A Spatiotemporal Perspective on the 31 May 2013 Tornado Evacuation in the Oklahoma City Metropolitan Area

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ABSTRACT: On 31 May 2013, an extremely large and violent tornado hit near the town of El Reno, Oklahoma, a small town in the Oklahoma City metropolitan area. The size and intensity of this tornado, coupled with the fact that it was heading toward Oklahoma City, prompted local broadcasters to warn residents to evacuate their homes and head south if they could not shelter belowground. This warning led to a large-scale evacuation of the metropolitan area and massive traffic jams on the interstates and major highways that could have caused casualties in the hundreds if the tornado had not dissipated before reaching Oklahoma City. The focus of this study was to understand the magnitude of the 31 May 2013 evacuation through the evaluation of traffic volume data and to determine how frequently such evacuations occur in Oklahoma City and other metropolitan areas. We found that of the six metropolitan areas tested, only Oklahoma City had mass anomalous traffic reversal (ATR) days (days with a mass evacuation signal) with 31 May 2013 having the largest mass ATR day by far. Despite the rarity of mass ATR days, the potential consequences of a large, violent tornado hitting gridlocked traffic is significant, and we recommend that communicators encourage more local sheltering options.

SIGNIFICANCE STATEMENT: On the evening of 31 May 2013, a large-scale evacuation of the Oklahoma City metropolitan area occurred as a result of a very large and dangerous tornado that had formed near the town of El Reno and was moving east toward Oklahoma City. If the tornado had not dissipated before it reached the city it could have caused hundreds of casualties as it passed over gridlocked roads. We sought to understand the frequency of such mass evacuations and found that no other event in six metropolitan areas studied during 2011–18 could compare. While such evacuations fortunately appear rare, more work should be done to understand why they happen when they do and to connect individuals with better local sheltering options.

KEYWORDS: Tornadoes; Geographic information systems (GIS); Societal impacts; Vulnerability

1. Introduction

Evacuation can save lives and property by removing them from the path of a hazard; however, it does introduce safety issues such as increased traffic jams and accidents (Wolshon 2001; Li et al. 2015). Evacuation is a common safety practice for hazards with a long lead time and/or slow progression (e.g., many wildfires and hurricanes) (Hasan et al. 2011; Beloglazov et al. 2016) as people have sufficient time to flee the hazard despite slow-moving traffic. For fast-moving and sudden hazards like tornadoes, the lead time is only minutes to hours (Simmons and Sutter 2008; Brooks and Correia 2018) providing little time to decide to evacuate, gather one's family, and make it through traffic to potential safety. Because of this, the U.S. National Weather Service (NWS) recommends the following: 1) if inside a sturdy building, shelter in place in the most interior room on the lowest level; 2) if in a mobile home, vehicle, or outside, seek shelter in the nearest sturdy building (Farley 2007; Edwards 2018). Despite the NWS recommendation, some events have had notable evacuations (Uccellini et al. 2014). Schultz et al. (2010) surveyed residents of Austin, Texas, and found that 39% of those driving would stay in their car and drive away from the tornado and 18% of those at home said they would flee their house to get out of the tornado's path. Durage et al. (2014) surveyed residents of Calgary, Alberta, Canada, and found that 58% of those driving would stay in the car and drive away from the tornado while 16.6% of those at home would either drive out of the path of the tornado or seek shelter in a nearby sturdy building.

Tornadoes are particularly dangerous for people in vehicles as vehicles provide little protection against falling debris (Paulikas and Schmidlin 2017) and they can experience some degree of uplift at 75 m s^{-1} [corresponding to tornadoes rated 4 on the enhanced Fujita (EF) scale]. While vehicles can allow a person to escape the path of a tornado under ideal traffic, visibility, and storm-motion conditions, sudden changes in the tornado path, the potential development of new tornadoes, and the occasional invisibility of the full tornado circulation can make it difficult to know when one is safe (Wurman et al. 2014). The risk to drivers also increases with other reductions in the visibility of the funnel, such as the presence of enhanced tree cover and high-relief topography (e.g., in the southeastern United States) and dense urban environments with many tall buildings (Ashley 2007) and the occurrence of tornadoes after dark (Ashley et al. 2008; Kis and Straka 2010). Also, heavy traffic can make travel slow, and the

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limited availability of interstate-highway exits or intersecting roads can make it difficult to change directions when needed (Blair and Lunde 2010). As a result, vehicle fatalities account for 10%–20% of all tornado fatalities (Hammer and Schmidlin 2002; Ashley 2007); with the percentage of vehicle fatalities caused by tornadoes reaching a maximum of 30% in recent years (Paulikas and Schmidlin 2017).

While vehicle fatalities have occurred during tornado evacuations (Glass et al. 1980), the total number of vehicle fatalities has rarely exceeded 15 in a single tornado (Paulikas and Schmidlin 2017). Despite this, a worst-case scenario where a violent tornado hits dense traffic could result in hundreds of fatalities (Garfield and Smith 2014). The potential for such a mass casualty event necessitates a better understanding of how often large-scale tornado evacuations occur. To address this question, we first assess how traffic in the Oklahoma City metropolitan area responds to the issuance of tornado watches and warnings. We then develop a method for determining the frequency of large-scale tornado evacuations, from traffic data, in the Oklahoma City metropolitan area and five other metropolitan areas located in tornado-prone regions of the United States.

2. The El Reno tornado and evacuation on 31 May 2013

The analysis begins with an examination of the weather conditions over Oklahoma on 31 May 2013, because it was one of the best-documented cases of mass tornado evacuation. On 31 May 2013, the intersection of a dryline and a slow-moving front in western Oklahoma, coupled with high surface dewpoints (in the low 20s in degrees Celsius), very unstable lapse rates and high vertical wind shear led to an observed environment that was conducive to the production of supercells capable of producing strong tornadoes and very large hail within central Oklahoma (Uccellini et al. 2014). By late afternoon, a line of storms had formed extending from near Weatherford, Oklahoma, to the northeast. The first supercell formed around 1700 central daylight time (CDT, which is equivalent to UTC − 5 h) on the southern end of this line of storms and primarily tracked to the east becoming tornado warned by 1736 CDT. At 1755 CDT a tornado was reported with this storm, and it tracked to the east and northeast for about 26 km, primarily over open country, passing south of the city of El Reno, Oklahoma, before dissipating at 1845 CDT, according to mobile Doppler observations (Wurman et al. 2014; Wakimoto et al. 2016). The El Reno tornado, as it became known, was a large, multivortex tornado with a maximum width of 4.2 km (widest on record) and maximum ground relative Doppler wind velocities over 135 m s^{-1} (at the theoretical beam height of <20 m above ground level) (Wurman et al. 2014; Bluestein et al. 2015). The intensity rating of the tornado was controversial, with the official rating from the NWS a category 3 on the EF scale (EF3); however, the Doppler velocities (not used in official ratings) exceeded the wind threshold for an EF5 (90 m s^{-1}) (Bluestein et al. 2015; Wakimoto et al. 2016). The El Reno tornado damaged few buildings, despite its size and intensity; however, it was still responsible for eight direct fatalities, all in vehicles, including three experienced storm chasers (Uccellini et al. 2014; Wurman et al. 2014; Wakimoto et al. 2016). Figure 1 shows a picture of the tornado (Fig. 1a), its damage path (Fig. 1b), and radar imagery of the parent supercell (Fig. 1c) for reference.

The El Reno tornado followed on the heels of the deadly EF5 tornado that struck the city of Moore, Oklahoma, on 20 May 2013, killing 24 people including 7 children (Atkins et al. 2014; Burgess et al. 2014) as well as the EF3–4 tornadoes striking near the cities of Carney and Shawnee on 19 May 2013 (Uccellini et al. 2014). By 31 May 2013, the public was on edge and with a large and powerful tornado heading east toward the Oklahoma City area accompanied by atypical media suggestions stating that "you cannot be above ground . . . you've got to go south and you need to go now," many people reportedly got in their cars and evacuated to the south, with some fleeing their homes and others staying on the road instead of heading directly home (Cooper 2013; Uccellini et al. 2014; Fox News 2015; Ross et al. 2015). Evacuees clogged highways as far south as Norman, where many individuals fled from their cars and sought shelter in the National Weather Center as the rotation from the El Reno tornado came south. Author Klockow-McClain talked with several of these evacuees, and they came from points all over the metropolitan area, many not knowing the city or building they had reached. The large number of people evacuating exacerbated the normal Friday rush hour traffic, causing traffic jams throughout the metropolitan area as well as accidents (Fig. 1d) (Uccellini et al. 2014). Fortunately, the El Reno tornado dissipated in the countryside, and no other tornado that evening caused any fatalities among the evacuees (https://www.weather.gov/oun/events-20130531).

