Revisiting U.S. Nocturnal Tornado Vulnerability and Its Influence on Tornado Impacts

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ABSTRACT: This research examines tornadoes and their fatalities by light condition (i.e., daytime and nighttime) for the United States. The study has two primary objectives: 1) to catalog and reassess differences in daytime and nighttime, or nocturnal, tornadoes and their fatalities from spatial and temporal perspectives and 2) to employ a spatially explicit Monte Carlo simulation technique to calculate differences in daytime and nocturnal tornado–population impact potential by combining climatological tornado risk data with fine-scale, gridded estimates of day and night population density. Results reveal that nocturnal tornadoes remain a substantial impediment to mitigating tornado casualties despite long-term improvements in detection and warning of these events. Nocturnal tornadoes are nearly 2 times as deadly as daytime events, with fatalities stemming from overnight (i.e., from local midnight to sunrise) tornadoes increasing fourfold since the late nineteenth century. The proportion of all tornado fatalities that occurred during daytime hours has decreased 20% over the last 140 years while the nocturnal fatality proportion has increased 20%. The stall, or even slight growth, in U.S. tornado mortality rates over the last 30 years has, at least in part, been driven by increasing nocturnal tornado fatalities. Overall, nocturnal tornadoes affect 13% more people on average than daytime tornadoes, revealing the importance of time of day in mitigating tornado–population impacts and disasters. Emergency managers, forecasters, first responders, policy makers, and researchers should continue to focus efforts on understanding nocturnal tornadoes, especially with regard to how populations receive warnings and respond to these nocturnal threats.

KEYWORDS: Tornadoes; Geographic information systems (GIS); Land use; Risk assessment; Societal impacts; Vulnerability

1. Introduction and background

During the evening and overnight hours on 2–3 March 2020, a supercell traveling at 26 m s^{-1} (65 mi h^{-1}) across Tennessee produced several significant [enhanced Fujita scale 2+ (EF2+)] tornadoes. The tornadoes resulted in 25 fatalities and over 100 injuries, with most deaths occurring in the EF4 Cookeville, Tennessee, tornado. Approximately 18 months later (10 December 2021), a devastating, cool-season tornado outbreak produced many intense tornadoes under the cover of darkness, including a long-track, 265-km (165 mi), EF4 tornado that killed more than 50 people in Kentucky. Unfortunately, these fatal nocturnal (NT) tornado events—that is, tornadoes that occur in the period from sunset to sunrise—are not uncommon in the Ohio River valley and Tennessee Valley and are a factor in this region's particularly high tornado mortality (Brooks et al. 2003; Ashley 2007; Ashley et al. 2008; Ashley and Strader 2016; Anderson-Frey and Brooks 2019). No matter the region, NT tornado events lead to vulnerability and mitigation issues that reduce warning and sheltering efficacy; those issues, in turn, lead to disproportionate—in comparison with their daytime (DT) counterparts—casualty rates (Ashley 2007; Krocak and Brooks 2018; Agee and Taylor 2019; Bunker et al. 2019; Ellis et al. 2020). For this reason, NT tornado risk, and the vulnerabilities it produces, need further study.

Tornado mortality is driven by a variety of socioeconomic, behavioral, physical, and climatological factors (Ashley 2007; Ashley et al. 2008; Coleman and Dixon 2014; Ashley and Strader 2016; Strader and Ashley 2018; Ash et al. 2020). Prior research has indicated the importance of examining both climatological risk (i.e., the probability of a tornado occurring at a specific location and time; Morss et al. 2011) and societal exposure when assessing tornado–society impact potential and disaster likelihood (Ashley et al. 2014; Ashley and Strader 2016; Strader et al. 2017a,b; Fricker et al. 2017; Moore 2017; Fricker and Elsner 2019; Fricker and Friesenhahn 2022). Whereas tornado frequency and other climatological factors set the stage for tornado disaster (Boruff et al. 2003; Brooks et al. 2003; Kis and Straka 2010), elements of exposure (i.e., buildings/structures, homes, and people) and vulnerability (i.e., income, race, age, gender, and other socioeconomic and human dimensions) often dictate tornado disaster severity (Cutter et al. 2003; Ashley 2007; Ashley et al. 2008; Strader and Ashley 2018; Fricker and Friesenhahn 2022). In addition, the prevalence and higher density of manufactured housing has been shown to be a critical factor when assessing tornado casualties, particularly in the Southeast (Ashley 2007; Ashley et al. 2008; Schmidlin et al. 2009; Sutter and Simmons 2010; Emrich and Cutter 2011; Simmons and Sutter 2011; Strader and Ashley 2018; Strader et al. 2019). Social science and behavioral researchers have also examined population self-efficacy, coping styles, and complacency as it relates to tornado hazards (Boruff et al. 2003; Howe et al. 2014; Ash 2017; Demuth 2018; Miran et al. 2018; Schumann et al. 2018; Lim et al. 2019; Liu et al. 2019; Broomell et al. 2020). These studies indicate that a better understanding of public tornado threat perception and resulting efforts aimed at improving vulnerable resident education

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are important if community resilience is to be strengthened and tornado survivability increased.

Recent high-casualty-inducing NT tornado outbreaks point to a need for further investigation into tornado impacts and their relationship to the 1) time of day and 2) underlying, and potentially shifting, population exposures. Prior research has illustrated that NT tornadoes are a critical factor in regions with high casualty rates (Ashley et al. 2008; Krocak and Brooks 2018; Bunker et al. 2019; Ellis et al. 2020). These events are 2 times as likely as DT events to result in a fatality (Ashley 2007; Fricker and Friesenhahn 2022). Higher NT tornado fatality rates are partially a result of people being less likely to receive a tornado warning because the event is taking place overnight when most people are asleep (Paul 2011; Simmons and Sutter 2007; Ashley 2007; Ellis et al. 2020). This breakdown in effective warning dissemination and receipt, among other factors such as elevated population density, manufactured home density, socioeconomically vulnerable populations, and so on, leads to greater odds of death for the affected portion of the U.S. population (Ashley 2007; Ashley et al. 2008; Ellis et al. 2020). From an operational forecasting standpoint, the probability of detection (POD) is lower and false alarm rates (FAR) are higher for NT tornadoes than for tornado events that occur during DT hours (from local sunrise to sunset). These forecasting and societal issues set the stage for more frequent high-impact NT tornado events across the United States.

Most studies examining tornado exposure have relied solely on population and/or built-environment (e.g., homes) enumerations from the census or similar datasets (Ashley et al. 2014; Strader et al. 2017a; Strader and Ashley 2018). While these exposure data are the most readily available and widely used within the disaster research community, they do not provide the most accurate measure of local population patterns and density during a 24-h period. For example, census population estimates are tied to the residential address where the person completing the census form resides (Bhaduri et al. 2007). Yet, most persons are not located in their homes during conventional work hours of 0900–1700 local time. While tornado frequency and severity are highly dependent on environmental factors that change during a given hour, day, and season (e.g., instability, moisture, and shear; Brooks et al. 2003; Gensini and Ashley 2011; Tippett et al. 2015; Anderson-Frey and Brooks 2019), population exposure is also a factor of time of day and other societal elements (e.g., population density, transportation, employment; Bhaduri et al. 2007). Past studies investigating population exposure to tornadoes have yet to consider the nonstationary character of both tornado risk and society when assessing tornado impact potential.

In addition to examining trends in tornado incidence and fatalities by light condition, this study addresses the nonstationary tornado risk and societal exposure issue by examining tornado–population impact potential during NT (local sunset to sunrise) and DT time frames over a 24-h period. We first update the most complete data source of NT tornado events, as this dataset is now over a decade old (Ashley 2007; Ashley et al. 2008). We then use these data to generate an update to the conterminous U.S. temporal and spatial climatology of tornado events and fatalities by ambient light condition or time of day. Last, we build on prior research by incorporating both DT–NT tornado data and a novel DT–NT population dataset (LandScan; Bhaduri et al. 2007) within a spatially explicit tornado event simulation tool [Tornado Impact Monte Carlo (TorMC) model] that can produce tornado–population impact likelihood and magnitude estimates across tornado-prone regions (Strader et al. 2016).

2. Data and methods

a. *Fatal tornado event dataset construction*

The 140-yr (1880–2020) conterminous U.S. tornado fatality dataset employed in this study was created using the methods outlined in Ashley (2007) and Ashley et al. (2008). Three primary tornado event sources were used to construct the fatality database: 1) the National Centers for Environmental Information (NCEI) *Storm Data* "Storm Events" database from 1959 to 2020; 2) a long-term tornado event database gathered in Significant Tornadoes 1680–1991 (Grazulis 1993) and its supplemental update covering the period 1992–95 (Grazulis 1997); and 3) the National Oceanic and Atmospheric Administration (NOAA) Storm Prediction Center's (SPC) 1991–2020 historical fatal tornado events dataset. Fatal tornado events and fatality information prior to 1950 were primarily derived from Grazulis (1993, 1997), and most of the fatality information from 1950 to 2020 was gathered from NCEI *Storm Data* and SPC sources. In addition to quantitative fatal event data provided by all three of these sources, both *Storm Data* and the Grazulis datasets contain tornado event narratives. This textual information was critical for obtaining key fatality details such as age, gender, specific geographic location along a path where a person was killed, and circumstance of death (e.g., permanent home, manufactured home, or vehicle). In many cases, the quantitative and qualitative narratives from the primary sources were also compared with additional resources such as news reports and local National Weather Service (NWS) event summaries to ensure that the data were as accurate and complete as possible. Although tedious and time consuming, this process was valuable and insightful as it revealed several discrepancies for many fatal tornado events across the data sources. Accordingly, we were able to address and correct for differences related to tornado event starting time and location, tornado damage rating, number of persons killed, fatality locations, and other pertinent issues. We strongly encourage the reader to examine Ashley (2007) and Ashley et al. (2008) for additional details on dataset creation methods and issues.

