overall, the 80th-percentile-ranked CWAs for FAW and UAW frequencies are all expected to contain 67.7 FAWs and 12.5 UWRs per year. Mean annual 80th-percentile FAW and UWR density rankings for all 80th-percentile CWAs also reveals that the associated CWAs will encompass 10.4 FAWs per 10 000 km^2 and 2.0 UWRs per 10 000 km^2 on average each year. LTW frequencies also tend to be lower near the edges of the entire study domain where tornado frequencies are lower (Fig. 3c). Conversely, FAW and UWR CWA frequencies tend to be higher in the SE domain (Figs. 3e,g). LTW and FAW percentages of all warnings illustrate similar spatial trends where CWAs in the southern portions of the SE and SP regions (i.e., EWX, HGX, LIX, and MOB), as well as those in the eastern side of the MW domain (i.e., DTX, GRR, IND, LMK, and JKL) are ranked higher.

d. *Mean warning lead time*

No particular region stands out when ranking CWA mean tornado warning lead times from shortest to longest (Table 7; Fig. 4). DTX (11.3 min), EWX (11.9 min), and LCH (11.2 min) all rank within the 90th percentile of mean warning lead time and contain mean lead times less than 12 min. All CWAs ranked within the 80th percentile of mean warning lead time comprise lead times less than 13 min. Conversely, CWAs such as GLD (18.4 min), MRX (18.2 min), MOB (17.7 min), and JAN (17.6 min) contain the longest mean warning lead times of all tornado-prone CWAs. Spatially, CWAs along the southwestern Gulf Coast (i.e., EWX, HGX, LCH, and LIX) have some of the shortest mean warning lead times. This is likely due to coastal thunderstorm processes and landfalling tropical storms where more commonly produced transient mesocyclones makes detecting and warning tornadoes more difficult (e.g., McCaul et al. 2004; Edwards 2012).

In comparing warning and report outcomes with housing density, it is seen that some of the highest-ranked CWAs in terms of fewer LTWs, more FAWs, and greater numbers of UWRs are associated with CWAs that contain high-density population centers. For example, DTX, EWX, and HGX all are within the 80th-percentile ranks for lower LWTs and higher FAWs and UWRs. These CWAs also encompass greater than 5.9 million people each and have higher percentages of exurban and suburban housing density. Thus, any unfavorable tornado warning outcome (e.g., shorter warning lead time, FAW, or UWR) within these CWAs has a magnified effect given the greater number of people and homes potentially exposed to tornadoes.

e. *Social vulnerability*

Examining social vulnerability using the SVI theme-1 (socioeconomic status) variables, CWAs within the SE are generally more vulnerable relative to all other CWAs (Table 8). As expected, this result is in agreeance with prior research such as Ashley (2007) and Strader and Ashley (2018) where the Southeast has been shown to have greater socioeconomic vulnerability that leads to increased tornado mortality. Specifically, SE CWAs make up a majority of the 80th-percentile percentage of persons living in poverty, unemployed, and lower income per capita rankings. However, JKL (MW region) ranks highest among all CWAs for SVI theme-1 variables with 28.5% of persons living in poverty (Fig. 5a), 9.7% unemployed (Fig. 5b), 24.9% with no high school diploma, and a mean per capita income of $18,741 (U.S. dollars). The SP CWAs such as AMA (18.7%), HGX (18.9%), LUB (19.8%), and MAF (23.2%) also all rank near the top in the percentage of population without a high school diploma. Last, SE CWAs such as BMX, JAN, LCH, and MEG are also ranked in the 80th percentile for

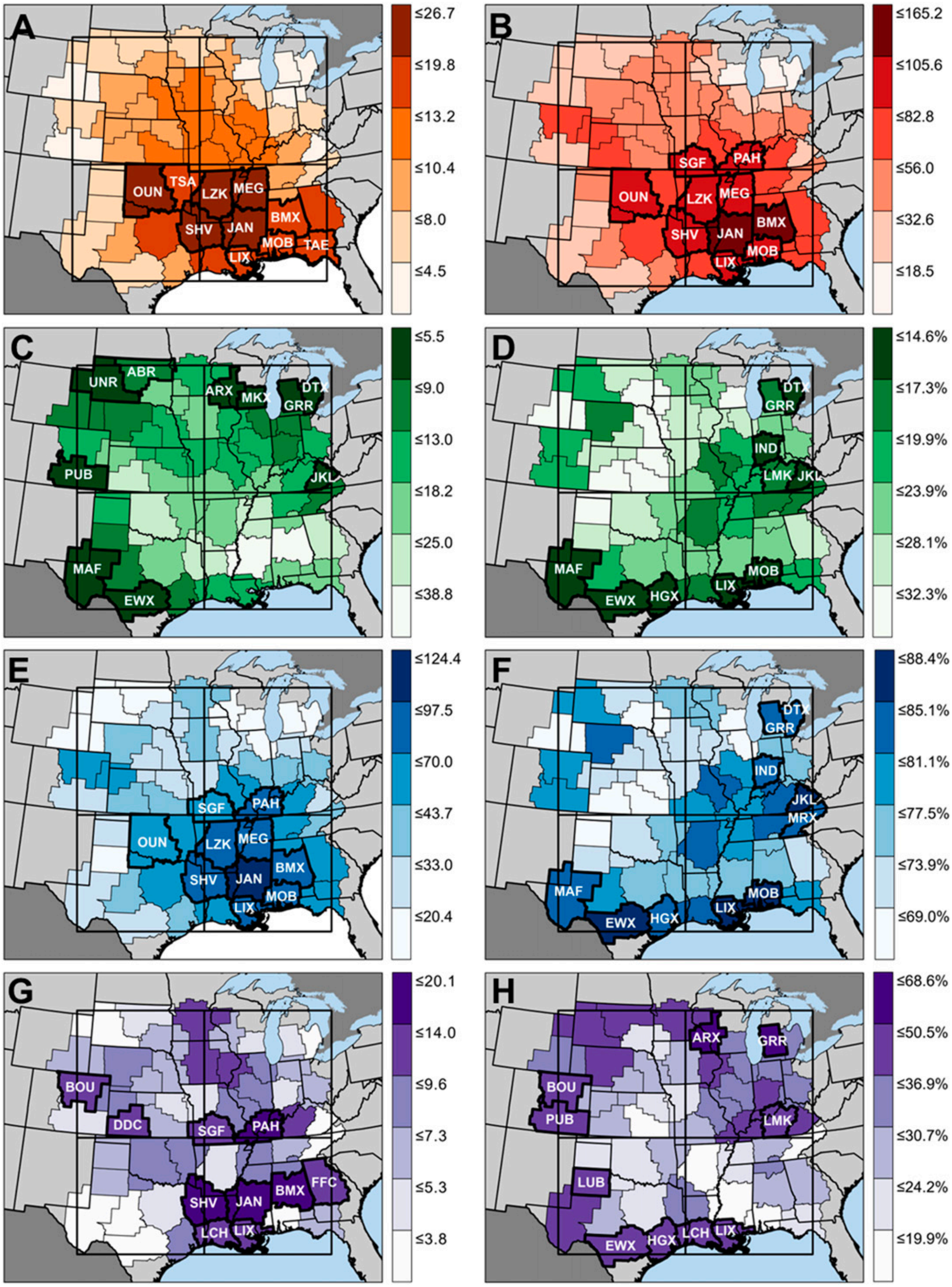

FIG. 3. Mean annual (a) tornado watch frequency, (b) tornado warning frequency, (c) LTW frequency, (d) percentage of all warnings that are LTWs, (e) FAW frequency, (f) percentage of all warnings that are FAWs, (g) UWR frequency, and (h) percentage of all reports that are UWRs. Note that the LTW count [in (c)] and percentage [in (d)] scales are reversed. CWAs within the 80th percentile for each variable are thickly outlined.

all SVI theme-1 variables. These findings related to socioeconomic status measures of vulnerability suggest that if a tornado were to impact a CWA in the SE region then recovery from such an event would indeed be difficult because of the higher unemployment rates, the larger number people below the poverty line, greater concentrations of populations with no insurance or health benefits, and lower educational attainment (Morrow 1999; Cutter et al. 2003; Brodie et al. 2006; Tierney

TABLE 7. Mean annual tornado warning frequency, density (per 10 000 km^2), and percentage of all warnings 80th and 90th percentiles for LTWs and FAWs. Mean annual CWA unwarned tornado report frequencies, densities, percentages of all tornado reports, and mean warning lead times are also illustrated. LTW frequency, density, percentage of all warnings, and mean warning lead times are ranked from shorter to longer. Parentheses indicate specific CWA warning attribute values. Subscript acronyms denote the parent CWA region.