3. Data and methods

a. Study area

We selected six metropolitan areas within the region of the United States most prone to tornadoes (Gensini and Ashley 2011; Hatzis et al. 2019): Oklahoma City, Oklahoma (OKC); Dallas–Fort Worth, Texas (DFW); Omaha, Nebraska (OMA); Saint Louis, Missouri (STL); Chicago, Illinois (CHI); and Tuscaloosa–Birmingham, Alabama (TBI) (Fig. 2). Each metropolitan area was approximated by a 160-km by 160-km box around the downtown area(s) to ensure equal-sized study areas. Hereinafter, all use of the term "metropolitan area" refers to these 160-km by 160-km boxes. The metropolitan areas vary in both population density (from 346.7 persons per kilometer squared in CHI to 46.6 persons per kilometer squared in OMA) [Center for International Earth Science Information Network (CIESIN) 2017] and frequency of significant (EF2+) tornadoes [from 2.3 yr^{-1} in OKC (during 1989–2018) to 0.7 yr^{-1} in CHI; Table 1] (Storm Prediction Center 2019).

b. Data

We collected hourly Federal Highway Administration (FHWA) traffic volume counts (FHWA 2019) for all available count sites (with traffic being measured in both directions along the

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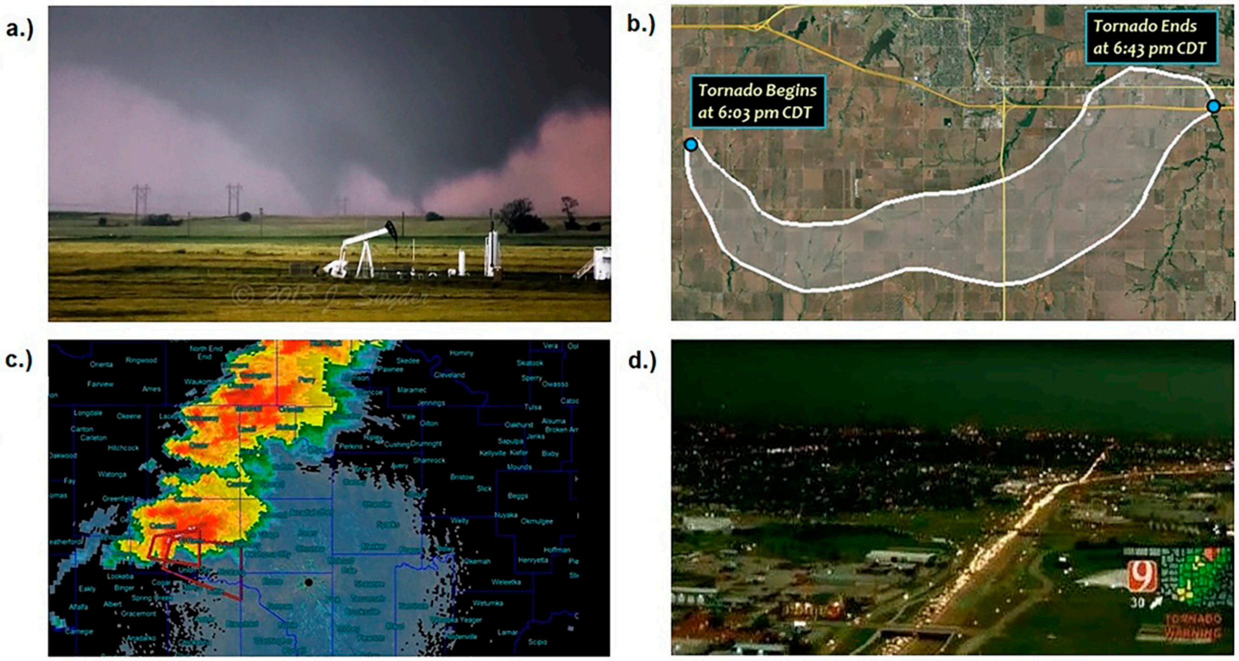

FIG. 1. El Reno tornado and evacuation on 31 May 2013. (a) Photograph of tornado provided through the courtesy of Dr. J. Snyder; (b) official damage path from the tornado and (c) WSR-88D imagery of the El Reno supercell at 1810 CDT, with tornado warning polygons in red, both provided through the courtesy of the National Weather Service Norman Office; and (d) traffic jams on I-35 in the Oklahoma City metropolitan area as seen from the Bob Mills SkyNews9 helicopter on Oklahoma City Channel 9 News (local CBS affiliate).

road) within the six metropolitan areas between 2011 and 2018. Each site has a unique identifier given by the state highway agency; however, to aid in comparing sites between different states [which may have similar site identifiers (IDs)] we combined the state's Federal Information Processing Standard (FIPS) code with the site ID to create a nationally unique site ID (e.g., 40AVC003 represents site AVC003 within the state of Oklahoma). Some sites that measured traffic in a single direction were also included if there was a paired site nearby that measured the traffic along the same road in the opposite direction (within a divided highway). In these cases, the station was identified by a combined site ID with all unique characters from the second ID added to the first ID after a forward slash (e.g., stations 40AVC072 and 40AVC073, which measure traffic eastbound and westbound, respectively, on U.S. Interstate Highway 40 (I-40) Crosstown, west of the Shields Boulevard Overpass in Oklahoma City, use a combined ID of 40AVC072/3).

Traffic volume is measured as the number of vehicles passing by the count site per hour and is detected using various active (e.g., video camera) and passive (e.g., weigh in motion) sensors. The data are available for all months at most of the sites, however, some sites do have missing data during this period. It is collected by state highway agencies and quality assured by the FHWA (FHWA 2016). Information about the site IDs, locations and annual average daily traffic for the Oklahoma City metropolitan area can be found in Fig. 3 and Table 2. In addition to traffic volume, we also wanted to determine the dominant direction of traffic at each site during each hour. We define this as traffic flow and calculate it as the difference between northbound and southbound (NB traffic flow) or eastbound and westbound (EB traffic flow) traffic at a given station during a given hour. NB or EB traffic flow is positive when the traffic is dominantly northbound or eastbound, respectively; it is negative when traffic is dominantly southbound or westbound, respectively. Low values of traffic flow indicate traffic volume in both directions is similar.

The primary limitations of the data are the short (8 yr) period of record and the fact that since the traffic volume is reported as a flux (vehicles per hour) it is difficult to know if low traffic volume is due to sparse traffic (a low number of vehicles on the road) or traffic jams (little movement due to bumper-to-bumper traffic). Loop detector occupancy data (FHWA 2016) can be used to determine the presence of nonmoving vehicles at a location; however, these data are unavailable in the FHWA traffic volume dataset. It is uncertain if low traffic volume is an indicator of sparse traffic or traffic jams; however, a more rapid than usual drop in traffic may indicate a traffic jam.