The primary focus of this study was to understand better the time of day and light condition present during tornadoes and corresponding deaths. All tornadoes in our database were separated into DT and NT events. We specifically used the Python package Astral, version 2.2, to determine whether a tornado event and fatality occurred during DT or NT time periods. Astral uses sun–Earth geometry calculations to determine exact light conditions (e.g., day, night, sunrise, sunset, twilight, dusk, golden hour, blue hour) provided location (latitude–longitude),

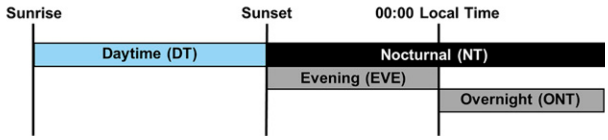

FIG. 1. Light conditions for the four periods assessed, including DT (local sunrise to sunset), NT (local sunset to sunrise), EVE (local sunset to local midnight), and ONT (local midnight to sunrise).

date (day, month, year), and time of tornado incidence (local time). Tornado events and deaths that occurred between sunrise and local sunset were categorized as DT events, and those that occurred from sunset to local sunrise were NT events (Fig. 1). Similar to Ashley et al. (2008), NT tornadoes and fatalities were then separated into two subcategories: evening (EVE; local sunset and midnight) and overnight (ONT; local midnight and sunrise).

b. *Tornado–population impact analyses by light condition*

Building on prior research (Strader et al. 2016, 2017a, 2018), the tornado fatality and light condition data were integrated into the TorMC model to estimate tornado–population impact likelihood and magnitude based on time of day. The TorMC is a spatially explicit model that ingests regional climatological tornado information (e.g., damage pathlength, width, damage rating, starting location, and path bearing) centered on the area of interest to generate synthetic tornado footprints across a user-defined spatiotemporal domain (Strader et al. 2016). The Monte Carlo portion of the TorMC model allows for the probabilistic estimation of tornado–population impact likelihood and magnitude given thousands of years simulated tornado events atop an exposure or cost surface (i.e., geospatial layer representing population, housing, or other entity) that spans a simulation domain. Spatial patterns in TorMC-generated tornadoes are weighted based on an 80 km × 80 km gridded surface representing historical tornado incidences. An 80-km grid resolution was chosen because it represents the SPC's defined probability of severe weather within 40 km (approximately 25 mi) of a location (Brooks et al. 2003). The TorMC model's performance and reliability were assessed in Strader et al. (2016) by using a 10 000-yr simulation of significant EF2+ tornado footprints across Oklahoma. Oklahoma was selected for model validation because of its high tornado risk and relatively large population centers (i.e., Oklahoma City and Tulsa). Simulated tornado footprint counts, lengths, widths, bearings, etc. were compared with historical observed tornado event measures and determined to be statistically similar (cf. Table 1 in Strader et al. 2016). We encourage the reader to examine Strader et al. (2016) for further detail on the TorMC modeling process and validation.

Whereas the historical tornado information incorporated into the TorMC model simulations is represented by the fatality dataset, the underlying population exposure data are determined by the 2019 LandScan data developed at the Oak Ridge National Laboratory (Bhaduri et al. 2007). The LandScan dataset was created by combining demographics (U.S. Census data), remote sensing data, and aerial imagery within a multivariate dasymetric model to generate a gridded, 90-m population dataset across the conterminous United States (Bhaduri et al. 2007). LandScan population enumerations are also grouped into two separate layers representing DT and NT population estimates. Thus, combining the tornado and light condition dataset with the LandScan data in TorMC simulations permits a more representative and detailed assessment of tornado–population impact probability during a 24-h period. The climatological tornado risk portions of the TorMC simulations are controlled by the DT, NT, EVE, and ONT tornado event data, and exposure is represented by the LandScan DT or NT population cost surfaces. For NT simulations, the NT LandScan population estimates are employed.

To determine tornado–population impact potential, magnitude, and frequency, several TorMC simulations were conducted across a number of regions. The east-central U.S. region represents the most tornado-prone region in the world (Brooks et al. 2003; Tippett et al. 2015). The three regional [i.e., central plains (CP), Midwest (MW), and Southeast (SE)] and metropolitan (i.e., Atlanta, Georgia; Chicago, Illinois; and Dallas–Fort Worth, Texas) domains permit a direct comparison of TorMC simulation results among domains with differing tornado risk and exposure patterns. The three regional domains selected also match that of Ashley et al. (2008) for comparative purposes. We simulated EF1+ tornadoes to remove the influence of large nonmeteorological trends that have been found in EF0 events (Ashley and Strader 2016). Although the NWS transitioned from using the Fujita scale (F) to the EF scale in 2007, we follow prior work by equating both scales and referencing tornado intensity estimates to the EF scale (Edwards et al. 2013). Each model run contained 7500 years of EF1+ tornadoes; this simulation length provided a balance between highly detailed TorMC output and computational resources. Last, all TorMC simulations control for differences in DT and NT tornado frequencies in the simulation domains. The controlled single tornado simulation scenarios permit a direct comparison of DT and NT tornado impacts while isolating the underlying population location and density effects on tornado impact potential. However, the TorMC simulations do not control for differences in DT and NT simulated tornado footprint characteristics (length, maximum path width, magnitude, bearing, etc.). These climatological characteristics are dictated by the simulation domain's historical tornado climatology.

3. Results

a. *Temporal analyses*

From 1880 to 1990, the U.S. tornado death rate decreased from 2.4 fatalities per 1 million persons to 0.3 fatalities per 1 million persons (Fig. 2). Simultaneously, the percentage of all fatalities caused by violent EF4 and EF5 tornadoes has decreased by nearly 23% over the last 70 years. The long-term decline in tornado mortality can be attributed to improved efforts with severe weather forecasting, hazard communication and education, warning practices, building codes/construction

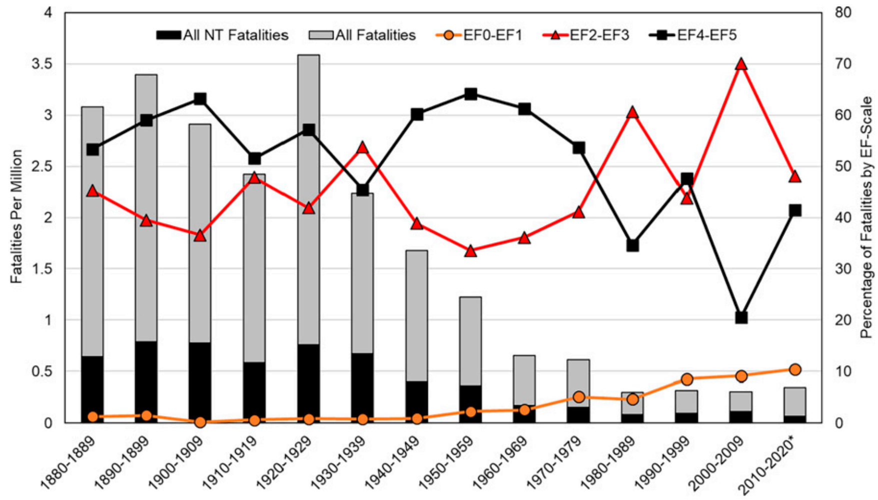

FIG. 2. Conterminous U.S. tornado fatality rates (deaths per 1 million persons) from 1880 to 2020 separated into all (gray bar; primary axis) and NT (black bar; primary axis) time periods. The percentage of tornado fatalities by EF scale from 1880 to 2020 (lines with markers; secondary axis) is also plotted. The asterisk indicates an 11-yr analysis (2010–20).

practices, spotter networks, development of the NEXRAD program, improved medical care, and so on (Brooks and Doswell 2002; Ashley and Strader 2016). However, tornado death rates since 1980 have been stagnant or increasing, transitioning from approximately 0.21 deaths per 1 million persons to nearly 0.3 deaths per 1 million persons. The stall in mortality is likely a result of increasing exposure and vulnerability (i.e., expanding bull's-eye effect; Ashley et al. 2014) and not of changes, or shortcomings, in NWS forecast and warning practices (Ashley and Strader 2016).

Since 1880, there have been a total of 19 848 tornado fatalities (Table 1). Of these fatalities, 13 147 (66.2% of all fatalities) occurred during the day and 6701 (33.8% of all fatalities) occurred at night. Approximately 75% and 25% of all fatalities of NT tornadoes occurred during EVE and ONT hours, respectively. Over the last 30 years, there have been 2129 fatalities with DT events making up 62% and NT tornadoes making up 38% of all deaths. EVE and ONT tornadoes were responsible for 63% and 14% of all NT tornado fatalities since 1990, respectively. The proportion of tornado deaths occurring during NT and ONT periods over the last three decades is approximately 5% and 6% greater, respectively, than the historical long-term average from 1880 to 2020. In fact, the percentage of NT tornado fatalities that transpired during ONT hours is over 11% greater from 1990 to 2020 relative to the entire 140-yr study period. Together, these findings suggest that the NT tornado problem is increasing over time, leading to a growing number of people being killed by tornadoes after dark.