	Mean (annual)									
	Frequency			Density (per 10^4 km^2)			Percent of all warnings or reports			
Rank	LTW	FAW	UWR	LTW	FAW	UWR	LTW	FAW	UWR	Mean warning lead time (min)
1	GRR_{MW} (2.0)	JAN_{SE} (124.4)	BMX_{SE} (20.1)	MAF_{SP} (0.35)	HUN_{SE} (21.5)	HUN_{SE} (3.7)	EWX_{SP} (10.7)	JKL_{MW} (88.4)	GRR_{MW} (68.6)	LCH_{SE} (11.2)
2	DTX_{MW} (2.2)	BMX_{SE} (97.5)	JAN_{SE} (19.4)	EWX_{SP} (0.36)	LIX_{SE} (19.4)	LIX_{SE} (2.8)	JKL_{MW} (11.1)	EWX_{SP} (88.1)	ARX_{MW} (53.8)	DTX_{MW} (11.3)
3	EWX_{SP} (3.4)	MOB_{SE} (89.6)	SHV_{SE} (16.7)	UNR_{NP} (0.40)	MOB_{SE} (19.1)	BMX_{SE} (2.7)	LIX_{SE} (12.8)	LIX_{SE} (86.5)	EWX_{SP} (50.5)	LMK_{MW} (11.7)
4	JKL_{MW} (3.4)	LIX_{SE} (87.5)	PAH_{MW} (16.0)	GRR_{MW} (0.55)	OHX_{SE} (14.3)	LCH_{SE} (2.6)	MOB_{SE} (13.6)	MOB_{SE} (86.0)	PUB_{NP} (45.7)	EWX_{SP} (11.9)
5 (90th PCTL)	UNR_{NP} (4.3)	MEG_{SE} (81.1)	FFC_{SE} (14.0)	PUB_{NP} (0.60)	JAN_{SE} (13.6)	PAH_{MW} (2.5)	HGX_{SP} (14.4)	HGX_{SP} (85.1)	LMK_{MW} (45.4)	CSY_{NP} (12.3)
6	MAF_{SP} (4.7)	SHV_{SE} (79.3)	LCH_{SE} (13.5)	DTX_{MW} (0.71)	BMX_{SE} (13.3)	LOT_{MW} (2.3)	MAF_{SP} (14.4)	MAF_{SP} (84.7)	LUB_{SP} (45.3)	HGX_{SP} (12.4)
7	PUB_{NP} (5.1)	LZK_{SE} (75.8)	SGF_{MW} (13.8)	ABR_{NP} (0.81)	PAH_{MW} (11.4)	LMK_{MW} (2.2)	IND_{MW} (14.4)	IND_{MW} (84.3)	LCH_{SE} (45.1)	DMX_{NP} (12.4)
8	ARX_{MW} (5.2)	PAH_{MW} (72.9)	LIX_{SE} (12.8)	CYS_{NP} (0.97)	LMK_{MW} (11.1)	DDC_{NP} (2.1)	DTX_{MW} (14.6)	GRR_{MW} (83.6)	LIX_{SE} (43.5)	ILN_{MW} (12.5)
9	MKX_{MW} (5.5)	OUN_{SP} (70.0)	BOU_{NP} (12.5)	ARX_{MW} (1.0)	SGF_{MW} (10.5)	JAN_{SE} (2.1)	LMK_{MW} (15.5)	DTX_{MW} (83.3)	BOU_{NP} (42.8)	LIX_{SE} (12.6)
10 (80th PCTL)	ABR_{NP} (6.4)	SGF_{MW} (67.7)	DDC_{NP} (12.5)	LBF_{NP} (1.0)	IND_{MW} (10.4)	SGF_{MW} (2.0)	GRR_{MW} (15.8)	MRX_{SE} (83.2)	HGX_{SP} (42.5)	OAX_{NP} (12.9)

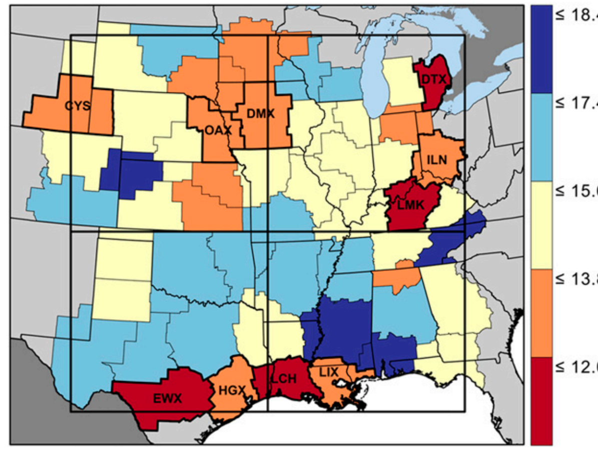

FIG. 4. Mean tornado warning lead time (min) by CWA from 2007 to 2019. CWAs within the 80th percentile and greater are thickly outlined.

2006). WFOs with a greater percentage of their CWA populations who are socioeconomically vulnerable should be aware that these individuals have reduced self-efficacy, resilience, and ability to absorb potential tornado impacts and losses.

SVI theme-2 (household composition and disability) measures of CWA vulnerability are more variable from CWA to CWA when compared with SVI theme-1 CWA rankings (Table 9). The 80th-percentile CWA ranking for the percentage of persons above 65 years old are mostly made up of those within NP and MW regions. The top four CWAs belong to the NP region and have greater than 19% of their population over the age of 65. In addition to the NP regions, SP region CWAs have the highest percentage of persons under the age of 17 (greater than 24%). The 80th-percentile rankings for CWA percentage of persons who are disabled or in single-parent households again highlight those CWAs in the SE region. Although JKL (MW region) illustrates the highest percentage of its population being disabled (26.5%), CWAs such as JAN, MEG, and TAW also have relatively large percentages of disabled individuals and single-parent households (Fig. 5c). In general, CWAs with higher percentages of persons who are disabled are clustered in the Mississippi and Tennessee River valleys within the MW and SE regions. SVI theme-2 CWA findings largely point to those populations or households who may be unable to properly respond to tornado threats since they commonly have lower self-efficacy and rely on outside assistance (e.g., the very young, elderly, disabled, and single parents; Morrow 2008). SVI theme-2 measures indicate that those CWAs with residents who may need assistance seeking shelter and/or take longer to get to proper shelter from a tornado are more likely to be killed or injured when a tornado strikes.

SP CWAs make up the greatest percentage of persons who are minorities and/or speak English "less than well" (Table 10; Fig. 5d). Specifically, 61.7% of the HGX CWA population are minorities and 9.6% speak English "less than well." This ranks HGX highest among all CWAs for both SVI theme-3 variables. In the SP region, these populations are mostly Latinx, where a

Table 8. Mean percentage and per capita CWA estimate ranks (80th and 90th percentile) based on SVI theme 1 (socioeconomic status). Income per capita is ranked from lowest to highest. Parentheses indicate specific SVI attribute values. Subscript acronyms indicate the parent CWA regions.

Rank	Percentage (%)			Per capita mean income ($)
	Below poverty	Unemployed	No high school diploma	
1	JKL_{MW} (28.5)	JKL_{MW} (9.7)	JKL_{MW} (24.9)	JKL_{MW} (18,741)
2	JAN_{SE} (25.7)	JAN_{SE} (9.6)	MAF_{SP} (23.2)	JAN_{SE} (22,105)
3	TAE_{SE} (22.3)	DTX_{MW} (8.7)	LUB_{SP} (19.8)	SHV_{SE} (23,357)
4	SHV_{SE} (22.1)	MEG_{SE} (8.5)	DDC_{NP} (19.0)	MEG_{SE} (23,762)
5 (90th PCTL)	MEG_{SE} (22.0)	TAE_{SE} (8.2)	HGX_{SP} (18.9)	SGF_{MW} (23,774)
6	BMX_{SE} (20.4)	LOT_{MW} (8.0)	AMA_{SP} (18.7)	TAE_{SE} (23,855)
7	LIX_{SE} (20.2)	BMX_{SE} (7.9)	JAN_{SE} (18.0)	PAH_{MW} (24,645)
8	LCH_{SE} (20.0)	MOB_{SE} (7.9)	LCH_{SE} (17.5)	LZK_{SE} (24,750)
9	LUB_{SP} (19.3)	LIX_{SE} (7.8)	MEG_{SE} (16.8)	LCH_{SE} (24,782)
10 (80th PCTL)	PAH_{MW} (19.1)	LCH_{SE} (7.3)	SHV_{SE} (16.6)	LUB_{SP} (24,900)

large percentage of the total population speaks Spanish as their first language (Peguero 2006). SE CWAs such as FFC, JAN, LIX and MEG all comprise greater than 43% minority populations, with most of this percentage being made up of African American or Black individuals. In general, minority populations in the SP CWAs likely have more difficulty responding to and recovering from tornado events due to existing cultural and language barriers (Peacock et al. 1997; Cutter et al. 2006; Nelson 2015; Donner et al. 2012; Strader and Ashley 2018). This, in turn, creates a more likely scenario where these populations are disproportionately affected by tornado events.