Information about historical severe weather watches, warnings, and advisories, from 2011 to 2018 over the six metropolitan areas, was collected from the Iowa Environmental Mesonet (2019). The information contains the type of hazard (e.g., tornado), the significance of the hazard (i.e., watch or warning), the location currently under a watch or warning (e.g., warning polygon), and the times during which the watches or warnings were active. A metropolitan area (traffic

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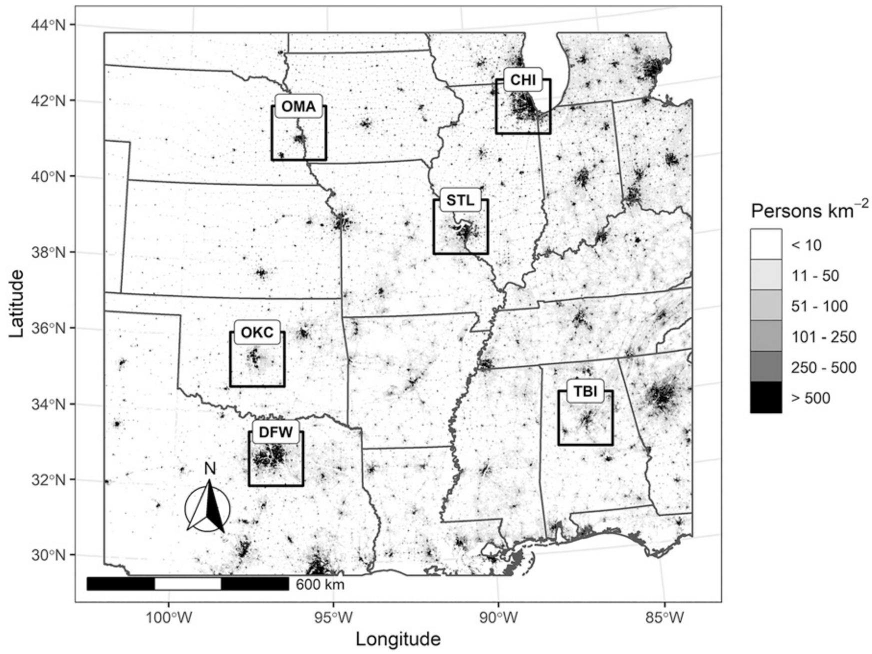

FIG. 2. Locations of metropolitan areas referenced in this study, including Omaha, Nebraska (OMA); Oklahoma City, Oklahoma (OKC); Dallas-Fort Worth, Texas (DFW); Chicago, Illinois (CHI); Saint Louis, Missouri (STL); and Tuscaloosa-Birmingham, Alabama (TBI). All metropolitan areas are represented by 160-km by 160-km boxes. Gridded 2010 population density (persons per kilometer squared) is provided for reference (CIESIN 2017).

count site) was considered to be under a watch or warning during a given hour if it spatially intersected any watch or warning polygon during that hour.

c. Traffic behavior and tornado watches and warnings

The first goal of this study was to assess differences between traffic volume under "normal" traffic conditions and those under a tornado watch or warning. We considered "normal" traffic days to be those that did not occur on a holiday or on a day with a weather warning that could have affected road conditions (e.g., heavy snow, dense fog, flooding, severe thunderstorms). To determine "normal" traffic volume at each site during each hour, we grouped the traffic data for all "normal" traffic days by day of the week and the month to take into account fluctuations in traffic volume throughout the week and the year and then calculated summary statistics (mean and 5th, 25th, 75th, and 95th percentiles) for the data. We calculated hourly traffic anomalies (the difference between the daily traffic volume and the mean) as both a count and as a percentage of the mean. To determine if the issuance of tornado watches and warnings influenced anomalies in traffic volume, we grouped anomalies in traffic volume, as a percent of the mean, into the following four categories for OKC, based on the presence or absence of tornado watches or warnings: no tornado watch or warning, tornado watch alone, tornado warning alone, tornado watch and warning. We then performed a Kruskal–Wallis test between the four groups at a 5% significance level to determine if there were any significant differences between the groups. We chose the Kruskal–Wallis test because it does not require normality and is well suited for comparisons between three or more groups (Kruskal and Wallis 1952). We also

TABLE 1. Information about metropolitan areas, including population and population density (persons per kilometer squared) in 2010, annual recurrence rate of EF2+ tornadoes, return period of EF4+ tornadoes in years, and the number of traffic volume stations. Population information is from CIESIN (2017). Tornado climatology is for the 1989–2018 climate period (Storm Prediction Center 2019).

Location	Population	Population density	EF2+ recurrence	EF4+ return period	No. stations
Omaha, Nebraska	1 193 535	46.6	1.3	10	33
Oklahoma City, Oklahoma	1 500 951	58.6	2.3	3.3	33
Dallas–Fort Worth, Texas	6 691 936	261.4	1.3	30	34
Chicago, Illinois	8 875 671	346.7	0.7	30	51
Saint Louis, Missouri	2 759 791	107.8	1.3	30	27
Tuscaloosa–Birmingham, Alabama	1 647 939	64.4	2	7.5	47

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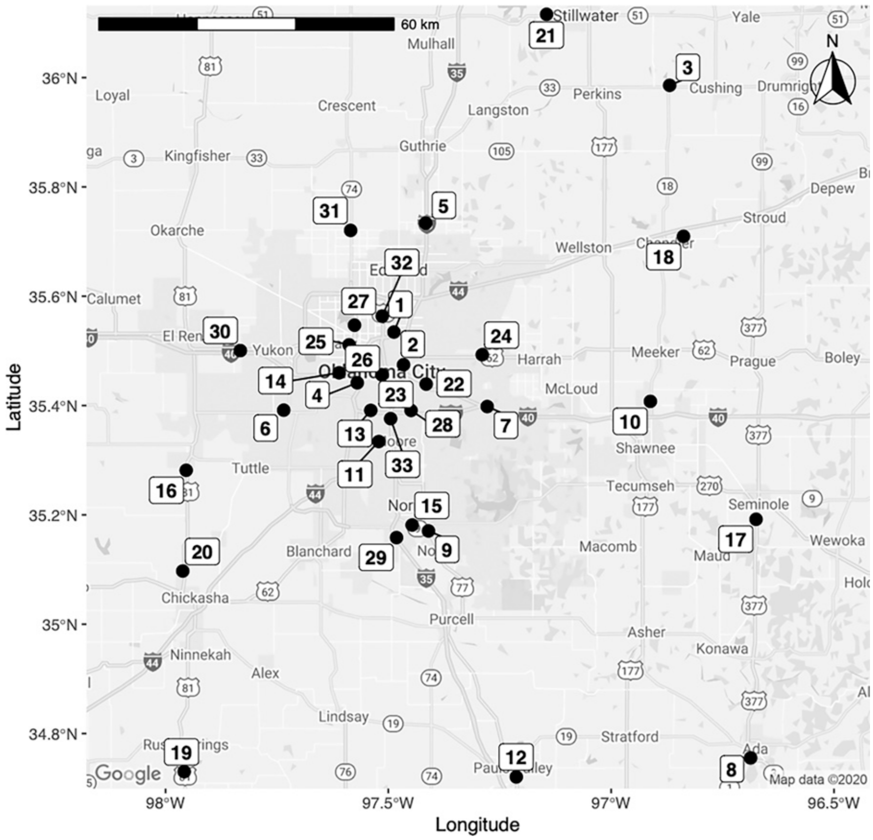

FIG. 3. Locations of traffic volume count stations within the Oklahoma City metropolitan area. The base map is provided through the courtesy of Google Maps (copyright Google 2021).

wanted to know if traffic behavior changed before the warning was issued (potentially under a watch). To determine this, we performed several paired Mann–Whitney tests with 5% significance levels between the following time periods relative to the issuance of a tornado warning: two hours before and one hour before, one hour before and the hour of, and the hour of and the hour after. We chose the Mann–Whitney test because it is commonly used in paired comparisons and does not require normality (Mann and Whitney 1947).

d. *Tornado evacuations*

Traffic is highly volatile and can change rapidly (Call 2011; Burow and Atkinson 2019); however, we theorize that sudden dramatic shifts in the primary direction of traffic flow typically only occur when many people are heading to and returning from a large event (e.g., football game) or are fleeing from some sudden, short-lived hazard (e.g., tornado) and then returning when it is safe. We refer to these sudden changes in the direction of traffic flow as anomalous traffic reversals (ATRs), and they occur when the traffic flow shifts from the top 5% of the normal traffic flow distribution to the bottom 5% or vice versa within a 3-h period in conjunction with a change in the sign (direction) of the flow. Values of traffic flow between −100 and 100 are considered too small (near the middle 50% of all traffic flows for OKC) to indicate a dominant traffic direction and thus are not counted as starting or ending points of an anomaly. We limit the reversal to occurring within a 3-h period as a visual inspection of the traffic flow data for 31 May 2013 in OKC showed that it can take several hours for the return flow to reach its peak after an evacuation. On days where an ATR begins during a tornado warning, we assume that the ATR is in response to that warning. Since we were interested in the occurrence of large-scale tornado evacuations, we define a mass ATR day as the co-occurrence of tornado warning induced ATRs at 20% or more of the traffic stations within a metropolitan area and assume this is indicative of a tornado evacuation (a mass evacuation signal). We chose 20% as the threshold as we wanted to ensure that there were ATRs at no fewer than five traffic stations in all metropolitan areas. Since we were interested in tornado evacuations, we limited the ATRs we considered to only those that occurred in conjunction with a tornado warning.