In addition to assessing tornado fatalities by light condition, the probability of a tornado producing a fatality under a specific light condition category was also assessed using the SPC SVRGIS tornado database from 1950 to 2019 (Table 2). Nearly 3.0% of tornadoes since 1950 produced a fatality, with 2.2% and 4.0% of all tornadoes respectively considered DT and NT events. Like Ashley et al. (2008), we found that NT tornadoes are approximately *2 times* as likely to result in a fatality than their DT counterparts. ONT tornado events are more than *2.5 times* more likely than DT tornadoes to result in a fatality. This finding illustrates that the NT tornado

TABLE 1. Tornado fatality counts, percentage of all tornado fatalities, and percentage of NT tornadoes by light conditions for the analysis periods of 1880–2020 and 1990–2020.

Temporal period of analysis	Tornado light condition	Count	% all	% NT
1880–2020	DT	13 147	66.2	—
	NT	6701	33.8	100.00
	EVE	5008	25.2	74.7
	ONT	1693	8.5	25.3
	Total	19 848	100.0	—
1990–2020	DT	1311	61.6	—
	NT	818	38.4	100.0
	EVE	518	24.3	63.3
	ONT	300	14.1	36.7
	Total	2129	100.0	—

TABLE 2. Total number of tornado events, fatal tornado events, and the probability (per 100 tornado events) that a tornado under each light condition produces a fatality from 1950 to 2019.

Light condition	*n* all events	*n* fatal events	*P* | fatality per 100 tornado events
DT	39 130	874	2.2
NT	16 076	640	4.0
EVE	12 077	453	3.8
ONT	3 999	187	4.7
Total	55 206	1514	2.7

fatality problem still exists and continues to be an issue nearly 15 years after initially established.

The trend in NT tornado deaths per 1 million persons is consistent since 1970, ranging from 0.1 to 0.2 deaths per 1 million persons (Fig. 3a). Since 1880, the percentage of all fatalities that occurred during DT hours declined by 20% while the proportion of NT deaths *nearly doubled*. The increasing NT fatality percentage is largely driven by a *fourfold* increase in ONT tornado fatality proportion since 1880 (Fig. 3b). Specifically, the proportion of fatalities that were due to ONT events increased from approximately 5% to 20% over the 140-yr period (Fig. 3b).

The proportion of DT EF1+ tornadoes decreased slightly since 1954, while the trend in NT EF1+ counts remained nearly constant (Fig. 4). The percentage of all tornadoes that are NT and EVE has increased by 1.5% and 1.4% per decade, respectively, since 1954. During this same 66-yr period, the percentage of NT tornado fatalities increased, from 11.4% to nearly 20% (Fig. 3b).

From 1985 through 2020, there were 2370 tornado fatalities where the circumstance of death (e.g., place of business, home, vehicle) was known. Approximately, 71% of tornado fatalities are in homes (Fig. 5). Manufactured homes encompass the greatest percentage (40%) of all tornado fatalities despite manufactured homes only representing approximately 6% of the U.S. housing stock (Ashley 2007; Simmons and Sutter 2011; Strader and Ashley 2018). More individuals have been killed in manufactured homes during NT hours (507) than during DT periods (435). Conversely, more people have perished inside of permanent homes during DT hours (484) than during NT periods (254). We surmise that the higher manufactured home NT fatality counts is a result of elevated rural and exurban manufactured home density in the Southeast United States where NT tornadoes are more common (Ashley 2007; Ashley et al. 2008; Schmidlin et al. 2009; Sutter and Simmons 2010; Emrich and Cutter 2011; Strader and Ashley 2018). Fatalities that occurred in vehicles or outside are more prevalent during the DT than during the NT. Tornado mortality is higher during EVE hours than ONT for all circumstances, which is an expected consequence of climatological risk (Krocak and Brooks 2018).

b. Spatial analyses

NT tornadoes are most common in the corridor from central Arkansas through western Tennessee and northern Mississippi

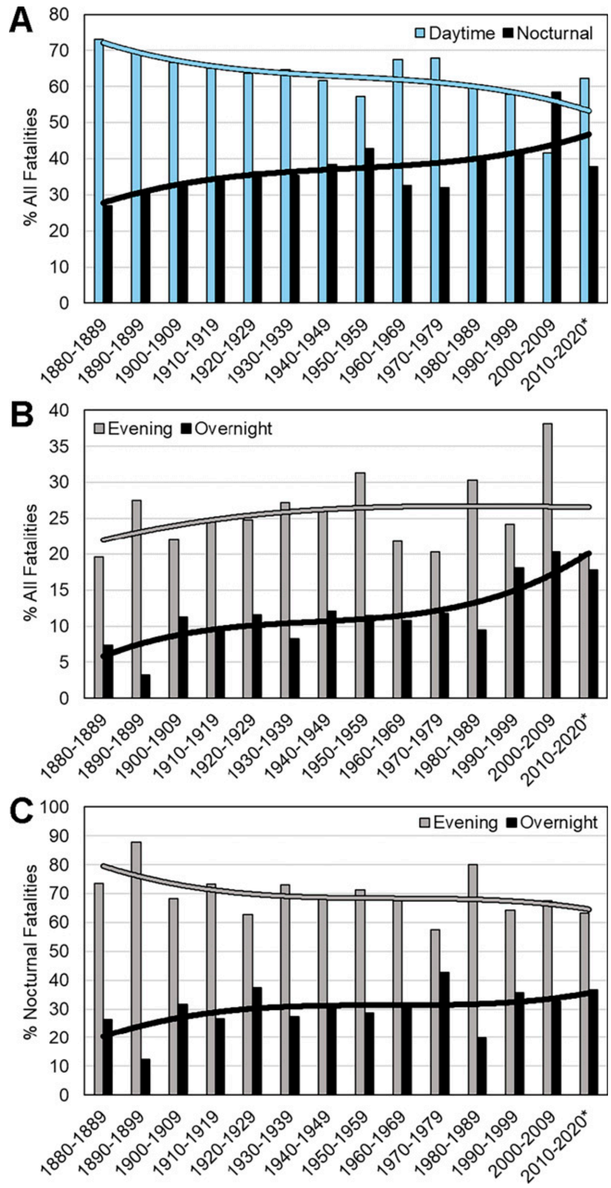

FIG. 3. Mean decadal percentage of all fatalities for (a) DT and NT light conditions and (b) EVE and ONT light conditions. Also shown is (c) the mean decadal percentage of NT fatalities that occurred during EVE and ONT conditions. Asterisks indicate an 11-yr analysis for percentage fatalities. A third-order polynomial trend line is fit to the decadal percentage fatality data.

and Alabama (Fig. 6a). The percentage of tornadoes that are NT events is much lower in the northern plains and Northeast. The higher percentage of NT tornado events in the Southeast is due to several climatological and meteorological factors, including a greater frequency of tornadoes in the Southeast during months with more hours of darkness (late fall and winter); more common occurrence of a strong low-level jet that offsets a lack of instability often present during late fall and winter tornadic storms in the region (Kis and Straka 2010). At the state scale, and as expected (Ellis et al. 2020), Tennessee has

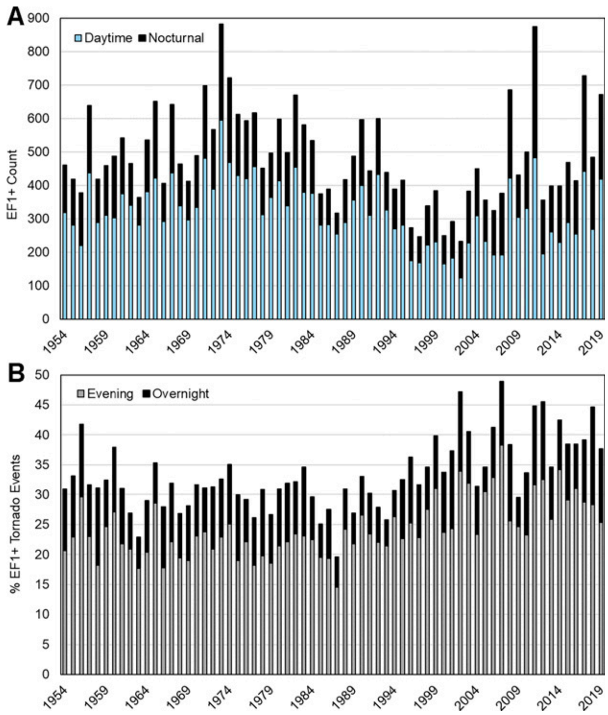

FIG. 4. (a) Total EF1+ tornado event counts in DT (light blue) and NT (black) light conditions, and (b) the percentage of all tornado events that began during NT EVE (light gray) and NT ONT (black) lighting conditions from 1954 to 2019.