The final SVI theme (theme 4) highlights housing type and transportation factors that relate to increased social vulnerability (Table 11). As expected, the percentage of homes that are multiunit structures are higher in CWAs where population density is greater (e.g., large cities such as Houston, Chicago, and Dallas–Fort Worth). The percentage of mobile and manufactured housing types are generally higher for those CWAs in the SE region (Fig. 5e). This finding is akin to many prior tornado studies (Ashley 2007; Strader and Ashley 2018) that have investigated mobile or manufactured housing and tornadoes in the Southeast. All CWAs but JKL (30.0%), MAF (15.0%), and UNR (16.6%) in the 80th percentile of mobile or manufactured home percentage are found in the SE region. The 80th-percentile CWA ranking of the percentage of households that are "crowded" (i.e., greater than 1.5 people per room) is mostly made up of SP CWAs. Over 5% of households in HGX and MAF are crowded, with four other SP CWAs within the 80th percentile (AMA, EWX, LUB, and TSA). At the CWA scale, crowding is loosely tied closely to larger percentages of minority populations and high-density cities (Tierney 2006). MW and SE CWAs make up the 80th-percentile rankings for the percentage of households with no vehicle, with higher population CWAs such as LOT (13.2%) and DTX (10.3%) being near the top (Fig. 5f). CWAs with higher percentages of populations with no vehicle are mostly in the eastern portion of the larger study domain where public transportation options are more readily available. However, some CWAs without large population centers [i.e., JKL (9.6%), ILX (8.8%), and JAN (8.6%)] are also in the "no vehicle" 80th percentile. This suggests that there is a link between poverty, income, and access to a vehicle (i.e., those in poverty cannot afford a vehicle although it may be crucial to survival during a tornado event). The percentages of persons living in group quarters (i.e., college dormitories, farm workers, psychiatric institutions, prisons, and assisted living facilities) are generally mixed among all four regions. SJT (6.6%), PUB (4.8%), and TAE (4.3%) are the three highest-ranked CWAs in terms of group quarter populations. In general, those living in group quarters are more prone to tornado impacts because of their special needs and immobility.

Taking all of the SVI themes into account, JAN and JKL rank highest in terms of social vulnerability as they appear in the 80th-percentile SVI theme rankings most frequently (Table 12; Fig. 6). Specifically, theme-1 (socioeconomic status), theme-2 (household and disability), and theme-4 (housing type and transportation) vulnerability measures are higher in JAN and JKL relative to all other tornado-prone CWAs. Other CWAs commonly found in the 80th-percentile SVI theme rankings include LUB, MAF, and SHV. Most (6) of the CWAs in the 80th-percentile rankings for all SVI themes are located in the SE region with three SP CWAs (LUB, MAF, SJT) and one MW CWA (JKL) making up the remaining top 10 ranking positions.

4. Discussion: Tying tornado risk, watch/warning outcomes, exposure, and vulnerability together

Analogous to prior research findings, CWAs across the United States have varying combinations of climatological tornado risk metrics and societal vulnerability that influence tornado impact frequency and magnitude. For instance, tornado impacts in the SE region are driven by a higher population density that places more vulnerable people in the path of potential tornadoes. CWAs in the SE frequently have greater percentages of persons living in poverty, mobile and manufactured homes, and/or disabled individuals. Simultaneously, higher tornado risk metrics such as mean tornado path damage footprint area and translational speed influence tornado impacts in the SE region. Because of these elevated tornado risk

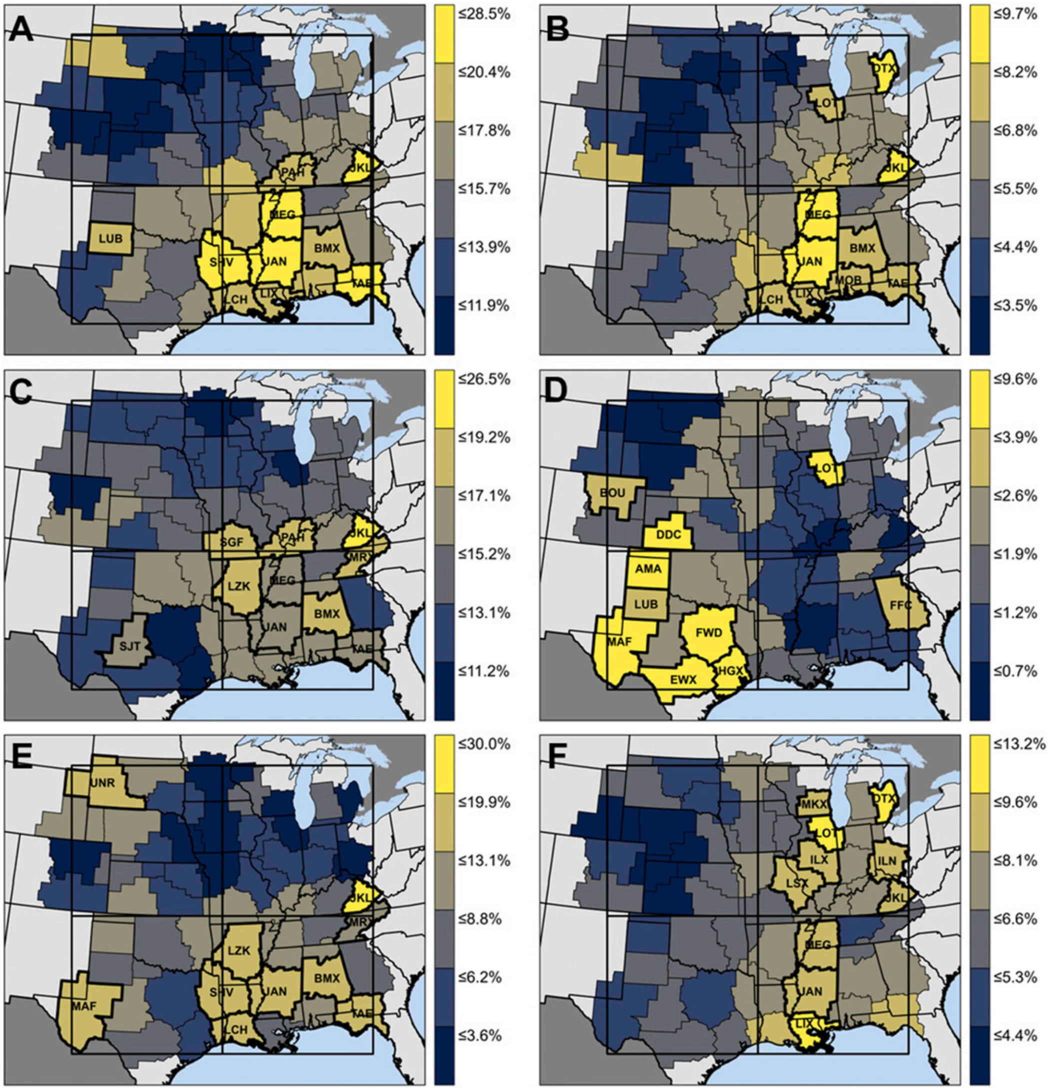

FIG. 5. Selected SVI variables of the percentage of CWA (a) population below the poverty level, (b) unemployed persons, (c) population on disability (d), persons who speak English ''less than well,'' (e) mobile or manufactured homes, and (f) households with no access to a vehicle. CWAs within the 80th percentile and greater are thickly outlined.

and vulnerability measures, SE CWAs are more prone to tornado losses compared to CWAs in other tornado-prone regions. Nowhere is this combination of increased climatological tornado risk and vulnerability more apparent than in JAN where it ranks the highest in terms of all SVI categories and in the 80th percentile for all tornado risk measures. Together, these vulnerability and risk measures make JAN the most tornado impact-prone and highest-risk CWA in the United States.