4. Results

a. *Traffic behavior and tornado watches and warnings*

To determine how tornado watches and warnings influenced anomalies in traffic volume, we performed a

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TABLE 2. Location information for traffic volume stations in the Oklahoma City metropolitan area, includes numbers corresponding to Fig. 3, station identifiers, physical locations, county, and annual average daily traffic (AADT) volume counts for each station. Here, SH indicates state highway and "U.S.-" indicates a federal route (1 mi. = 1.6 km; 1 ft = 30.5 cm).

No.	Site ID	Location	County	AADT
1	40AVC026	On I-44, 0.40 mi east of Kelly Avenue, in Oklahoma City	Oklahoma	62 717.9
2	40AVC056	On I-35, 0.40 mi south of NE 10th Street	Oklahoma	76 898.4
3	40AVC040	On SH-33, 0.50 mi east of SH-18, west of Cushing	Payne	6111.4
4	40AVC023	On I-44, 0.5 mi north of SW 29th Street, in Oklahoma City	Oklahoma	127 996.8
5	40WIM104	On I-35, 0.50 mi north of Waterloo Road	Logan	39 257.3
6	40AVC004	On SH-152, 0.55 mi west of SH-4, in Mustang	Canadian	18 384.7
7	40AVC067	On I-40, 0.80 mi east of I-240	Oklahoma	56 789.4
8	40WIM009	On SH-3, 1.10 mi east of SH-1, in Ada	Pontotoc	7682.4
9	40AVC002	On U.S.-77, 1.10 mi south of SH-9, in Norman	Cleveland	17 293.7
10	40AVC070	On SH-18, 1.62 mi north of I-40	Pottawatomie	8571.9
11	40AVC001	On SH-37, 1.70 mi west of I-35, in Moore	Cleveland	18 769.7
12	40AVC022	On U.S.-77, 1.74 mi south of SH-19, in Pauls Valley	Garvin	4765.6
13	40AVC061	On I-240, 2.00 mi east of I-44, in Oklahoma City	Oklahoma	106 223.9
14	40AVC007	On I-40, 2.00 mi west of I-44, in Oklahoma City	Oklahoma	105 824.1
15	40AVC003	On SH-9, 2.10 mi east of I-35, in Norman	Cleveland	31 486.5
16	40AVC033	On U.S.-81, 2.10 mi south of SH-37, south of Minco	Grady	4360.4
17	40AVC053	On SH-99, 2.10 mi south of U.S.-270, south of Seminole	Seminole	6862.0
18	40AVC047	On SH-66, 2.40 mi east of SH-18N, east of Chandler	Lincoln	4354.4
19	40WIM011	On U.S.-81, 2.46 mi south of U.S.-81B S, south of Rush Springs	Grady	7453.9
20	40AVC055	On U.S.-81, 2.50 mi north of U.S.-62, north of Chickasha	Grady	5177.0
21	40AVC032	On SH-51, 3.50 mi east of SH-51C, west of Stillwater	Payne	12 609.3
22	40AVC008	On I-40, 3.80 mi east of I-35, in Midwest City	Oklahoma	64 980.4
23	40AVC020	On I-35, 500 ft south of the Grand Ave (SE 36th Street) Bridge	Oklahoma	120 049.8
24	40AVC005	On U.S.-62, 9.75 mi east of I-35, in Choctaw	Oklahoma	15 026.9
25	40AVC006	On 39th Street (SH-66), 1.00 mi west of I-44, in Oklahoma City	Oklahoma	36 315.3
26	40AVC072/3	On I-40 Crosstown, EB 265 ft west of Shields Boulevard OP	Oklahoma	51 644.6
27	40AVC065	On Hefner Parkway, 0.70 mi north of 63rd Street Bridge, OKC	Oklahoma	107 930.3
28	40WIM003	On I-240, 2.57 mi east of I-35, in Oklahoma City	Oklahoma	55 205.7
29	40WIM030	On I-35, 0.47 mi west of SH-74	McClain	48 058.6
30	40WIM028	On I-40, 300 ft west of Gregory Road	Canadian	49 063.1
31	40AVC071	On SH-74, 0.32 mi south of Waterloo Road	Oklahoma	8462.1
32	40AVC024	On U.S.-77, 0.1 mi south of Britton Road	Oklahoma	86 961.2
33	40AVC069	On I-35, at south end of SE 89th Street Bridge	Cleveland	112 558.4

Kruskal–Wallis test between the following four categories for OKC, based on the presence or absence of tornado watches or warnings: no tornado watch or warning, tornado watch alone, tornado warning alone, tornado watch and warning. We found that the difference between the four groups was highly significant ($p < 0.001$) with reduced traffic volume occurring during tornado-warned hours for OKC.

To determine the timing of the changes in the anomalies in traffic volume we compared the anomalies for the 2 h before and after the tornado warning was issued via several paired Mann–Whitney tests. We found that the anomalies were not significantly different ($p > 0.05$) before the warning was issued while they were highly significant ($p < 0.001$) after. We also compared the anomalies in traffic volume between the hours before and after a tornado warning was issued. The timing of the changes in traffic volume can also be seen in Fig. 4 for four prominent tornado days (24 May 2011, 19 May 2013, 20 May 2013, and 31 May 2013) at one particular traffic station in OKC. For each of the four days, there is a clear reduction in traffic volume that occurs during the warned period (pink shaded area).

b. Mass ATR days

To determine the frequency of mass ATR days during the 2011–18 period for OMA, OKC, DFW, CHI, STL, and TBI we identified ATRs within the traffic flow data. An example of an ATR can be seen in Fig. 5d between 1700 and 2200 CDT on 31 May 2013. We found days with ATRs in all six metropolitan areas with DFW and OKC having the most: 26 and 24 days, respectively (Table 3). Figure 6 shows the traffic station locations (open circles) as well as those in ATR (closed circles) for each day and metropolitan area with at least five ATRs [TBI on 27 April 2011 and 22 December 2011 (Figs. 6a,c, respectively); OKC on 24 May 2011, 19 May 2013, and 31 May 2013 (Figs. 6b,d,e, respectively); DFW on 10 May 2015 (Fig. 6f)]. Only OKC had mass ATR days (24 May 2011, 19 May 2013, and 31 May 2013), but DFW and TBI had at least one day with more than five stations with ATRs. The date with the greatest number of stations with an ATR (14)