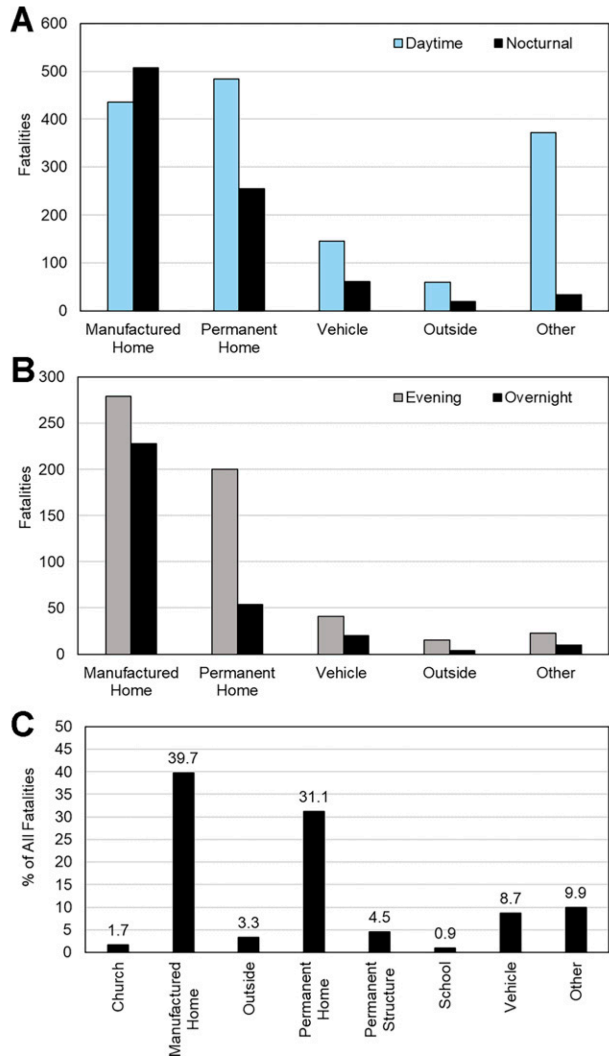

FIG. 5. (a) Total fatality counts from 1985 to 2019 for location circumstance (manufactured home, permanent home, vehicle, etc.) by DT and NT light conditions. (b) As in (a), but for EVE and ONT light conditions. (c) The percentage of all fatalities from 1985 to 2019 by location circumstance.

the largest NT tornado percentage with 46% (Fig. 6b). More than 40% of tornadoes in Arkansas (44%), Kentucky (40%), Mississippi (40%), and Missouri (42%) are NT events (Fig. 6b). Alabama, Arkansas, Georgia, Missouri, Mississippi, Oklahoma, and West Virginia had increases in the proportion of tornadoes that are NT over the last decade and a half.

Tornado fatalities are most common in the Southeast, although annual tornado frequency is slightly greater in the central plains (Fig. 7; Brooks et al. 2003; Simmons and Sutter 2011; Ashley and Strader 2016; Strader and Ashley 2018). Nearly two-thirds of all tornado fatalities occur during DT hours because critical severe weather ingredients such as instability and shear are more prevalent during the day (cf. Fig. 2 in Tippett et al. 2015). Patterns in DT tornado fatalities mirror that of all tornado fatalities, with fatal tornadoes being most common in the central/southern plains, Mississippi River valley, and Southeast. NT tornado events are concentrated in the Southeast, with nine of the top ten 80-km grid cells with the highest fatal tornado counts in Alabama, Arkansas, Mississippi, and Tennessee (Fig. 7c). The grid cells with the highest EVE tornado fatality counts are in the Tennessee and lower Mississippi River valleys, and elevated ONT tornado fatalities are concentrated in lower Tennessee Valley and Southeast (Fig. 7e).

Most fatalities in the upper Midwest and central plains occur during DT hours (Fig. 8). The Midwest and northern portions of the lower Ohio, Tennessee, and Arkansas River valleys experience the greatest percentage of NT fatalities during the EVE hours, as opposed to ONT time periods. ONT fatalities are primarily isolated to the most southern portions of the Southeast and southern plains. This result is likely due to a higher risk of tornadoes in this region during the fall and winter months (Brooks et al. 2003; Krocak and Brooks 2018).

Many locations across northern Arkansas, Kentucky, and Tennessee have tornado fatality probabilities greater than 0.1 (i.e., 10% chance that a tornado within an 80-km cell results in a fatality; Table 2; Fig. 9). When solely assessing DT tornado fatality probabilities, the spatial pattern is more dispersed and variable (Fig. 9b). Again, NT tornado fatality probabilities are higher in the Southeast, with Kentucky and Tennessee having the largest NT tornado fatality probabilities. All 80-km grid

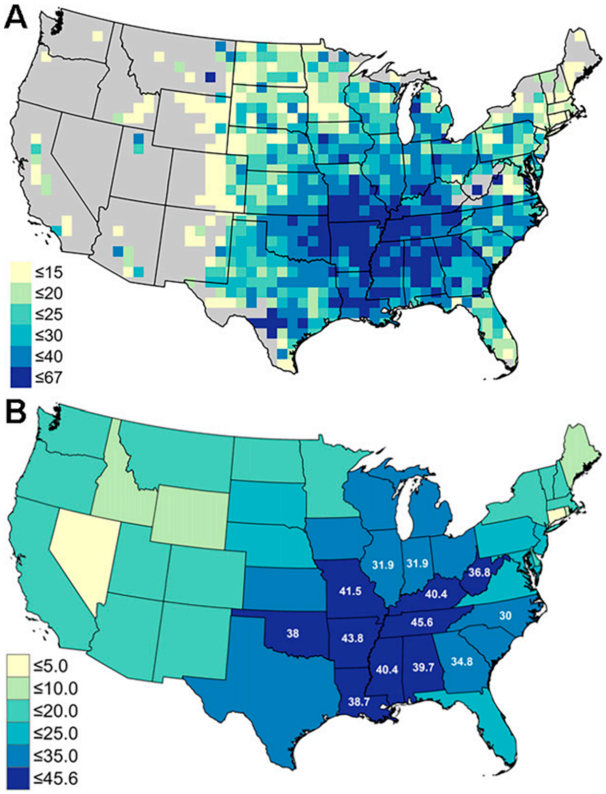

FIG. 6. (a) Percentage of tornado events (1950–2019) in an 80 km × 80 km grid cell that are NT. All grid cells with less than 10 tornado events for the period of record are not displayed. (b) Percent of all tornadoes (1950–2019) that are NT events by state. States with greater than 30% of tornadoes that are NT are labeled.

cells with the greatest probability of tornado deaths occurring ONT are in the Southeast, except for a few locations in Illinois and Missouri.

c. *Tornado impact simulations by light condition*

1) East-central domain

For the east-central simulation domain (Fig. 10a), DT population totals were approximately 171 000 (0.15%) people less than NT population estimates (Table 3). This subtle difference of 0.14% is largely attributed to people migrating across our analysis region boarders during DT or NT hours. Mean simulated tornado lengths were 1.1 km during NT hours, while there was virtually no difference in DT and NT maximum tornado widths. NT tornadoes represented 33% of all EF1+ tornadoes in the large simulation domain.

When controlling for differences in DT and NT tornado frequencies across a region, NT tornadoes affect more people on average (Table 4; Fig. 10b). This finding highlights the importance of considering the nonstationarity character of the underlying exposed population in estimating a region's tornado impact potential, severity, and frequency during a 24-h period. NT tornadoes are expected to impact 13% *more people* than DT tornadoes across the east-central U.S. region because of a more dispersed population pattern during NT hours. A more dispersed population and development pattern leads to greater median and mean tornado–society impact probabilities (Strader et al. 2018). The 90th percentile tornado–population impact measures indicate that nearly *3 times* as many people are exposed to NT tornadoes than to DT tornado events (Table 4). The large difference in DT–NT tornado–population impacts occurs despite NT tornadoes representing approximately one-third of all tornado events in east-central U.S. domain. The standard deviation in tornado–population exposure also reveals the importance of DT and NT population patterns on tornado impact potential. During DT hours, people are more likely to leave their residences for work. Many of these individuals work in urban centers or central business districts. Thus, DT populations are often more clustered than at NT when people are much more likely to be in their suburban and exurban dwellings. Illustrating this effect on tornado exposure, DT tornado–population impact standard deviation measures are nearly 20% greater than NT standard deviation values. In more general terms, DT tornadoes most often affect empty suburban or exurban dwellings, but, when a DT tornado traverses a central business district or large employment region, the more dense and clustered DT population leads to a higher number of persons exposed to the tornado.

2) Central plains, Midwest, and Southeast domains

Both Midwest and Southeast populations contain between 14 and 15 million people (Table 3). As expected, total DT and NT population estimates for the central plains are much lower (6 million fewer people) than the Midwest and Southeast regions. Tornado lengths were 2 km longer on average (mean) in the Southeast and Midwest than in the central plains, whereas mean maximum tornado widths were all within a few meters of each other across the three regions. The Southeast and central plains regions had longer-tracked tornadoes during NT hours due to faster storm speeds in the Southeast region (Dixon et al. 2011; Strader et al. 2021). Like results in Ashley and Strader (2016), tornado damage footprints (i.e., maximum path width multiplied by pathlength) NT tornadoes in the Southeast and central plains tend to be larger than DT counterparts. The Southeast region had the greatest number of tornadoes per year, as well as the highest percentage of NT tornadoes per year at 38% (Table 3). Central plains and Midwest regions experience approximately 12.4 NT tornadoes per year (26% of all tornadoes) and 18 NT tornadoes per year (31%), respectively. These regional differences reveal that climatological risk is an important factor in tornado–population impact potential.