Unfortunately, many SE CWAs also experience an elevated number of FAWs and UWRs every year. This higher frequency of FAWs suggests that if there is a ''cry wolf effect'' (e.g., Lim et al. 2019), then it may be more prevalent or have a greater effect on those in the SE United States where social vulnerability is elevated. In addition, the combination of a larger population density in the SE United States and more frequent unwarned tornadoes indicates that CWAs such as BMX, FFC, HUN, JAN, LCH, and LIX not only contain more individuals potentially affected by unwarned tornadoes but also more socially vulnerable persons exposed to unwarned events. It should be noted that in recent years, Southeast WFOs have been actively trying to lower the false alarm ratios associated with tornado warnings (Brooks and Correia 2018). These findings support their efforts and point to the continued effort needed to reduce Southeast FAWs and UWRs while increasing LTWs.

In terms of lower mean tornado warning lead time, LCH ranks highest of all CWAs. It also ranks sixth for overall SVI vulnerability metrics, indicating that a larger percentage of vulnerable persons in LCH are often given shorter tornado

TABLE 9. As in Table 6, but for SVI theme 2 (household and disability).

Rank	Percentage (%)			
	Age ≥65	Age ≤17	Disabled	Single-parent household
1	LBF_{NP} (22.7)	DDC_{NP} (27.1)	JKL_{MW} (26.5)	JAN_{SE} (12.6)
2	GLD_{NP} (21.4)	MAF_{SP} (26.9)	LZK_{SE} (19.2)	MEG_{SE} (11.5)
3	GID_{NP} (19.4)	AMA_{SP} (26.3)	PAH_{MW} (18.7)	LCH_{SE} (11.1)
4	ABR_{NP} (19.3)	UNR_{NP} (25.1)	MRX_{SE} (18.5)	SHV_{SE} (10.9)
5 (90th PCTL)	SGF_{MW} (18.6)	FWD_{SP} (25)	BMX_{SE} (17.8)	LIX_{SE} (10.6)
6	MRX_{SE} (18.6)	HGX_{SP} (25)	SGF_{MW} (17.7)	HGX_{SP} (10.6)
7	ARX_{MW} (18.4)	ABR_{NP} (24.8)	TAE_{SE} (17.1)	MKX_{MW} (10.4)
8	LZK_{SE} (18)	ICT_{NP} (24.7)	MEG_{SE} (17.1)	UNR_{NP} (10.3)
9	PAH_{MW} (17.8)	FSD_{NP} (24.6)	SJT_{SP} (16.8)	TAE_{SE} (10.2)
10 (80th PCTL)	DVN_{MW} (17.8)	LUB_{SP} (24.5)	JAN_{SE} (16.8)	FWD_{SP} (10.2)

warning lead times. In all, the commingling of elevated measures of tornado risk, social vulnerability, and more frequent LTWs and UWRs signifies that SE CWAs are most prone to tornado losses and casualties.

Although WFOs in the SE region should be most concerned with tornado events due to both a greater threat of tornadoes and an elevated societal vulnerability, CWAs in other tornado-prone regions (MW, NP, SP) are not immune to the effects of social vulnerability. MW CWAs often have greater percentages of FAWs and UWRs, higher population densities, and faster tornado translational speeds that increase tornado impact potential. Because MW CWAs also have the highest population densities compared to other tornado-prone CWAs, their lower percentages of all warnings and reports that are LTWs and UWRs exacerbate social vulnerability factors. DTX and LMK also are within the 95th percentile of shorter mean tornado warning lead times, providing socially vulnerable CWA populations with less time on average to respond to tornado threats. This is especially true for DTX where there is a large percentage of the population that is unemployed. However, JKL stands out as the MW region's most vulnerable and impact-prone CWA. Although JKL has a lower overall tornado risk than does JAN (SE region), it is equivalent to JAN in terms of being ranked highest in most social vulnerability measures. This suggests that although tornadoes are less frequently experienced by JKL populations, when a tornado event does occur it is more likely to have a greater impact on the underlying population.

NP CWAs generally contain lower population densities but experience longer-tracked tornadoes. Moreover, NP CWAs often encompass greater percentages of vulnerable populations related to age (65+ and <17 years old) and minorities (e.g., Native American populations). This suggests that when a tornado does intersect a NP CWA or community, impacts may be magnified due to the aforementioned vulnerability factors. As prior research has also indicated, many rural populations may be more vulnerable to tornado impacts given less access to critical resources such as medical facilities and first responder services (Cutter et al. 2003; Strader and Ashley 2018; Strader et al. 2019). Because NP CWAs such as BOU and DDC contain elevated percentages of UWRs, minor populations, 65+ persons, multiunit structures, and populations in group quarters, a large portion of their CWA populations may be more reliant on others for assistance when tornadoes do occur. Thus, an emphasis should be placed on providing these individuals with greater warning lead times, so they have more time to take proper shelter. This is especially true for NP CWAs such as UNR and ABR where there is a higher percentage of vulnerable Native American populations (e.g., Cutter et al. 2003; Flanagan et al. 2011).

Many SP CWAs also contain elevated tornado event frequencies that intersect highly vulnerable populations. In particular, CWAs such as DFW and OUN contain some of the highest climatological risk measures (i.e., path frequency, path density, etc.) in the country as well as high-density population centers (i.e., Oklahoma City and Dallas–Fort Worth). These factors alone make OUN and FWD more likely to experience high-impact tornado events. However, social vulnerability plays a greater role during tornado events for SP CWAs such as EWX, LUB, MAF, and SJT. These CWAs contain higher percentages of minorities, nonnative English-speaking Latinx individuals, minor (less than 17 years old) populations, and more crowding. Tornado warning lead times also tend to be lower in these CWAs, while the percentage of FAWs and UWRs are greater. Thus, while CWAs such as DFW and OUN have to consider the effects of greater tornado frequencies and large population centers, tornado impact frequency and magnitude in many

TABLE 10. As in Table 6, but for SVI theme 3 (minority and language).

Rank	Percentage (%)	
	Minority	Speaks English "less than well"
1	HGX_{SP} (61.7)	HGX_{SP} (9.6)
2	MAF_{SP} (58.3)	MAF_{SP} (6.8)
3	EWX_{SP} (56.5)	FWD_{SP} (6.5)
4	JAN_{SP} (54.3)	DDC_{NP} (6.5)
5 (90th PCTL)	FWD_{SP} (49.8)	AMA_{SP} (5.7)
6	LUB_{SP} (49.6)	EWX_{SP} (5.6)
7	LOT_{MW} (48.8)	LOT_{MW} (5.2)
8	FFC_{SE} (47.8)	LUB_{SP} (3.9)
9	LIX_{SE} (47.1)	BOU_{NP} (3.3)
10 (80th PCTL)	MEG_{SE} (43.8)	FFC_{SE} (3.1)

TABLE 11. As in Table 6, but for SVI theme 4 (housing type and transportation).

Rank	Percentage (%) Multiunit structures	Mobile or manufactured homes	Crowding	No vehicle	Group quarters
1	HGX_{SP} (18.9)	JKL_{MW} (30.0)	HGX_{SP} (5.5)	LOT_{MW} (13.2)	SJT_{SP} (6.6)
2	BOU_{NP} (16.7)	TAE_{SE} (19.9)	MAF_{SP} (5.4)	LIX_{SE} (10.5)	PUB_{NP} (4.8)
3	MPX_{NP} (16.4)	UNR_{NP} (16.6)	FWD_{SP} (4.8)	DTX_{MW} (10.3)	TAE_{SE} (4.3)
4	FWD_{SP} (15.2)	SHV_{SE} (16.5)	UNR_{NP} (4.5)	JKL_{MW} (9.6)	TOP_{NP} (4.1)
5 (90th PCTL)	LOT_{MW} (14.3)	MAF_{SP} (15.0)	EWX_{SP} (4.3)	MKX_{MW} (9.4)	ILX_{MW} (4.1)
6	EWX_{SP} (14.1)	JAN_{SE} (14.8)	DDC_{NP} (4.0)	MEG_{SE} (9.0)	JAN_{SE} (4.0)
7	MKX_{MW} (13.7)	LCH_{SE} (14.7)	LUB_{SP} (3.9)	ILX_{MW} (8.8)	OUN_{SP} (4.0)
8	OAX_{NP} (12.2)	LZK_{SE} (14.1)	AMA_{SP} (3.9)	ILN_{MW} (8.7)	GRR_{MW} (4.0)
9	FFC_{SE} (11.8)	BMX_{SE} (13.8)	SHV_{SE} (3.2)	LSX_{MW} (8.6)	PAH_{MW} (3.9)
10 (80th PCTL)	TOP_{NP} (9.6)	MRX_{SE} (13.1)	TSA_{SP} (3.2)	JAN_{SE} (8.6)	CYS_{NP} (3.8)

other SP CWAs are more influenced by social vulnerability factors.