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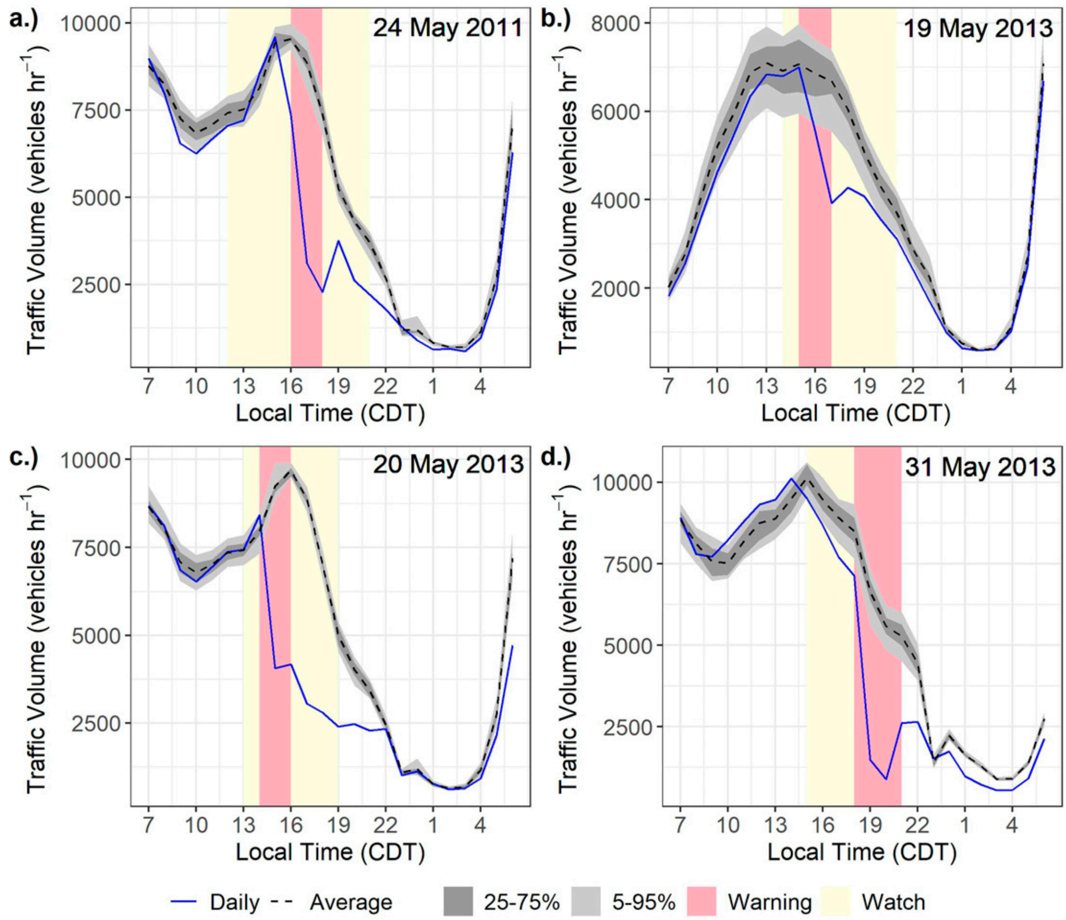

FIG. 4. Hourly traffic volume at traffic station 40AVC020 (on I-35, south of the Grand Avenue Bridge in Oklahoma City) for (a) 24 May 2011, (b) 19 May 2013, (c) 20 May 2013, and (d) 31 May 2013. The solid blue line represents the daily traffic volume, and the black dashed line represents the average daily traffic for the day of the week and the month matching the specified date (i.e., since 31 May 2013 was a Friday, the average would be for all Fridays in the month of May). The light-gray shading corresponds to the 5–95 percentiles of the traffic volume distribution, and the dark-gray shading corresponds to the 25–75 percentiles. The yellow and red background shadings refer to the hours during which a tornado watch and tornado warning were active, respectively.

was 31 May 2013. Figure 7 shows the traffic flow at each north–south-oriented traffic station between 1600 and 2200 CDT on 31 May 2013 and how the traffic flow becomes dominantly southbound (negative) by 1800 CDT 31 May 2013 (Fig. 7b) indicating the beginning of the evacuation and shifts to dominantly northbound (positive) by 2000 CDT 31 May 2013 (Fig. 7c) indicating the beginning of the return flow. Figure 8 shows the total combined northbound flow over all north–south-oriented stations for each day and metropolitan area with at least five ATRs. It is clear that 31 May 2013 stands out in terms of both the length and magnitude of the southbound flow (Fig. 8e) as well as in the number and distributions of the stations with ATRs (Fig. 7e). Figure 9 shows the progression of the starting time for the ATRs at each station with an ATR in OKC on 31 May 2013 (Fig. 9a) as well as the dominant traffic direction at the time when the ATR began (Fig. 9b). We can see that the most common time for the ATR to begin was at 1800 CDT, the hour when the El Reno tornado formed and the media warning to "go south" was issued. The dominant directions of travel once the ATRs began were to the south and east (away from the tornado); however, for some locations to the north, the dominant direction was away from the metropolitan area to avoid heavy traffic and still get away from the storms.

5. Discussion

Our study on the 31 May 2013 tornado evacuation was the first to look at the frequency of tornado evacuations (as represented by mass ATR days) within the United States using traffic volume data (FHWA 2019). We confirmed the findings of Garfield and Smith (2014) that traffic volume does respond to tornado warnings with traffic volume typically decreasing after a warning is issued. This finding likely indicates that people are responding to the tornado warnings by getting off the road and hopefully into buildings as recommended by the

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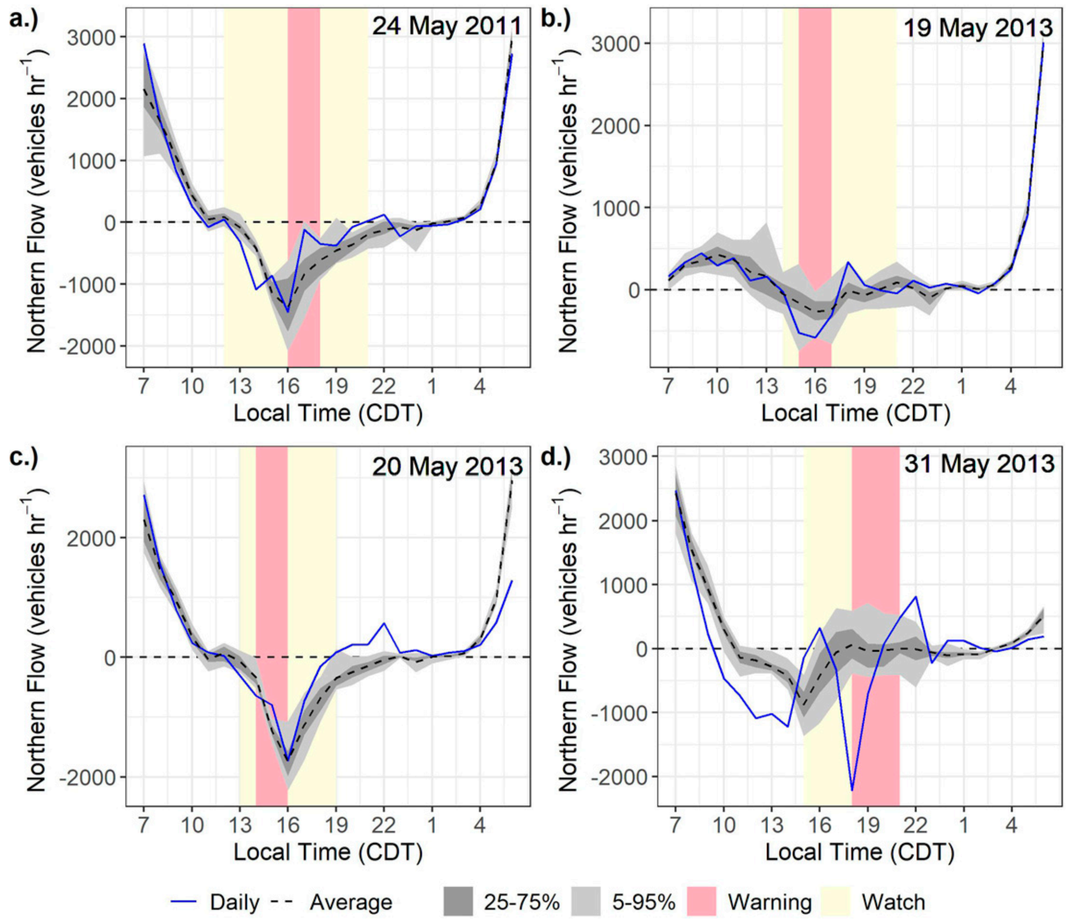

FIG. 5. As in Fig. 4, but for the difference between the northbound and southbound traffic volumes, expressed as northbound traffic flow with positive values indicating that the flow is dominantly to the north and negative values indicating that the flow is dominantly toward the south.