Populations in the southeastern United States are the most exposed to tornadoes, as seen by comparing the TorMC-generated probability-of-exceedance (POE) curves and population impact statistics for the three subdomains (Table 4; Fig. 11). There is a stark difference between Southeast region NT tornado–population impact potential and all other regions. For instance, a NT tornado is 10% more likely to affect 100 people in the Southeast than in the central plains (Fig. 11a), whereas DT tornadoes

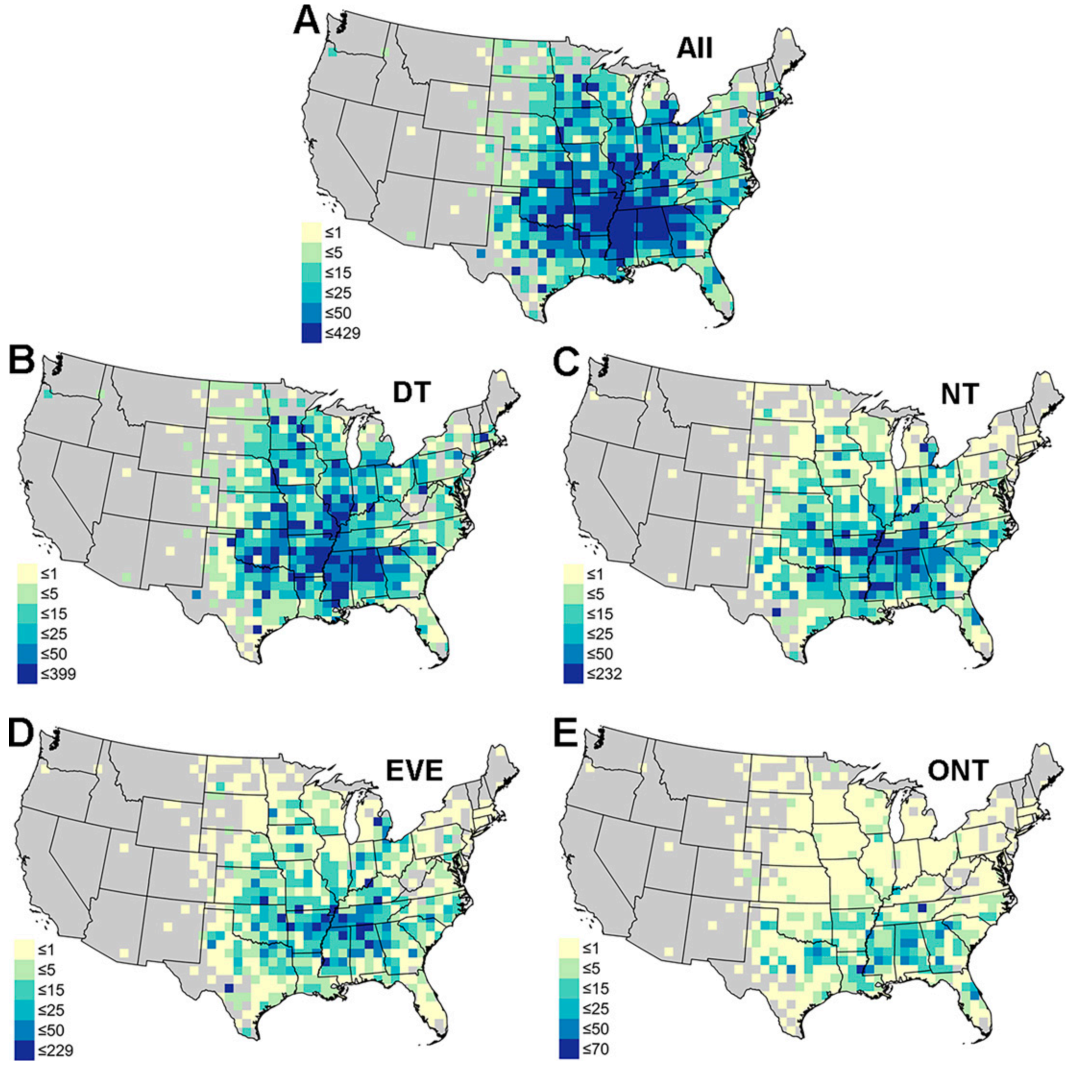

FIG. 7. Tornado fatality counts in 80 km × 80 km grid cells from 1950 to 2019 by light condition categories including: (a) all, (b) DT, (c) NT, (d) EVE, and (e) ONT.

in the Southeast are only 4%–5% more likely to impact 100 people than those in the central plains (Fig. 11b). Although the mean number of persons affected by tornadoes during DT hours (94 people) in the Midwest is greater than in the Southeast (82), mean NT tornado–population impact measures in the Southeast (98) is higher than in the Midwest (90) and central plains (52).

The 90th- and 95th-percentile tornado–population impact statistics are greater in the Southeast than in any other region, regardless of whether a tornado occurs during DT or NT hours. However, Midwest 99th-percentile expected DT impacts are slightly larger than NT impact values. This reversal from the 90th- and 95th-percentile Midwest population impact values is attributed to simulated EF1+ tornado paths that traversed large, densely populated metropolitan areas such as Chicago, Milwaukee (Wisconsin), and Minneapolis–Saint Paul (Minnesota) where persons tend to cluster in central business districts during DT hours. Central plains DT and NT impacts are also less than those in the Southeast and Midwest. This is attributed to the region's lower overall population, as well as smaller commuting rates (Burd et al. 2019; Table 4). Together, these findings suggest that the combination of a greater frequency of NT tornadoes and a more sprawling NT population pattern in the Southeast leads to higher odds of NT tornado–population impacts when compared with the central plains and Midwest regions.

3) METROPOLITAN DOMAINS

TorMC simulations were also conducted for three metropolitan domains across the United States: Atlanta (ATL), Chicago (CHI), and Dallas–Fort Worth (DFW; Fig. 12). All three metropolitan domains contain greater than 6 million people, with the CHI domain containing the largest population (Table 3). ATL is the only metropolitan region to have a higher NT population (+98 142 people) than its DT population total. The ATL domain has the longest-tracked NT

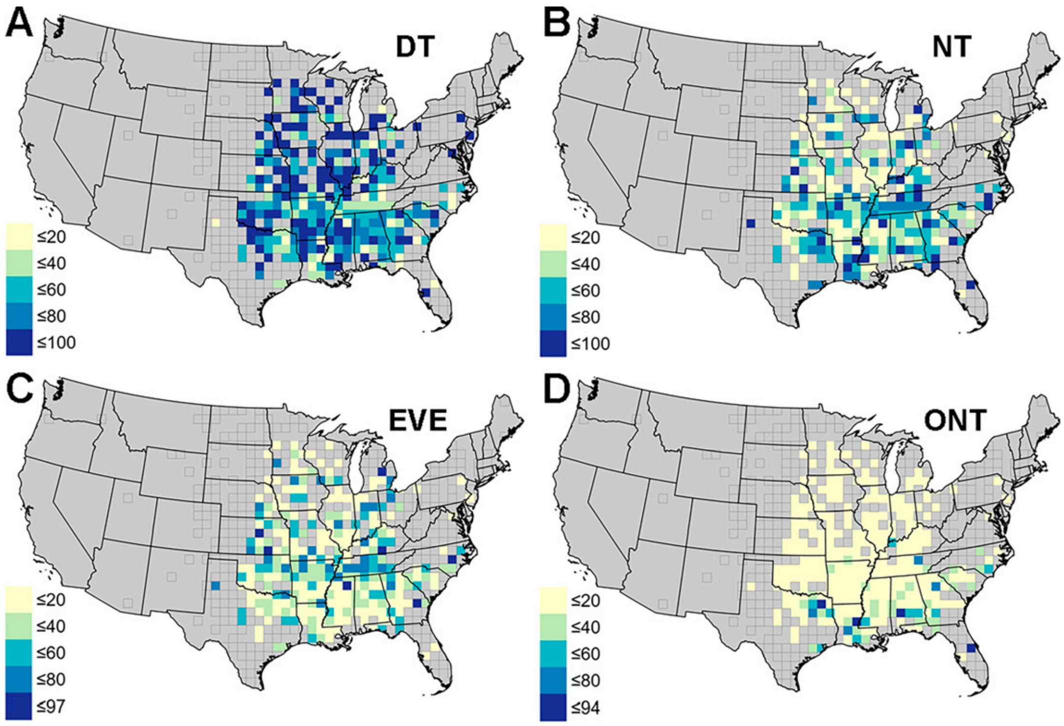

FIG. 8. Percentage of all fatalities in an 80 km × 80 km grid cell from 1880 to 2019 that occurred during (a) DT, (b) NT, (c) EVE, and (d) ONT light conditions. An open grid cell indicates fewer than five fatal events from 1880 to 2019. Grid cells that contain less than 10 total fatalities from 1880 to 2019 are not illustrated with color.

tornadoes on average, with a mean of 17.0 km. NT mean pathlengths for ATL and DFW regions were larger than DT pathlengths, and mean NT CHI pathlengths were 2.2 km shorter than DT events. Maximum tornado widths were similar for all metropolitan domains, with NT tornado widths slightly greater than DT paths. Each metropolitan domain had approximately three to four DT (one to two NT) EF1+ tornado paths per TorMC simulation year. The percentage of all simulated tornadoes that were NT (40%) was also very similar across the three domains. These results indicate that DT and NT tornado frequencies are not a cause any of the TorMC simulation differences found among the three domains; rather, the differences are attributed to nonstationary patterns in population density between DT and NT hours.

Mean tornado–population impacts are greatest in the CHI region for DT events and the ATL region for NT events, with 90th-, 95th-, and 99th-percentile tornado–population metrics following the same pattern (Table 4; Fig. 11). This suggests that, during DT periods, the CHI region is at greatest risk for high-impact tornadoes, while during the NT, Atlanta has the greatest likelihood of elevated tornado–population impacts. Elevated CHI DT tornado–population impact values can be attributed to a much greater population density in Chicago's central business district and polycentric urban cores during DT hours (Table 4). Alternatively stated, Chicago's urban cores are so densely populated during DT hours, a single tornado traversing this region could result in a substantially large number of people being exposed to the tornado relative to a NT event. This higher-impact tornado scenario inflates mean, 90th-, 95th-, and 99th-percentile statistics. Evidence of this effect is apparent when examining the similarity of the DT and NT POE curves (Fig. 11).