5. Conclusions

Although prior research has examined regional differences in tornado risk and vulnerability across the United States, this information has yet to be tied to the parent WFOs that are responsible for informing or warning the public about possible tornado threats. The findings presented in this study not only provide valuable climatological tornado risk information for tornado-prone CWAs, but also yield key knowledge about underlying CWA population vulnerabilities throughout the United States. Given tornado impact magnitude and frequency is controlled by both environmental factors that generate tornadoes and the underlying population exposure and vulnerability, it is critical the NWS forecasters and associated IWT members understand all elements that influence tornado impact magnitude, frequency, and disaster potential within their CWAs. This study is the first of its kind to combine elements of climatological tornado risk, societal exposure and vulnerability, and watch/warning characteristics at the CWA scale. Aggregating these elements within CWAs not only provides NWS forecasters and local IWT members with a better sense of CWA tornado climatologies, but also informs forecasters about the underlying population character that is likely to be affected by tornadoes within the region. Examining together risk, exposure, and vulnerability also allows WFOs to better assess the potential consequences of a tornado event intersecting their CWA. Moreover, assessing risk, exposure, and vulnerability measures in relation to tornado warning outcomes enables WFOs to reevaluate their warning issuance practices so that CWA population characteristics and vulnerabilities are taken into account.

Findings in this research also illustrate that tornado impacts across the United States are driven by a variety of risk, exposure, and vulnerability combinations. Thus, a uniform or ''one size fits all'' solution for all WFOs is not possible. Rather, we suggest that results from this study are used in three primary means. Our first suggestion is that WFOs and future researchers utilize the findings presented herein as a jumping-off point to develop, execute, correct, and supplement their own local, finescale investigations into CWA tornado risk, exposure, *and* vulnerability. While most WFOs (e.g., BMX, LOT, and OUN) have already generated their own CWA climatologies of tornado risk, few have considered exposure and vulnerability within their assessments. Conducting and incorporating such research into existing WFO summaries will help WFOs and IWT members improve knowledge, tornado warning practices and mitigation, response, and recovery strategies. In addition, WFOs and IWT partners should consider creating educational outreach programs or public engagement opportunities that

TABLE 12. As in Table 6, but for all SVI themes.

Rank	Percentage (%) Theme 1 (socioeconomic status)	Theme 2 (household composition and disability)	Theme 3 (minority status and language)	Theme 4 (housing type and transportation)	All themes
1	JKL_{MW} (0.85)	JKL_{MW} (0.77)	MAF_{SP} (0.75)	UNR_{NP} (0.69)	JAN_{SE} (0.68)
2	JAN_{SE} (0.73)	LZK_{SE} (0.72)	HGX_{SP} (0.75)	JKL_{MW} (0.60)	JKL_{MW} (0.68)
3	MEG_{SE} (0.69)	JAN_{SE} (0.71)	EWX_{SP} (0.69)	SHV_{SE} (0.60)	SHV_{SE} (0.67)
4	SHV_{SE} (0.68)	SHV_{SE} (0.71)	FWD_{SP} (0.66)	MAF_{SP} (0.59)	LUB_{SP} (0.66)
5 (90th PCTL)	TAE_{SE} (0.68)	GLD_{NP} (0.71)	LUB_{SP} (0.65)	ABR_{NP} (0.59)	MAF_{SP} (0.65)
6	LCH_{SE}(0.66)	PAH_{MW} (0.70)	AMA_{SP} (0.62)	SGF_{MW} (0.59)	LCH_{SE} (0.64)
7	BMX_{SE} (0.64)	LCH_{SE} (0.70)	LOT_{MW} (0.60)	ARX_{MW} (0.59)	TAE_{SE} (0.63)
8	LZK_{SE} (0.62)	MEG_{SE} (0.69)	SJT_{SP} (0.55)	LUB_{SP} (0.58)	MEG_{SE} (0.62)
9	LUB_{SP} (0.62)	SGF_{MW} (0.68)	DDC_{NP} (0.55)	JAN_{SE} (0.58)	SJT_{SP} (0.61)
10 (80th PCTL)	LIX_{SE} (0.62)	TSA_{SP} (0.67)	FFC_{SE} (0.54)	LCH_{SE} (0.57)	LZK_{SE} (0.59)

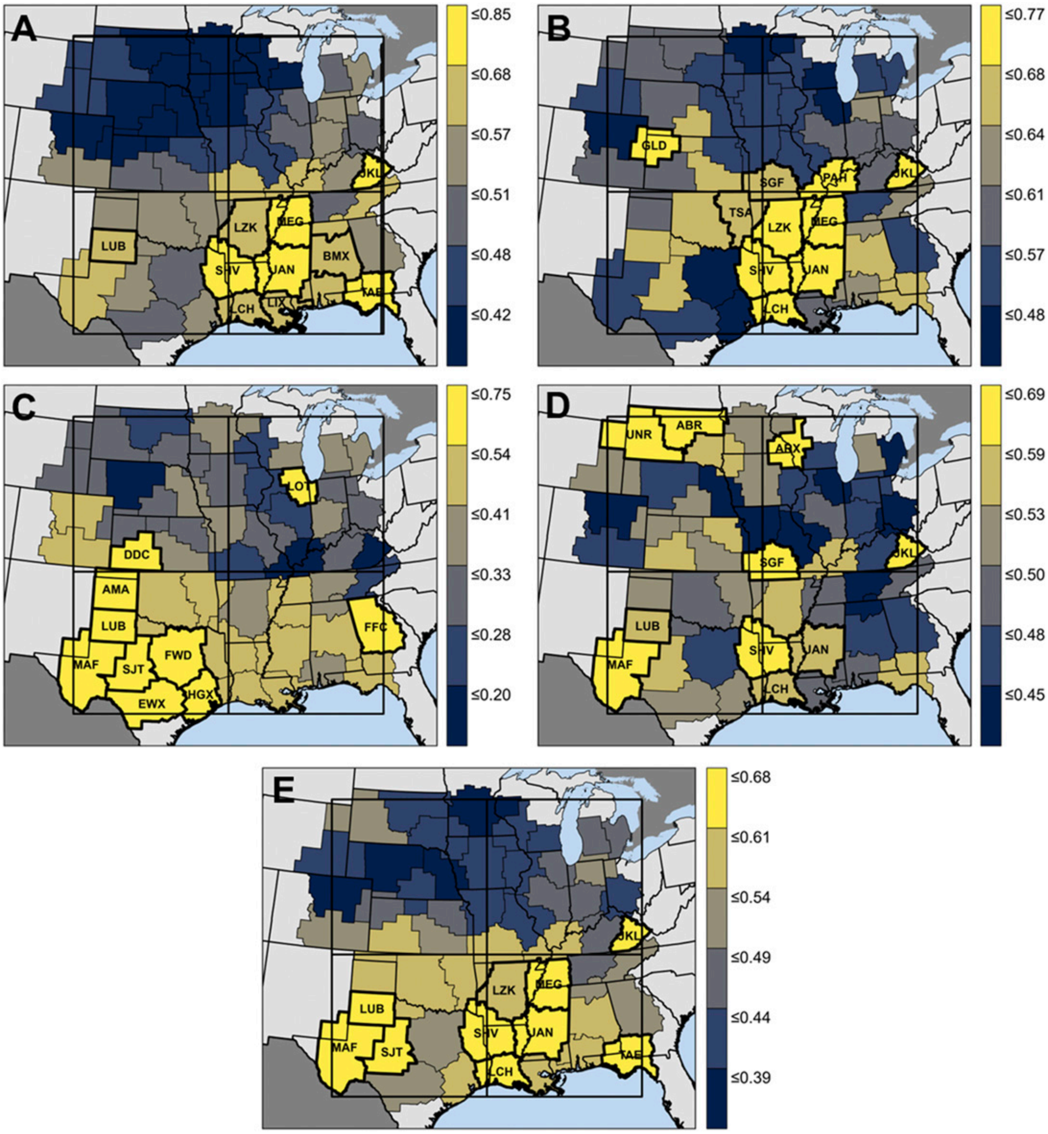

FIG. 6. SVI CWA percentile rankings for (a) theme 1 (socioeconomic status), (b) theme 2 (household composition and disability), (c) theme 3 (minority status and language, (d) theme 4 (housing type and transportation), and the average (mean) for all themes. CWAs within the 80th percentile and greater are thickly outlined.

target specific vulnerable population subsets. If WFOs are already participating in such activities, then the results from this work should be employed to help determine the populations that are in greatest need of assistance. In general, because *local* risk and vulnerabilities influence tornado impact frequency, mortality, and disaster severity, *local* solutions must be developed by individual WFOs and IWT members.