NWS (Farley 2007; Edwards 2018). It is possible that some of these reductions could be due to traffic jams, however, we expect that traffic jams large enough to cause significant traffic volume reductions for a whole hour are rare. Even in the most congested cities in the United States, traffic congestion adds less than 20 min per day on average (based on 2017 data; Willingham 2019). Our finding that traffic volume tends to not change until after a warning is issued is in line with research

TABLE 3. Number of days with ATR signals at one or more traffic stations for each metropolitan area and number of days with tornado evacuations (defined as days on which at least 20% of the traffic stations within a metropolitan area have an ATR signal).

Location	ATR days	Evacuation days
OMA	16	0
OKC	24	3
DFW	26	0
STL	5	0
CHI	11	0
TBI	18	0

that people tend to wait and confirm that there is actually a threat before reacting to a watch or warning (Kugliowski et al. 2013; Wood et al. 2018). While reductions in traffic volume that coincide with ATRs (e.g., Figs. 4 and 5) may appear to counter the idea that an evacuation is taking place these reductions may be indicative of traffic jams, where the total traffic volume drops suddenly because traffic is moving very slowly if at all. While we assume that traffic jams that significantly affect traffic for an hour are rare, they may be more common during an evacuation when more cars are on the road. For example, on 31 May 2013, the traffic volume at station 40AVC020 (Fig. 4d) drops more rapidly (7133–888 vehicles per hour) than usual (8509–5593 vehicles per hour) for a Friday in May between 1800 and 2000 CDT. Note also that evacuations for different hazards have significantly different response rates with the number of people indicating they would evacuate for a tornado (e.g., 16%–18% of survey respondents would leave home to get away from the tornado; Schultz et al. 2010; Durage et al. 2014) significantly lower than those who would evacuate for a hurricane (e.g., 68%–85% for a major hurricane; Meyer et al. 2018). With the evacuation response for tornado warnings so much

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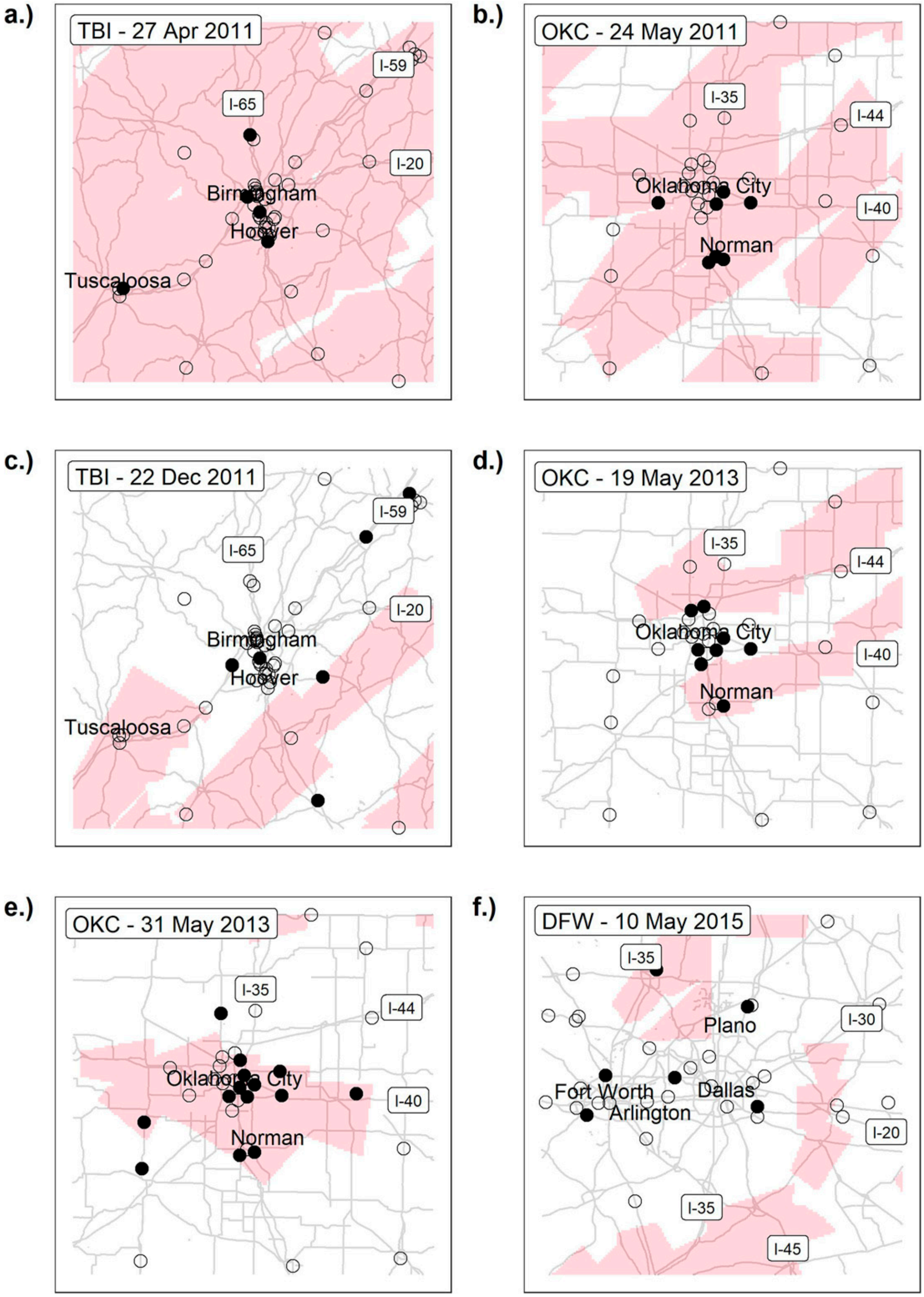

FIG. 6. The locations of all traffic stations in each of the six metropolitan areas with at least five ATRs on a single day. The stations that are in ATR on the specified date are filled in black (6 for TBI on 27 Apr 2011, 7 for OKC on 24 May 2011, 6 for TBI on 22 Dec 2011, 8 for OKC on 19 May 2013, 14 for OKC on 31 May 2013, and 6 for DFW on 10 May 2015) whereas all others are not filled. The red shading indicates areas that were under tornado warnings for some part of the day.