A comparison of ATL, CHI, and DFW POE curves reveals that ATL and CHI are very similar in terms of their expected DT tornado–population exposure (Fig. 11b). However, the differences between ATL and CHI 95th- and 99th-percentile regional impacts are more evident when examining the POE curves. The CHI region, by far, encompasses the greatest risk of a high-end tornado impact; there is a 5% chance that 2265 people and a 1% chance that 10 229 people are affected by a single tornado. Differences between NT POE curves and exposure illustrate that ATL experiences the greatest threat of high-impact NT tornado events of those metros sampled, while CHI encompasses the highest DT tornado impact probabilities.

4. Summary, discussion, and conclusions

An assessment of tornado–population impact potential is critical for furthering our knowledge and understanding of how DT and NT tornado disasters commonly unfold across the United States. Local emergency manager, forecasters, and policy makers may use the findings herein to create hazard mitigation, response, and recovery plans to reduce future tornado disaster severity, especially in the Southeast where NT tornado frequency and mortality is of great concern. Critical findings from this research include the following:

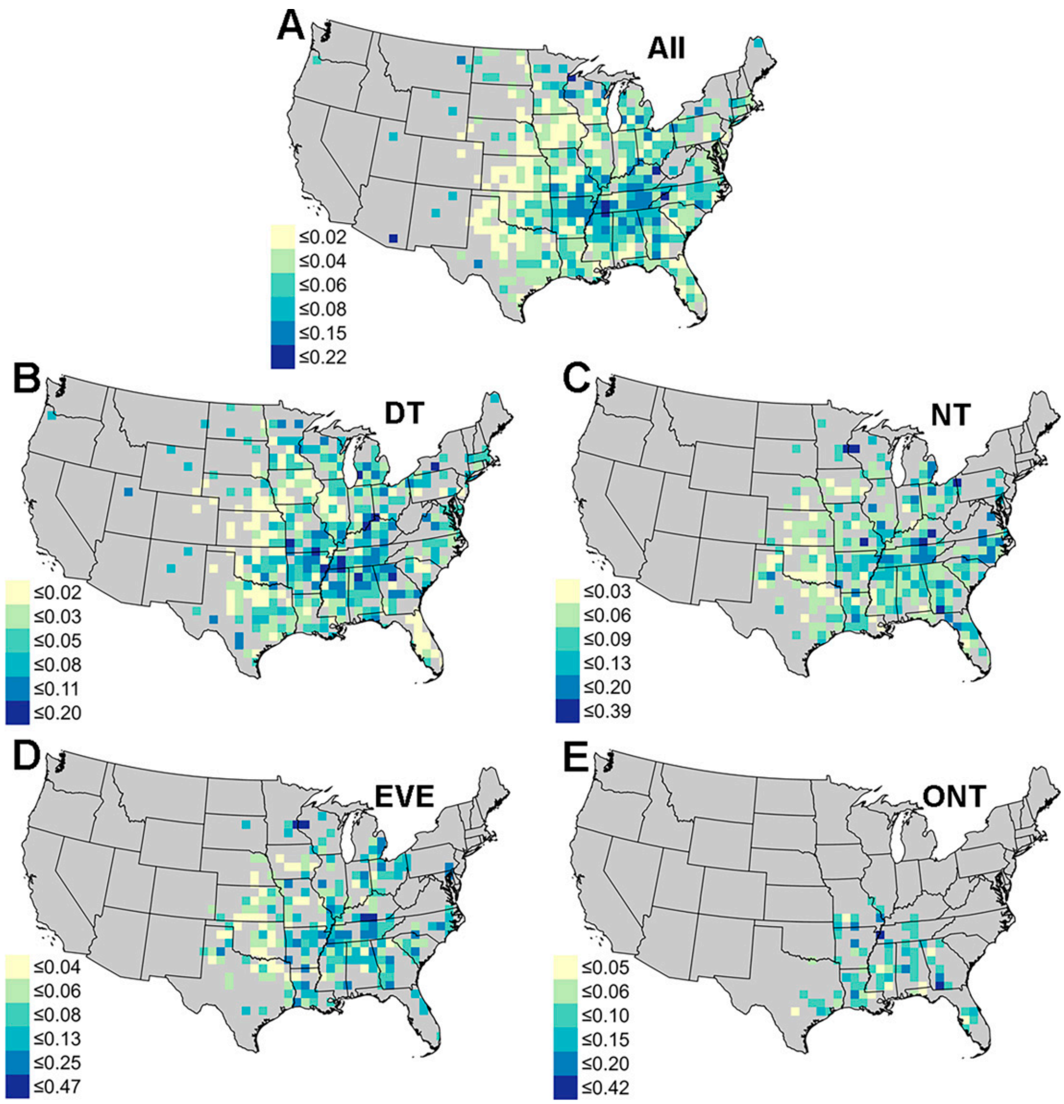

FIG. 9. Fatal tornado event probability in 80 km × 80 km grid cells from 1950 to 2019 in light condition (a) all, (b) DT, (c) NT, (d) EVE, and (e) ONT. All grid cells with fewer than 10 total tornado events in the specific light condition category and no fatal tornado events in the specific light category are not illustrated with color.

- While tornado fatality rates in the United States have steadily fallen since 1880 (Brooks and Doswell 2002; Ashley and Strader 2016), the percentage of all tornado fatalities that occurred during NT hours over the last 140 years has *nearly doubled*. ONT tornado fatalities have *increased* 400% during this same period.
- DT tornado fatality percentages have *decreased* by 20% over the last 140 years, whereas NT fatality percentages have *increased* by 20% since 1880.
- The trend in percentage of fatalities occurring during EVE hours (26%) has remained *consistent* since 1950, and ONT fatality percentages have increased *fourfold* (5%–20%) since 1880.
- Updating and reconfirming Ashley et al. (2008), NT tornadoes are still *2 times* as likely to produce a fatality relative to DT events, with ONT tornadoes almost *2.5 times* as likely to cause a death.
- In the most-tornado-prone region of the United States (east-central), NT tornadoes are expected to impact approximately *13% more people* per event than DT tornadoes do.
- There is a balance between climatological tornado risk and societal exposure with differences in a region's DT and NT tornado fatality likelihood. However, when controlling for the differences in DT and NT tornado frequency across a region, *NT tornadoes affect a greater number of people on average than DT events*. This is largely attributed to a more dispersed population density pattern during NT periods, not climatological tornado risk factors.

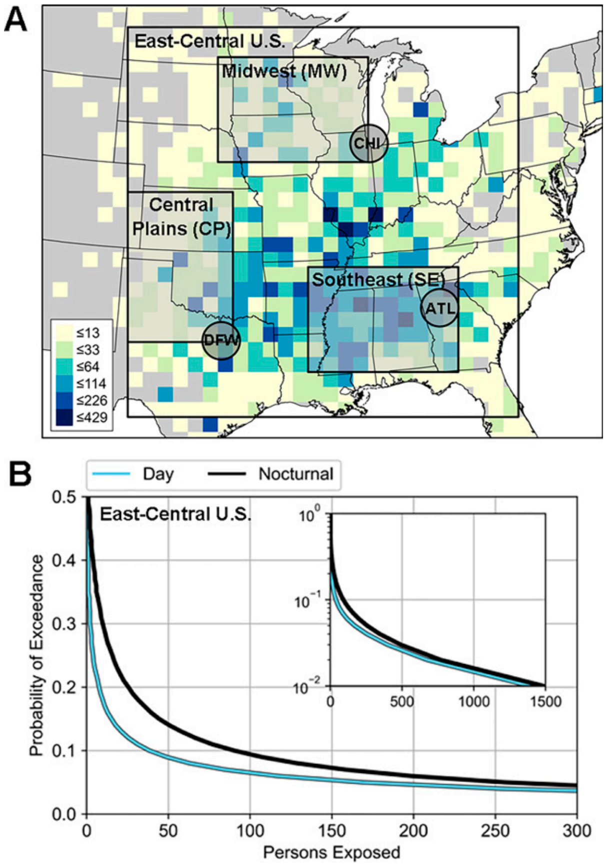

FIG. 10. (a) TorMC impact simulation regions and total tornado fatality counts on an 80 km × 80 km grid from 1880 to 2020. (b) POE curves for DT and NT tornado events simulated across the east-central region. The inset graph in (b) highlights 90th-, 95th-, and 99th-percentile tornado–population impacts.

- Tornado-prone cities or regions with many commuters from exurban and suburban locations (e.g., Chicago) illustrate the highest variability in DT and NT tornado impact potential. The larger the difference between a region's DT and NT population density patterns is, the *greater is the variability* in DT and NT impacts.