Our second recommendation is that results from this work and the aforementioned suggested local WFO CWA investigations be incorporated into existing training modules—such as those developed by the WDTD—or utilized to develop new training modules that are WFO specific. For example, SE CWAs (e.g., BMX, HUN, and JAN) should focus their training efforts on how elevated tornado risk and higher frequencies of FAWs and UWRs within the region intersect more vulnerable poverty-stricken and/or mobile or manufactured housing populations who are disproportionately killed more often during tornado events. MW CWA (e.g., DTX, IND, LOT, and LSX) training modules should consider the spectrum of vulnerabilities (e.g., minority, no access to a vehicle) associated with high-density population centers. This recommendation also holds true for CWAs that enclose high-density population centers in other tornado-prone regions [e.g., FFC (Atlanta), DWF (Dallas–Fort Worth), and OAX (Omaha)]. NP CWAs should develop training materials that are aimed at better understanding vulnerability within rural areas. In particular, these NP CWA modules should concentrate on understanding how tornado events with shorter average lead times affect vulnerable elderly, very young, and/or Native American populations. SP CWAs in the southern and western portions of the SP region should more strongly consider communication aspects of tornado watch and warning issuance for Latinx and nonnative English speakers. For instance, EWX may need to develop training materials aimed at understanding the relationship between Latinx populations that may not speak English as a first language and the effects of a higher number of FAWs and UWRs.

The findings presented in this study are not a critique of NWS WFO forecaster performance, current knowledge, or existing efforts being made to reduce tornado impacts within their CWAs. It is likely WFOs in these regions have existing knowledge of and are aware of many vulnerability factors within their CWAs. However, results from this project reinforce current efforts being made and illustrate the need for additional and more formal training modules for all tornado-prone WFOs. Such training materials would again allow NWS WFOs to better educate existing forecasters, but also ensure that forecasters new to a WFO/CWA are educated about the CWA's risk, exposure, and vulnerability character.

Last, our final recommendation is that outcomes from this research be applied to existing efforts being made by WFOs and large-scale research projects such as the Verifications of the Origins of Rotation Experiment in the Southeast (VORTEX-SE), Forecasting a Continuum of Environmental Threats (FACETs), and Warn-on-Forecast. Given these projects are examples where tornado risk measures and societal vulnerability are being assessed in conjunction with each other within large research ventures, findings from this research should be directly included within existing studies. Combining efforts from large-scale research projects to local social science-driven research, all parties need to concentrate on developing mitigation, response, and recovery strategies that reduce future tornado mortality and improve community resilience.

This work only presents a brief overview of the interrelationships between CWA tornado risk, warning outcomes, exposure, and vulnerability. Future assessments stemming from this research should also investigate further the relationship between tornado warning outcomes, severe weather environments, storm morphologies, seasonality, and social vulnerability. For example, this research is the first of its kind to discuss translational tornado speed as a factor of tornado risk. Additional research is needed that relates environmental factors to potential impacts on populations and the warning process. Future research should also consider examining these tornado disaster constituents in greater and more finescale detail within tornado-prone CWAs. Specifically, research that investigates social vulnerability more thoroughly using social science-led resident interviews or surveys, more detailed and comprehensive social vulnerability data (e.g., SoVI; Cutter et al. 2003), and/or geographic information system techniques must also be conducted within highly vulnerable CWAs such as HUN, JAN, JKL, LUB, MAF, OUN, and SHV (Fig. 1b).

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REFERENCES

Agee, E., and S. Childs, 2014: Adjustments in tornado counts, F-scale intensity, and path width for assessing significant tornado destruction. *J. Appl. Meteor. Climatol.*, **53**, 1494–1505, https://doi.org/10.1175/JAMC-D-13-0235.1.

Anderson, C. J., C. K. Wikle, Q. Zhou, and J. A. Royle, 2007: Population influences on tornado reports in the United States. *Wea. Forecasting*, **22**, 571–579, https://doi.org/10.1175/WAF997.1.

Anderson-Frey, A. K., Y. P. Richardson, A. R. Dean, R. L. Thompson, and B. T. Smith, 2019: Characteristics of tornado events and warnings in the southeastern United States. *Wea. Forecasting*, **34**, 1017–1034, https://doi.org/10.1175/WAF-D-18-0211.1.

Ash, K. D., 2017: A qualitative study of mobile home resident perspectives on tornadoes and tornado protective actions in South Carolina, USA. *GeoJournal*, **82**, 533–552, https://doi.org/10.1007/s10708-016-9700-8.

——, M. J. Egnoto, S. M. Strader, W. S. Ashley, D. B. Roueche, K. E. Klockow-McClain, D. Caplen, and M. Dickerson, 2020: Structural forces: Perception and vulnerability factors for tornado sheltering within mobile and manufactured housing in Alabama and Mississippi. *Wea. Climate Soc.*, **12**, 453–472, https://doi.org/10.1175/WCAS-D-19-0088.1.

Ashley, W. S., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880–2005. *Wea. Forecasting*, **22**, 1214–1228, https://doi.org/10.1175/2007WAF2007004.1.

——, and S. M. Strader, 2016: Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bull. Amer. Meteor. Soc.*, **97**, 767–786, https://doi.org/10.1175/BAMS-D-15-00150.1.

——, A. Krmenec, and R. Schwantes, 2008: Vulnerability due to nocturnal tornadoes. *Wea. Forecasting*, **23**, 795–807, https://doi.org/10.1175/2008WAF2222132.1.

——, S. Strader, T. Rosencrants, and A. J. Krmenec, 2014: Spatiotemporal changes in tornado hazard exposure: The case of the expanding bull's-eye effect in Chicago, Illinois. *Wea. Climate Soc.*, **6**, 175–193, https://doi.org/10.1175/WCAS-D-13-00047.1.

——, A. M. Haberlie, and J. Strohm, 2019: A climatology of quasi-linear convective systems and their hazards in the United States. *Wea. Forecasting*, **34**, 1605–1631, https://doi.org/10.1175/WAF-D-19-0014.1.

Brodie, M., E. Weltzian, D. Altman, R. J. Blendon, and J. M. Benson, 2006: Experiences of Hurricane Katrina evacuees in Houston shelters: Implications for future planning. *Amer. J. Public Health*, **96**, 1402–1408, https://doi.org/10.2105/AJPH.2005.084475.

Brooks, H. E., 2004a: Tornado-warning performance in the past and future: A perspective from signal detection theory. *Bull. Amer. Meteor. Soc.*, **85**, 837–844, https://doi.org/10.1175/BAMS-85-6-837.

——, 2004b: On the relationship of tornado path length and width to intensity. *Wea. Forecasting*, **19**, 310–319, https://doi.org/10.1175/1520-0434(2004)019<0310:OTROTP>2.0.CO;2.

——, and C. A. Doswell III, 2002: Deaths in the 3 May 1999 Oklahoma City tornado from a historical perspective. *Wea.*

Forecasting, **17**, 354–361, https://doi.org/10.1175/1520-0434(2002)017<0354:DITMOC>2.0.CO;2.

——, and J. Correia Jr., 2018: Long-term performance metrics for National Weather Service tornado warnings. *Wea. Forecasting*, **33**, 1501–1511, https://doi.org/10.1175/WAF-D-18-0120.1.

——, C. A. Doswell III, and M. P. Kay, 2003: Climatological estimates of local daily tornado probability for the United States. *Wea. Forecasting*, **18**, 626–640, https://doi.org/10.1175/1520-0434(2003)018<0626:CEOLDT>2.0.CO;2.

——, G. W. Carbin, and P. T. Marsh, 2014: Increased variability of tornado occurrence in the United States. *Science*, **346**, 349–352, https://doi.org/10.1126/science.1257460.