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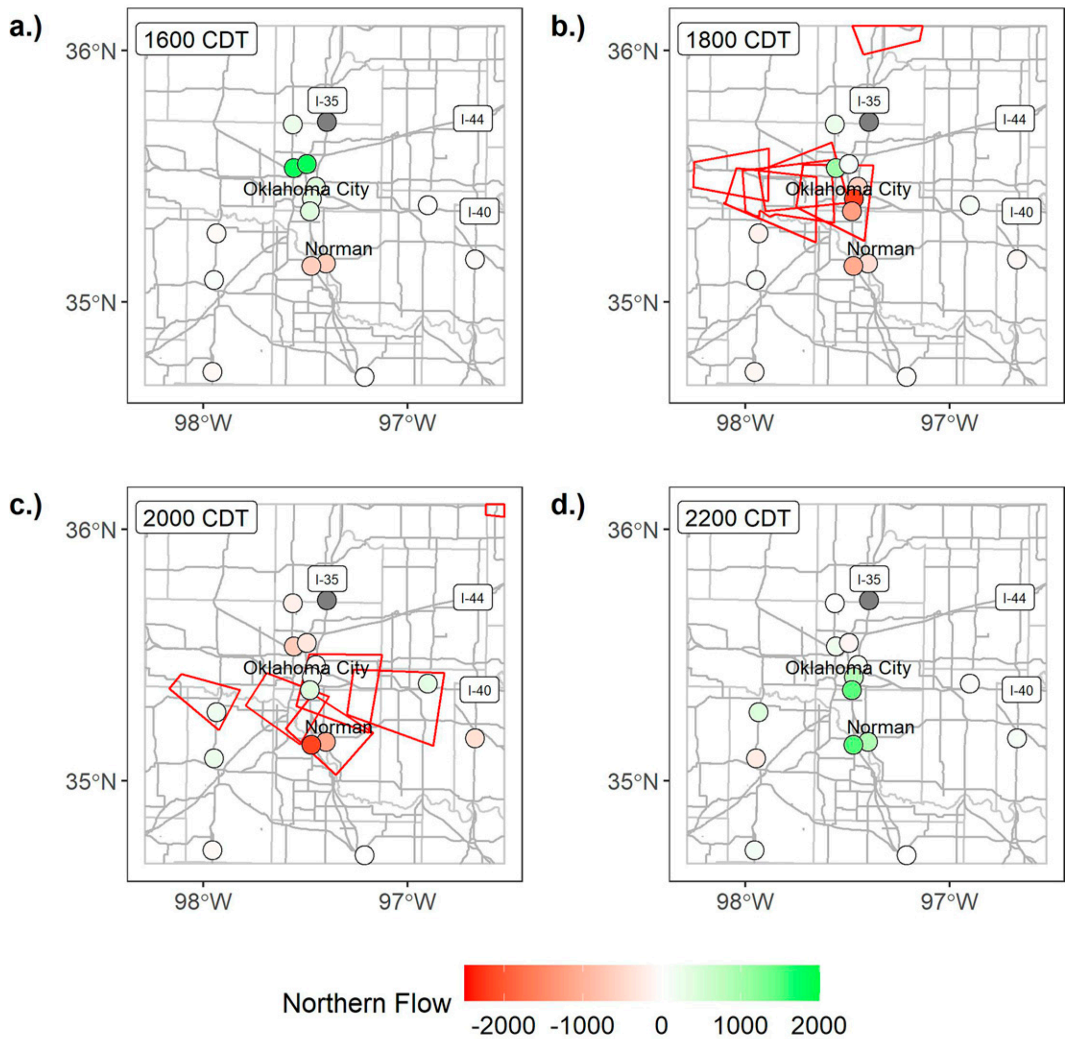

FIG. 7. The northbound traffic flow at each north–south-oriented traffic station in OKC for the following hours on 31 May 2013: (a) 1600, (b) 1800, (c) 2000, and (d) 2200 CDT. Gray dots show stations for which the data were not available, and red polygons correspond to tornado warnings active during the hour.

lower it is possible for a tornado evacuation to occur with lower-than-normal traffic volume as long as the traffic flow dominates in the direction opposite the tornado.

The mass ATR day on 31 May 2013 in OKC stands out among all other mass ATR days that occurred between 2011 and 2018 in the six metropolitan areas studied. The number of stations with an ATR was nearly double that of all other days (Table 3) and the overall traffic flow for all north–south-oriented traffic stations in OKC was dominantly southbound for 3 h with a magnitude and duration far higher than any other mass ATR day (Fig. 9). This is likely a result of the unique set of circumstances occurring on this day: two weeks of severe weather threats including three EF4+ tornadoes (Uccellini et al. 2014), the fear that was still fresh from the EF5 tornado that hit Moore on 20 May 2013, killing 24 people (Kurdzo et al. 2015), and an unconventional warning from the media to evacuate or risk death (Uccellini et al. 2014).

The primary limitations of this study were the length of the traffic record (8 years), the size of the study area, and the frequency of the traffic volume data (hourly). The FHWA traffic volume dataset is the only one available for the entire United States, and while tornado warnings often last less than an hour (Brooks and Correia 2018), the hourly data were sufficient to identify at least one case of known tornado evacuation. Future studies will look into acquiring 15-min-frequency traffic volume data to potentially better ascertain smaller-scale evacuations across other places. These data are available from some state departments of transportation (DOT); however, based on the availability of the data from the Oklahoma Department of Transportation, it may only be possible to get the most recent five years of data. State DOTs use the traffic volume data for maintaining the road networks and placing traffic control devices and thus do not require long-term traffic records (FHWA 2016). Future studies will also look into

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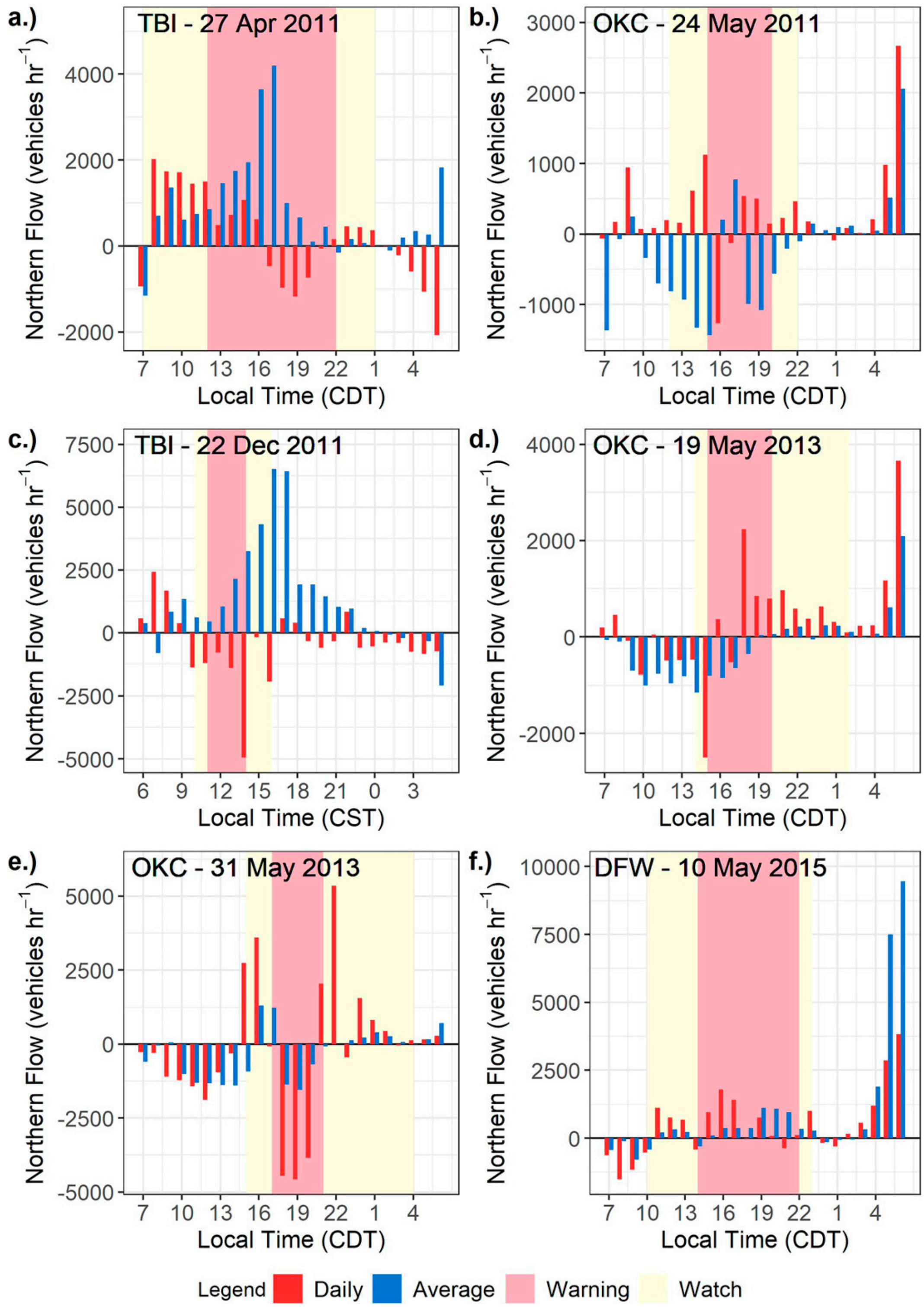

FIG. 8. The overall northern traffic flow for the six metropolitan areas with at least five ATRs. The red bars represent the daily traffic flow, and the blue bars represent the average traffic flow. The yellow and red shading represent hours with tornado watches and tornado warnings in the respective metropolitan areas.