Our analyses of tornadoes by light condition illustrate that the NT tornadoes are a primary impediment in mitigating tornado mortality and, by extension, injuries. The percentage of all tornado fatalities that occur during the NT has doubled since 1880, with the proportion of ONT fatalities increasing fourfold. This increase is attributed to potential changes in severe weather environments driven by climate change (e.g., Tippett et al. 2015; Gensini and Brooks 2018) and/or better tornado detection and warning practices (e.g., Brooks 2004; Coleman et al. 2011; Brooks and Correia 2018). Conversely, the percentage of all tornado fatalities that occur during DT hours has decreased since 1880, revealing that the most recent 30-yr stall in the tornado fatality rate is primarily the result of NT tornadoes. Counterintuitively, the increase in the proportion of tornado fatalities due to NT events is not due to more NT tornado events as there has been no substantial change in either DT or NT EF1+ tornado frequencies across the United States. Rather, the increase in NT fatality proportions is likely a result of 1) a growing percentage of observed NT tornadoes occurring during ONT hours when people are most likely to be asleep and unable to take protective actions successfully (Paul 2011; Simmons and Sutter 2007; Ashley 2007; Ellis et al. 2020), 2) an increasingly vulnerable society (Cutter and Finch 2008), and 3) an expanding built-environment footprint in NT tornado-prone regions such as the Southeast (Ashley and Strader 2016; Strader et al. 2017a).

Prior work has illustrated that most manufactured homes in the Southeast—where NT tornadoes are most common—are in rural [>40 acres (1 acre = 0.4 ha) per housing unit] and exurban (2–40 acres per housing unit) land-use densities (Fig. 5; Strader et al. 2018, 2019). Manufactured home residents situated in rural and exurban locations often fall into one or more socioeconomically vulnerable categories (Schmidlin et al. 2009; Sutter and Simmons 2010; Emrich and Cutter 2011; Simmons and Sutter 2011; Strader and Ashley 2018; Strader et al. 2021). As such, the combination rural and exurban manufactured housing, socioeconomic vulnerability, and elevated frequency of

TABLE 3. Total population in each TorMC simulation domain for DT and NT periods, mean simulated lengths (km), maximum path width (m), mean number of EF1+ tornadoes per simulation year, and the mean percentage of all simulated tornadoes that are NT by study region.

Simulation region	Light condition	Population	Length (km)	Width (m)	Tornadoes per year	% NT
East-central	DT	118 518 919	9.4	101.6	277.0	32.7
	NT	118 689 946	10.5	106.8	134.5	
Southeast (SE)	DT	14 550 571	11.3	102.7	43.9	38.0
	NT	14 752 966	13.5	109.9	26.9	
Midwest (MW)	DT	14 842 034	12.1	108.4	34.5	26.4
	NT	14 805 628	10.5	107.4	12.4	
Central plains (CP)	DT	8 659 581	9.7	106.6	40.3	30.9
	NT	8 365 014	10.6	110.3	18.0	
Atlanta (ATL)	DT	5 063 835	13.5	108.8	3.5	39.7
	NT	5 161 977	17.0	115.0	2.3	
Chicago (CHI)	DT	6 967 051	13.0	110.0	3.4	40.4
	NT	6 769 849	10.8	110.7	2.3	
Dallas–Fort Worth (DFW)	DT	6 031 023	6.5	106.9	3.9	39.1
	NT	6 009 481	8.3	113.7	2.5	

TABLE 4. TorMC simulation descriptive statistics for DT and NT light conditions in the east-central U.S., central plains, Midwest, Southeast, Atlanta, Chicago, and Dallas–Fort Worth simulation domains. Values represent the number of persons exposed per simulated tornado footprint.

Simulation region	Light condition	Median	Mean	Std dev	90th percentile	95th percentile	99th percentile
East-central	DT	0	68	695	38	169	1378
	NT	1	78	590	90	256	1455
CP	DT	0	47	701	8	45	880
	NT	0	52	570	23	87	1039
MW	DT	0	94	841	58	261	1936
	NT	2	90	712	85	272	1809
SE	DT	1	82	641	75	276	1602
	NT	5	98	599	152	369	1685
ATL	DT	16	474	2425	836	1970	8018
	NT	53	544	1946	1168	2493	8550
CHI	DT	1	566	4953	854	2265	10 229
	NT	2	441	2119	811	1964	8343
DFW	DT	3	262	1905	322	1054	4923
	NT	9	328	1425	557	1593	6183

NT tornado events likely leads to greater odds of tornado deaths when NT events traverse a region like the Southeast, or any area and time when these risks and vulnerabilities comingle.

Spatial analyses indicate that Arkansas, Kentucky, Missouri, and Tennessee experience greater than 40% of their tornadoes during the NT. Analyses examining tornado fatality counts and percentage of all tornadoes indicate that DT tornadoes are responsible for a higher tornado mortality since they are more frequent than NT events. However, the spatial trends in tornado fatality counts suggest that specific geographies are more prone to NT fatalities. DT tornado fatality counts and percentages of all tornado events that occur during DT periods are more dispersed across the central plains, Midwest, and Southeast. As expected, NT tornado fatalities are much more common in the Southeast. However, further categorizing NT events into EVE and ONT reveals that EVE tornado fatalities are most common in the lower Ohio River valley and Tennessee Valley, with ONT fatality counts being greater in the lower Mississippi River valley and Southeast. This finding is especially critical since ONT tornadoes are now *more than 2 times* as likely to result in a fatality relative to DT events. This statistic is in line with prior work (Ashley et al. 2008), suggesting that efforts over the last few decades aimed at reducing ONT fatalities are still being impeded, potentially by a comingling of exposure, vulnerability, sheltering, and warning efficacy factors.

Tornado-population impact simulations for DT and NT events capture the importance of different tornado frequencies, spatial characteristics, etc., of tornadoes across the two light condition categories (DT and NT), while also encapsulating the effect a nonstationary population on potential tornado impact. TorMC simulations highlight the critical balance between climatological risk and population density factors that control impacts and fatality likelihood. For instance, nearly two-thirds of all tornadoes in the east-central domain were DT events. Yet, when controlling for DT–NT tornado simulation frequencies, NT events impacted 13% *more people* on average (mean). This result is largely explained by a more sprawling NT population pattern, not differences in simulated tornado path characteristics. A more dispersed population density, which is more characteristic of NT period, leads to, on average, greater tornado impacts when compared with those exposure characteristics typically found during DT periods. Again, this is supported by prior research (Ashley and Strader 2016; Strader et al. 2018), which revealed that a more sprawling development pattern, all else being equal, leads to a greater number of people affected by tornadoes.

Regional and metropolitan simulation results also indicate that NT tornado impacts are greater per tornado in comparison with DT events. From a climatological risk standpoint, the Southeast experiences the highest frequencies in NT tornadoes. The proportion of tornadoes in the Southeast that are NT (38%) is largest among the three regional domains examined. The Southeast has a relatively high population density in comparison with the central plains, and, when these risk and exposure factors overlap, a higher relative mortality in the Southeast results. Indeed, the likelihood of NT tornadoes affecting someone who resides in the Southeast region is *nearly double* that of the central plains.

Metropolitan analyses mirror those of the regional assessments with NT tornadoes more likely to affect populations in the ATL region. However, the effects of a metropolitan city structure (e.g., monocentric vs polycentric development), public transportation and other infrastructure, etc., also play a role in controlling where people are located during DT and NT periods. This, in turn, influences tornado impact potential over the course of a day. For example, DT tornado impacts for the CHI region were much larger than the ATL and DFW domains. In addition, the CHI simulation tornado–population mean and standard deviation impact values are much higher during the DT hours than during NT periods. These results are attributed to the CHI region population being greater than the other two domains and the commute of people from Chicago suburbs to the central business district (i.e., "Chicago Loop") and other urban cores during the DT. In all, there exist the potential for a DT or NT tornado event in the CHI or ATL region, respectively, to impact as many as 10 000 people.

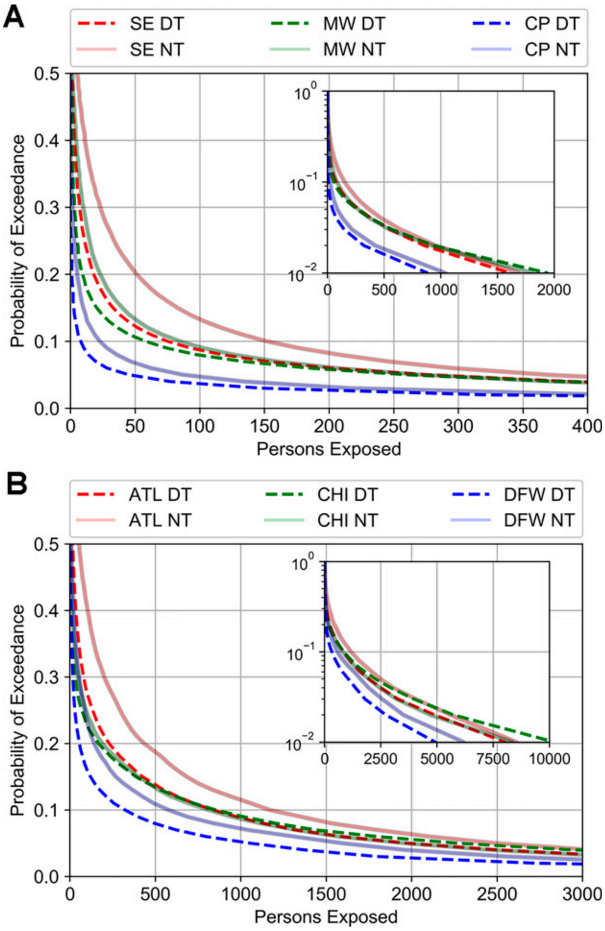

FIG. 11. POE curves for (a) CP, MW, SE, and (b) the ATL, CHI, and DFW regions. Dashed POE curves represent DT tornado–population impact probabilities, and semitransparent POE curves signify NT tornado–population impact probabilities for the same region. The inset graphs highlight 90th-, 95th-, and 99th-percentile tornado–population impacts.