Brotzge, J., and S. Erickson, 2009: NWS tornado warnings with zero or negative lead times. *Wea. Forecasting*, **24**, 140–154, https://doi.org/10.1175/2008WAF2007076.1.

——, and ——, 2010: Tornadoes without NWS warning. *Wea. Forecasting*, **25**, 159–172, https://doi.org/10.1175/2009WAF2222270.1.

——, ——, and H. E. Brooks, 2011: A 5-yr climatology of tornado false alarms. *Wea. Forecasting*, **26**, 534–544, https://doi.org/10.1175/WAF-D-10-05004.1.

Center for Disease Control/Agency for Toxic Substances and Disease Registry, 2020: CDC's social vulnerability index (SVI). Accessed 3 June 2020, https://svi.cdc.gov/data-and-tools-download.html.

Chaney, P. L., and G. S. Weaver, 2010: The vulnerability of mobile home residents in tornado disasters: The 2008 Super Tuesday tornado in Macon County, Tennessee. *Wea. Climate Soc.*, **2**, 190–199, https://doi.org/10.1175/2010WCAS1042.1.

Chiu, C. H., A. H. Schnall, C. E. Mertzlufft, R. S. Noe, A. F. Wolkin, J. Spears, M. Casey-Lockyer, and S. J. Vagi, 2013: Mortality from a tornado outbreak, Alabama, April 27, 2011. *Amer. J. Public Health*, **103**, e52–e58, https://doi.org/10.2105/AJPH.2013.301291.

Coleman, T. A., and P. G. Dixon, 2014: An objective analysis of tornado risk in the United States. *Wea. Forecasting*, **29**, 366–376, https://doi.org/10.1175/WAF-D-13-00057.1.

Cutter, S. L., 1996: Vulnerability to environmental hazards. *Prog. Hum. Geogr.*, **20**, 529–539, https://doi.org/10.1177/030913259602000407.

——, J. T. Mitchell, and M. S. Scott, 2000: Revealing the vulnerability of people and places: A case study of Georgetown County, South Carolina. *Ann. Amer. Assoc. Geogr.*, **90**, 713–737, https://doi.org/10.1111/0004-5608.00219.

——, B. J. Boruff, and W. L. Shirley, 2003: Social vulnerability to environmental hazards. *Soc. Sci. Quart.*, **84**, 242–261, https://doi.org/10.1111/1540-6237.8402002.

——, C. T. Emrich, J. T. Mitchell, B. J. Boruff, M. Gall, M. C. Schmidtlein, C. G. Burton, and G. Melton, 2006: The long road home: Race, class, and recovery from Hurricane Katrina. *Environ. Sci. Policy*, **48**, 8–20, https://doi.org/10.3200/ENVT.48.2.8-20.

——, ——, J. J. Webb, and D. Morath, 2009: Social vulnerability to climate variability hazards: A review of the literature. Oxfam America Final Rep., 44 pp.

Dean, A., 2006: A look at the tornado report and watch climatology for the continental United States from 1986–2005. *23rd Conf. on Severe Local Storms*, Saint Louis, MO, Amer. Meteor. Soc., P2.2, https://ams.confex.com/ams/pdfpapers/115113.pdf.

Department of Homeland Security, 2010: DHS risk lexicon. Department of Homeland Security Tech. Rep., 72 pp., https://www.cisa.gov/sites/default/files/publications/dhs-risk-lexicon-2010_0.pdf.

Dixon, P. G., A. E. Mercer, J. Choi, and J. S. Allen, 2011: Tornado risk analysis: Is Dixie Alley an extension of Tornado Alley? *Bull. Amer. Meteor. Soc.*, **92**, 433–441, https://doi.org/10.1175/2010BAMS3102.1.

Dixon, R. W., and T. W. Moore, 2012: Tornado vulnerability in Texas. *Wea. Climate Soc.*, **4**, 59–68, https://doi.org/10.1175/WCAS-D-11-00004.1.

Donner, W. R., H. Rodriguez, and W. Diaz, 2012: Tornado warnings in three southern states: A qualitative analysis of public response patterns. *J. Homeland Secur. Emerg. Manage.*, **9**, https://doi.org/10.1515/1547-7355.1955.

Doswell, C. A., III, and J. A. Flueck, 1989: Forecasting and verifying in a field research project: DOPLIGHT'87. *Wea. Forecasting*, **4**, 97–109, https://doi.org/10.1175/1520-0434(1989)004<0097:FAVIAF>2.0.CO;2.

——, R. Davies-Jones, and D. L. Keller, 1990: On summary measures of skill in rare event forecasting based on contingency tables. *Wea. Forecasting*, **5**, 576–585, https://doi.org/10.1175/1520-0434(1990)005<0576:OSMOSI>2.0.CO;2.

——, H. E. Brooks, and M. P. Kay, 2005: Climatological estimates of daily local nontornadic severe thunderstorm probability for the United States. *Wea. Climate Soc.*, **20**, 577–595, https://doi.org/10.1175/WAF866.1.

Edwards, R., 2012: Tropical cyclone tornadoes: A review of knowledge in research and prediction. *Electron. J. Severe Storms Meteor.*, **7** (6), https://ejssm.org/ojs/index.php/ejssm/article/viewArticle/97.

——, J. LaDue, J. Ferree, K. Scharfenberg, C. Maier, and W. Coulbourne, 2013: Tornado intensity estimation: Past, present and future. *Bull. Amer. Meteor. Soc.*, **94**, 641–653, https://doi.org/10.1175/BAMS-D-11-00006.1.

Elder, K., S. Xirasagar, N. Miller, S. A. Bowen, S. Glover, and C. Piper, 2007: African Americans' decisions not to evacuate new Orleans before Hurricane Katrina: A qualitative study. *Amer. J. Public Health*, **97**, S124–S129, https://doi.org/10.2105/AJPH.2006.100867.

Elsner, J. B., T. H. Jagger, and T. Fricker, 2016: Statistical models for tornado climatology: Long and short-term views. *PLOS ONE*, **11**, e0166895, https://doi.org/10.1371/journal.pone.0166895.

Emrich, C. T., and S. L. Cutter, 2011: Social vulnerability to climate-sensitive hazards in the southern United States. *Wea. Climate Soc.*, **3**, 193–208, https://doi.org/10.1175/2011WCAS1092.1.

Flanagan, B. E., E. W. Gregory, E. J. Hallisey, J. L. Heitgerd, and B. Lewis, 2011: A social vulnerability index for disaster management. *J. Homeland Secur. Emerg. Manage.*, **8**, 0000102202154773551792, https://doi.org/10.2202/1547-7355.1792.

——, E. J. Hallisey, E. Adams, and A. Lavery, 2018: Measuring community vulnerability to natural and anthropogenic hazards: The Centers for Disease Control and Prevention's social vulnerability index. *J. Environ. Health*, **80** (10), 34–36, https://svi.cdc.gov/Documents/Publications/CDC_ATSDR_SVI_Materials/JEH2018.pdf.

Fothergill, A., and L. Peek, 2004: Poverty and disasters in the United States: A review of recent sociological findings. *Nat. Hazards*, **32**, 89–110, https://doi.org/10.1023/B:NHAZ.0000026792.76181.d9.

Fricker, T., 2020: Tornado-level estimates of socioeconomic and demographic variables. *Nat. Hazards Rev.*, **21**, 04020018, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000379.

Gensini, V. A., and W. S. Ashley, 2011: Climatology of potentially severe convective environments from the North American Regional Reanalysis. *Electron. J. Severe Storms Meteor.*, **6** (8), http://www.ejssm.org/ojs/index.php/ejssm/article/viewArticle/85.

——, and H. E. Brooks, 2018: Spatial trends in United States tornado frequency. *npj Climate Atmos. Sci.*, **1**, 38, https://doi.org/10.1038/s41612-018-0048-2.

Grossi, P., 2005: *Catastrophe Modeling: A New Approach to Managing Risk*. Vol. 25, Springer Science and Business Media, 252 pp.

Harrison, D. R., and C. D. Karstens, 2017: A climatology of operational storm-based warnings: A geospatial analysis. *Wea. Forecasting*, **32**, 47–60, https://doi.org/10.1175/WAF-D-15-0146.1.

Hoekstra, S., K. Klockow, R. Riley, J. Brotzge, H. Brooks, and S. Erickson, 2011: A preliminary look at the social perspective of Warn-On-Forecast: Preferred tornado warning lead time and the general public's perceptions of weather risks. *Wea. Climate Soc.*, **3**, 128–140, https://doi.org/10.1175/2011WCAS1076.1.