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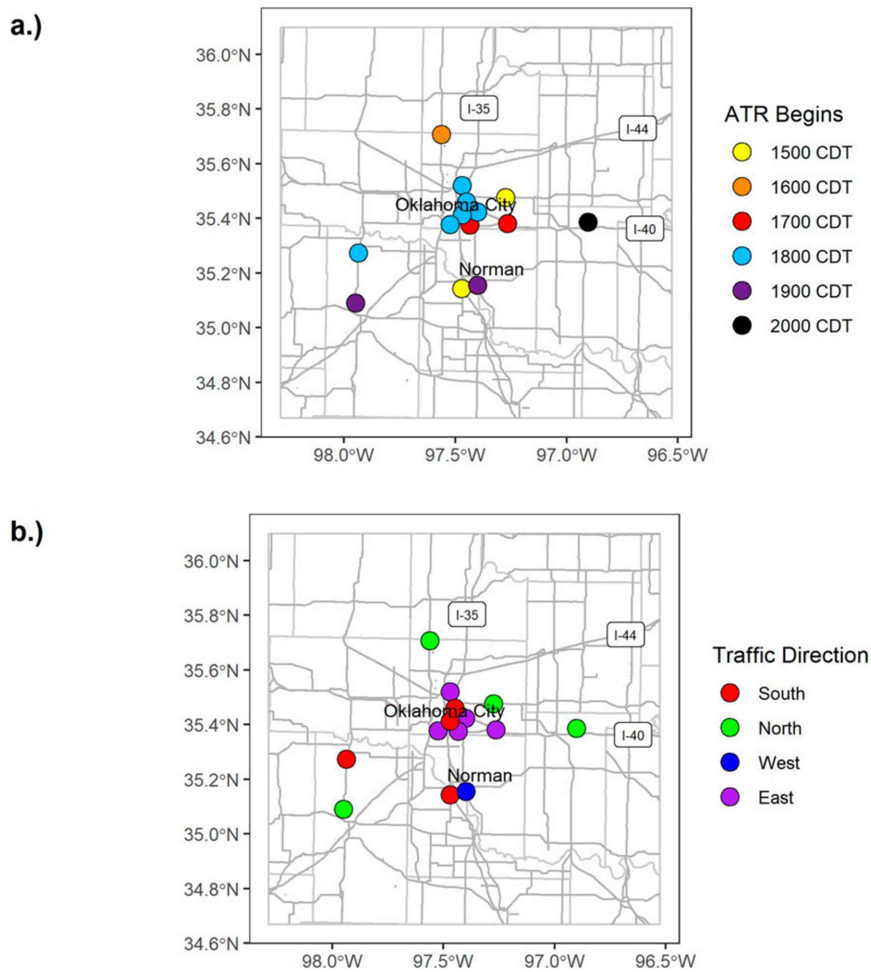

FIG. 9. (a) Timing of the beginning of the ATRs for all traffic stations with an ATR in OKC on 31 May 2013, and (b) dominant traffic direction at the hour during which the ATR began.

expanding the study area to cover all metropolitan areas within the continental United States to determine if there are any variations in the frequency of ATRs and mass ATR days across the country. The inability to conclusively distinguish between sparse traffic and traffic jams was also a limitation in this study. We showed that there was a traffic response to the warnings, however, we could not be certain traffic was actually decreasing during tornado warnings. Future studies will look into obtaining loop detector occupancy data to determine if traffic is truly sparse.

Another limitation is in the definition of the ATR. While ATRs do appear to capture the evacuation that occurred on 31 May 2013 in OKC, ATRs can occur when any major event occurs that would draw people to a single location and then have them travel back to their homes or jobs (e.g., Fourth of July fireworks displays). We do not know with certainty that ATRs occurring during tornado warnings are actually in response to the warning. It is possible that there were events that coincided with the warning that were prompting travel. We can also see from Fig. 9 the variation in the timing of the beginning of the ATRs in OKC on 31 May 2013 and the pattern is inconsistent with the timing of the tornado. The ATRs began in the northern and eastern part of the city first and then progressed to the west; however, the storms began in the west and moved east. It is possible that people were not considering evacuation until the storms got closer to Oklahoma City and that people on the eastern edge of the metropolitan area were the first to succumb to fear and start evacuating; however, it seems unusual that the stations in the west were not the first to evacuate. Despite this, we believe the ability of the ATR to capture the 31 May 2013 evacuation argues for its validity as a measure of tornado evacuation behavior. Future work will look at the thresholds used for the ATRs to see if changing the threshold to the top 1% of flow (or other thresholds) changes the timing patterns for the ATRs on 31 May 2013.

A final limitation on this study is that we have no way to quantify the number of people who actually evacuated during the 31 May 2013 tornado evacuation. No records were taken of the number of people fleeing and it would have been

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impossible to determine which cars on the road were fleeing versus those that were just traveling to some destination. Unlike in cases of mandatory evacuation where most people flee and it is safe to assume that all anomalous traffic is evacuation traffic (Li et al. 2013), in the case of a spontaneous evacuation, such as that for a tornado, we cannot discern evacuation traffic from local traffic through the traffic data. We know that many people were fleeing from the storm leading to gridlocked traffic in many places through the NWS assessment report (Uccellini et al. 2014) and through various news stories (Admin 2013; Cooper 2013; Mannette 2013; Fox News 2015), but the exact magnitude of the evacuation is unknown.

The 31 May 2013 evacuation in OKC did not result in any casualties among the evacuees, since the El Reno tornado dissipated west of the densely populated areas of OKC (Bluestein et al. 2015) and no other major tornadoes hit OKC during the period of the evacuation (Storm Prediction Center 2019). However, the supercell that produced the El Reno tornado did continue to track eastward over the more populated parts of OKC and could have potentially produced another major tornado. Garfield and Smith (2014) conservatively projected that if a tornado the same size and intensity as the El Reno tornado had formed in the outskirts of OKC and hit evacuation traffic killing half of the drivers within the 200-m-wide EF4+ wind swath, the casualty count among the drivers could have been 225, making this hypothetical tornado at least the fourth deadliest in recorded history for the United States (Grazulis 1993; Storm Prediction Center 2019). Although fleeing from the path of a tornado is sometimes advisable (e.g., if one lives in a mobile home or a weak structure), it is not advisable for most people because the odds of death in a destroyed building are still only 1%–2% for permanent homes in EF5 tornadoes, let alone weak tornadoes (Brooks et al. 2008; Prevatt et al. 2012), while the odds of a car being lofted in a violent tornado are 18%–31% (Paulikas et al. 2016). Advising an audience that is already on edge from 2 weeks of nearly continuous severe weather and tornadoes (Uccellini et al. 2014) that they need to flee if they cannot get belowground is unwise and may lead to a fear-based response and maladaptive behavior, putting many lives at unnecessary risk.

6. Conclusions

On 31 May 2013, a violent tornado hit near the town of El Reno in the far west of the Oklahoma City metropolitan area prompting a mass evacuation throughout the metropolitan area leading to traffic jams for hours and putting many lives at risk (Uccellini et al. 2014). This evacuation (as represented by the mass ATR day) was extremely anomalous with no other mass ATR day, occurring between 2011 and 2018 in Oklahoma City, Dallas–Fort Worth, Omaha, Saint Louis, Chicago, or Tuscaloosa–Birmingham, coming close to its duration or magnitude. The 31 May 2013 tornado evacuation in Oklahoma City was likely the cause of a set of unique events including a heightened state of fear due to very recent violent and deadly tornadoes combined with media warnings that sheltering in place was unsafe unless the shelter was belowground. While the circumstances surrounding the 31 May 2013 evacuation were unique, the potential consequence of a violent tornado hitting a gridlocked road network is severe enough that it needs to be considered as a part of mitigation efforts. Efforts should be redoubled to educate the public on the eminent survivability of even violent tornadoes from within sturdy buildings (Brooks et al. 2008; Hatzis et al. 2019). It is also vital that the media promotes these lessons and recommends more local sheltering options for those who truly live in vulnerable housing.

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Data availability statement. Data analyzed in this study were a reanalysis of existing data, which are openly available at locations cited in the reference section. Further documentation about data processing is available upon request from author Joshua J. Hatzis (joshuajhatzis@gmail.com).

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