5. Working toward solutions

There will always be a need for solutions that increase tornado survivability, and continued research into NT tornado risk and its resulting vulnerabilities will be paramount in increasing our understanding and promoting successful mitigation strategies. The NT tornado issue has been examined at varying spatial scales over the last decade (e.g., Ashley et al. 2008; Krocak and Brooks 2018; Bunker et al. 2019; Ellis et al. 2020), with many researchers investigating this problem from physical, social, and interdisciplinary science perspectives (Mason et al. 2018; Bunker et al. 2019; Ellis et al. 2020; Krocak et al. 2021). These studies have resulted in an improved understanding of NT tornado ingredients, environmental factors, and how people respond to and heed tornado warnings during NT hours, but more research is needed. Continued efforts should include educating the many vulnerable publics, while also providing opportunities for local emergency managers, forecasters, members of the media, first responders, policy makers, and researchers to learn from these populations.

Note also that our study assumes that individuals are working outside of their homes or residences during the 0900–1700 LT period. We recognize that in recent years—starting in late 2019—the COVID-19 pandemic likely altered this assumption substantially. As such, research building on this study may need to adjust hazard impact analyses to account for the larger percentage of persons working from their residences during typical 0900–1700 work hours. Studies (e.g., Quigley et al. 2020; First and Houston 2022) have already began studying the intersection of tornado events and COVID-19, but future work should consider the effects social distancing and quarantining may have on tornado hazard exposure and population impact potential.

We acknowledge caveats and potential biases in our study, especially during earlier parts of the period of record. Specifically, prior studies (e.g., Grazulis 1993, 1997; Brooks and Doswell 2002; Ashley 2007; Ashley et al. 2008) have pointed to issues around tornado event recording practices, accuracy, and consistency before the 1950s. For example, we assume in our fatal tornado probability analyses (Table 2; Figs. 8 and 9) that the number of recorded fatal and nonfatal tornado events are in proportion with each other over time and across light conditions. This may not be true given the expectation that NT tornadoes from earlier time periods (before the 1970s) would be less likely to be captured within the tornado datasets used in this study. We are unable to correct for every issue that may affect the 140-yr tornado fatality dataset since there are, in many cases, no perfect "ground truth" data to use for further verification; thus, we acknowledge there may be biases—some likely unknown—caused by potential dataset incompleteness.

Research on tornadoes and many other types of atmospheric hazards has consistently pointed to the importance of population and built-environment exposure in setting the stage for tornado disasters (e.g., Ashley et al. 2014; Ashley and Strader 2016; Strader et al. 2017a). Our population and developed land area are increasing, leading to many more people and their structures affected by these deadly hazards (i.e., expanding bull's-eye effect; Strader and Ashley 2015). We illustrated in this study that assessing changes in populations over the course of a 24-h period is also important, as exposure and affiliated vulnerabilities are dynamic and are not fixed per a conventional unit of measure such as a census enumeration. As such, tornado survivability enhancing measures must move beyond residential preparedness strategies such as retrofitting homes, improving building codes for residential structures, and building at-home storm shelters. There needs to be an equal emphasis on tornado safety and sheltering in the workplace, as well as the influence of commutes and traffic flows on tornado impact potential (e.g., Blair and Lunde 2010). The devastating 10–11 December 2021 NT tornadoes highlights the importance of workplace tornado safety as dozens lost their lives at work in large-span structural facilities because of supervisor-to-worker threat communication issues and the lack of adequate storm shelters (Sorkin et al. 2021).

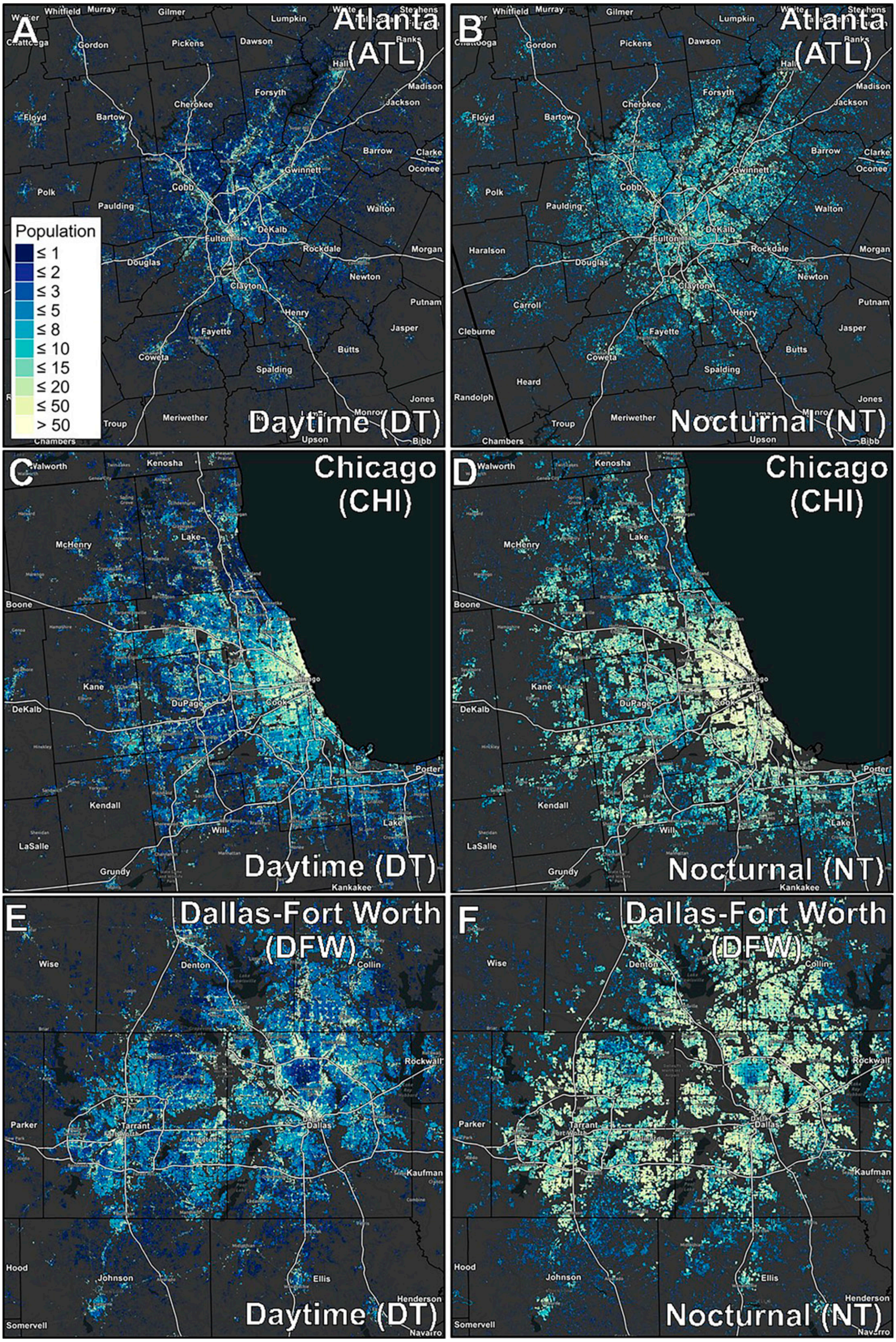

FIG. 12. (left) DT and (right) NT population density (people per 90-m grid cell) estimates for the (a),(b) ATL; (c),(d) CHI; and (e),(f) DFW metropolitan regions.

Like Ellis et al. (2020), more research should be conducted on how populations in NT tornado-prone regions receive tornado warnings during ONT hours. NOAA and the NWS recommend that all persons in tornado-prone regions have a NOAA Weather Radio (NWR) so they may receive timely and critical weather warnings. NWRs are currently the most effective way for populations to receive tornado warnings during ONT hours when individuals are most likely to be asleep. However, as we have illustrated, ONT fatalities have continued to rise over time. While there are justifiably many efforts ongoing across the country by NWS officials, emergency managers, and media partners to provide residents with NWRs, future work should also continue to investigate the effectiveness of the NWR system. Further research is needed to better understand why NWR efforts are not working effectively in some cases, or, perhaps, determine if these efforts are simply being outpaced by an expanding population and built environment and/or other vulnerabilities.

Last, emergency managers should be aware of how community-level population flows affect tornado impact potential. Emergency managers should be more prepared for high-impact events to occur during DT hours, especially near large employment hubs such as central business districts. They should also be prepared for more widespread residential housing impacts during NT hours. Time-specific disaster response strategies should continue to be developed and adapted so that tornado survival rates may be enhanced, especially in the Southeast where NT fatalities remain elevated. We began to address this issue by assessing DT–NT populations in this study; however, more data and research are needed to understand the dynamics of community exposure. For instance, standard commuting flows in a city depend on a multitude of factors such as day of week, time of year, and, as we have all recently learned, during a pandemic. Simultaneously, there is a need for additional research on the effects of climate change on severe weather environmental controls; for instance, are these changing ingredients shifting tornado risk during the NT? Researchers, forecasters, the media, emergency managers, policy makers, and the public should recognize that tornado risk and vulnerabilities are not the same over a 24-h cycle. As we collectively improve our understanding of how the disaster constituents of risk, exposure, and vulnerability dynamically comingle, we can continue to advance policy and mitigation strategies that increase tornado survivability in the face of a rapidly changing society and environment.

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Data availability statement. Data and model output requests may be made to the corresponding author of this study.

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