Hoffman, R. R., D. S. LaDue, H. M. Mogil, J. G. Trafton, and P. J. Roebber, 2017: *Minding the Weather: How Expert Forecasters Think*. MIT Press, 488 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. C. B. Field et al., Eds., Cambridge University Press, 582 pp., https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/.

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588–612, https://doi.org/10.1175/1520-0434(1992)007<0588:SLSF>2.0.CO;2.

Knupp, K. R., and Coauthors, 2014: Meteorological overview of the devastating 27 April 2011 tornado outbreak. *Bull. Amer. Meteor. Soc.*, **95**, 1041–1062, https://doi.org/10.1175/BAMS-D-11-00229.1.

Krocak, M. J., and H. E. Brooks, 2018: Climatological estimates of hourly tornado probability for the United States. *Wea. Forecasting*, **33**, 59–69, https://doi.org/10.1175/WAF-D-17-0123.1.

Lim, J. R., B. F. Liu, and M. Egnoto, 2019: Cry wolf effect? Evaluating the impact of false alarms on public responses to tornado alerts in the southeastern United States. *Wea. Climate Soc.*, **11**, 549–563, https://doi.org/10.1175/WCAS-D-18-0080.1.

McCaul, E. W., Jr., D. E. Buechler, S. J. Goodman, and M. Cammarata, 2004: Doppler radar and lightning network observations of a severe outbreak of tropical cyclone tornadoes. *Mon. Wea. Rev.*, **132**, 1747–1763, https://doi.org/10.1175/1520-0493(2004)132<1747:DRALNO>2.0.CO;2.

McNulty, R. P., 1995: Severe and convective weather: A central region forecasting challenge. *Wea. Forecasting*, **10**, 187–202, https://doi.org/10.1175/1520-0434(1995)010<0187:SACWAC>2.0.CO;2.

Morrow, B. H., 1999: Identifying and mapping community vulnerability. *Disasters*, **23**, 1–18, https://doi.org/10.1111/1467-7717.00102.

——, 2008: Community resilience: A social justice perspective. The Community and Regional Resilience Initiative Research Rep. 4, 31 pp.

Morss, R., O. Wilhelmi, G. A. Meehl, and L. Dilling, 2011: Improving societal outcomes of extreme weather in a changing climate: An integrated perspective. *Annu. Rev. Environ. Resour.*, **36**, 1–25, https://doi.org/10.1146/annurev-environ-060809-100145.

NCEI, 2020: Storm Events Database. NOAA/NCEI, accessed 25 May 2020, https://www.ncdc.noaa.gov/stormevents/.

Nelson, J. E., 2015: The effects of severe weather warnings on limited English proficient (LEP) Hispanics/Latinos in rural Nebraska. M.S. thesis, Emergency Preparedness, University of Nebraska Medical Center, 60 pp.

Paul, B. K., 2011: *Environmental Hazards and Disasters*. John Wiley and Sons, 322 pp.

Peacock, W. G., B. H. Morrow, and H. Gladwin, 1997: *Hurricane Andrew: Ethnicity, Gender, and the Sociology of Disasters*. Psychology Press, 277 pp.

Peguero, A., 2006: Latino disaster vulnerability: The dissemination of hurricane mitigation information among Florida's homeowners. *Hisp. J. Behav. Sci.*, **28**, 5–22, https://doi.org/10.1177/0739986305284012.

Phillips, B. D., and P. L. Hewett, 2005: Home alone: Disasters, mass emergencies, and children in self-care. *J. Emerg. Manage.*, **3**, 31–35, https://doi.org/10.5055/jem.2005.0018.

Potvin, C. K., C. Broyles, P. S. Skinner, H. E. Brooks, and E. Rasmussen, 2019: A Bayesian hierarchical modeling framework for correcting reporting bias in the US tornado database. *Wea. Forecasting*, **34**, 15–30, https://doi.org/10.1175/WAF-D-18-0137.1.

Schmidlin, T. W., B. O. Hammer, Y. Ono, and P. S. King, 2009: Tornado shelter-seeking behavior and tornado shelter options among mobile home residents in the United States. *Nat. Hazards*, **48**, 191–201, https://doi.org/10.1007/s11069-008-9257-z.

Sherman-Morris, K., and M. E. Brown, 2012: Experiences of Smithville, Mississippi residents with the 27 April 2011 tornado. *Natl. Wea. Dig.*, **36**, 93–101.

Simmons, K. M., and D. Sutter, 2008: Tornado warnings, lead times, and tornado casualties: An empirical investigation. *Wea. Forecasting*, **23**, 246–258, https://doi.org/10.1175/2007WAF2006027.1.

——, and ——, 2009: False alarms, tornado warnings, and tornado casualties. *Wea. Climate Soc.*, **1**, 38–53, https://doi.org/10.1175/2009WCAS1005.1.

——, and ——, 2011: Tornado climatology and society's tornado risk. *Economic and Societal Impacts of Tornadoes*, Amer. Meteor. Soc., 9–44.

SPC, 2020: SVRGIS. NOAA, accessed 1 May 2020, https://www.spc.noaa.gov/gis/svrgis/.

Strader, S. M., and W. S. Ashley, 2018: Finescale assessment of mobile home tornado vulnerability in the central and southeast United States. *Wea. Climate Soc.*, **10**, 797–812, https://doi.org/10.1175/WCAS-D-18-0060.1.

——, ——, T. J. Pingel, and A. J. Krmenec, 2017: Projected 21st century changes in tornado exposure, risk, and disaster potential. *Climatic Change*, **141**, 301–313, https://doi.org/10.1007/s10584-017-1905-4.

——, K. Ash, E. Wagner, and C. Sherrod, 2019: Mobile home resident evacuation vulnerability and emergency medical service access during tornado events in the southeast United States. *Int. J. Disaster Risk Reduct.*, **38**, 101210, https://doi.org/10.1016/j.ijdrr.2019.101210.

——, D. Roueche, and B. David, 2020: Unpacking tornado disasters: Illustrating the southeast U.S. tornado-mobile and manufactured housing problem using the March 3, 2019 Beauregard-Smith Station, Alabama tornado event. *Nat. Hazards Rev.*, 04020060, **22**, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000436.

Sutter, D., and K. M. Simmons, 2010: Tornado fatalities and mobile homes in the United States. *Nat. Hazards*, **53**, 125–137, https://doi.org/10.1007/s11069-009-9416-x.

Theobald, D. M., 2005: Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecol. Soc.*, **10**, 32, https://doi.org/10.5751/ES-01390-100132.

Thompson, R. L., B. T. Smith, J. S. Grams, A. R. Dean, and C. Broyles, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part II: Supercell and QLCS tornado environments. *Wea. Forecasting*, **27**, 1136–1154, https://doi.org/10.1175/WAF-D-11-00116.1.

Tierney, K., 2006: Foreshadowing Katrina: Recent sociological contributions to vulnerability science. *Contemp. Sociol.*, **35**, 207–212, https://doi.org/10.1177/009430610603500302.

Tippett, M. K., J. T. Allen, V. A. Gensini, and H. E. Brooks, 2015: Climate and hazardous convective weather. *Curr. Climate Change Rep.*, **1**, 60–73, https://doi.org/10.1007/s40641-015-0006-6.

Trainor, J. E., D. Nagele, B. Philips, and B. Scott, 2015: Tornadoes, social science, and the false alarm effect. *Wea. Climate Soc.*, **7**, 333–352, https://doi.org/10.1175/WCAS-D-14-00052.1.

Verbout, S. M., H. E. Brooks, L. M. Leslie, and D. M. Schultz, 2006: Evolution of the US tornado database: 1954–2003. *Wea. Forecasting*, **21**, 86–93, https://doi.org/10.1175/WAF910.1.

Wind Science and Engineering Center, 2006: A recommendation for an enhanced Fujita scale (EF-scale). Texas Tech University Wind Science and Engineering Center Rep., 95 pp., https://www.depts.ttu.edu/nwi/Pubs/EnhancedFujitaScale/EFScale.pdf.

Wolkin, A., J. R. Patterson, S. Harris, E. Soler, S. Burrer, M. McGeehin, and S. Greene, 2015: Reducing public health risk during disasters: Identifying social vulnerabilities. *J. Homeland Secur. Emerg. Manage.*, **12**, 809–822, https://doi.org/10.1515/jhsem-2014-0104.