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Implications of the 2011 Tuscaloosa EF4 tornado for shelter and refuge decisions

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Abstract This research provides an overview and discussion of language used in tornado safety recommendations along with development of a rubric for scaled tornado safety recommendations. Residents living in affected areas and those temporarily housed at relief stations were surveyed to collect information on their experiences during a 2-week period following the April 27, 2011 Tuscaloosa, Alabama EF4 tornado. Respondents were asked about their refuge plans during the storm and about any future changes to those plans. A specific focus of this research evaluated the adequacy of each respondent's plan. Each refuge plan was compared using a tornado refuge rubric developed through the use of enhanced Fujita (EF) scale degree of damage ratings for available damage indicators. There was a significant difference in the counts of refuge adequacy for Tuscaloosa residents when holding the locations during the April 27 tornado constant and comparing adequacy ratings for weak (EF0–EF1), strong (EF2–EF3), and violent (EF4–EF5) tornadoes. There was also a significant difference when comparing the future tornado refuge plans of those same participants to the adequacy ratings for weak, strong, and violent tornadoes. This research introduces renewed discussion on proper refuge and shelter alternatives for days when violent tornadoes are forecasted.

Keywords Shelter · Refuge · Adequacy · Tornado · Safety

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1 Introduction

Despite advances in radar technology (Simmons and Sutter 2005), warning lead time (Erickson and Brooks 2006; Hoekstra et al. 2011), probability of tornado detection (Simmons and Sutter 2011), construction practices, and building codes (FEMA 2012), 553 lives were lost in the USA in 2011 as a result of tornadoes. This ranked behind only 1925 (794) in the number of tornado fatalities (NWS Storm Prediction Center 2012a). The high number of tornado fatalities was primarily a result of the anomalous number of tornadoes in densely populated areas, yet other factors such as false alarms from previous events (Simmons and Sutter 2009) may have also contributed to the record number of fatalities in the modern weather warning era.

Refuge and sheltering location for tornadoes was a potential latent factor for fatalities in 2011, a subject which has been poorly represented in the literature. A recent publication (FEMA 908) from The United States Federal Emergency Management Agency (FEMA) discussed many aspects of tornado safety and building failure. Refuge, specifically the term "tornado refuge area," is defined in FEMA 908, chapter 1, page 12 (2012) as:

> "A general term used to describe any location where people go to seek cover during a tornado. Tornado refuge areas may have been constructed to comply with basic building code requirements that do not consider tornado hazards. These areas may also have continuous load paths, bracing, or other features that increase resistance to wind loads. It is important for people to know that such an area may not be a safe place to be when a tornado strikes and they still may be injured or killed during a tornado event."

In contrast, "shelter" is defined by FEMA 908 as an area designed to provide protection from severe weather events. These areas can be in the form of hardened areas designed and constructed to provide some level of protection or storm shelters and safe rooms designed following FEMA guidelines. "Shelter" often refers to actual storm shelters, which are described as areas which provide life-safety protection and are designed and constructed to meet International Code Council (ICC) 500 criteria for safe rooms which provide near-absolute protection in addition to criteria in FEMA 361 (2000) and FEMA 320 (1999). FEMA 361 and FEMA 320 are both publications that describe the proper specifications for building residential, small business or community safe rooms. Hence, from this point forward in the manuscript, refuge will refer to actions or locations that are either unsafe or not completely safe while shelter implies a threshold of protection based on a design standard.

Tornado intensity is not known a priori; however, the NOAA/NWS Storm Prediction Center (SPC) provides daily tornado and other severe weather probability in the form of high, moderate, and slight risk outlooks (available at: http://www.spc.noaa.gov/products/outlook/). An additional product produced by the SPC is a "public watch" with explicit hazard information. This product features a probability table outlining the likelihood of various hazards, including the possibility of EF2–EF5 tornadoes and the possibility of multiple tornadoes (Probabilities tab at: www.spc.noaa.gov/products/watch/). Although forecasting the number and intensity of tornadoes across a region for a tornado outbreak will always contain inherent uncertainty, this uncertainty has been greatly reduced in recent years (Vescio and Thompson 2001; Hitchens and Brooks 2012). The performance of the SPC in forecasting the April 27, 2011, tornado outbreak was particularly impressive (Fig. 1). Accurate deterministic forecasting for smaller and weaker tornado outbreaks is more ambiguous and difficult; however, these weaker events are less of a risk to public safety. Thus, we are now at a point where we can forecast the probability of a day with violent tornadoes with enough certainty so that residents may seek shelter options in advance instead of refuge options after a tornado warning is issued.

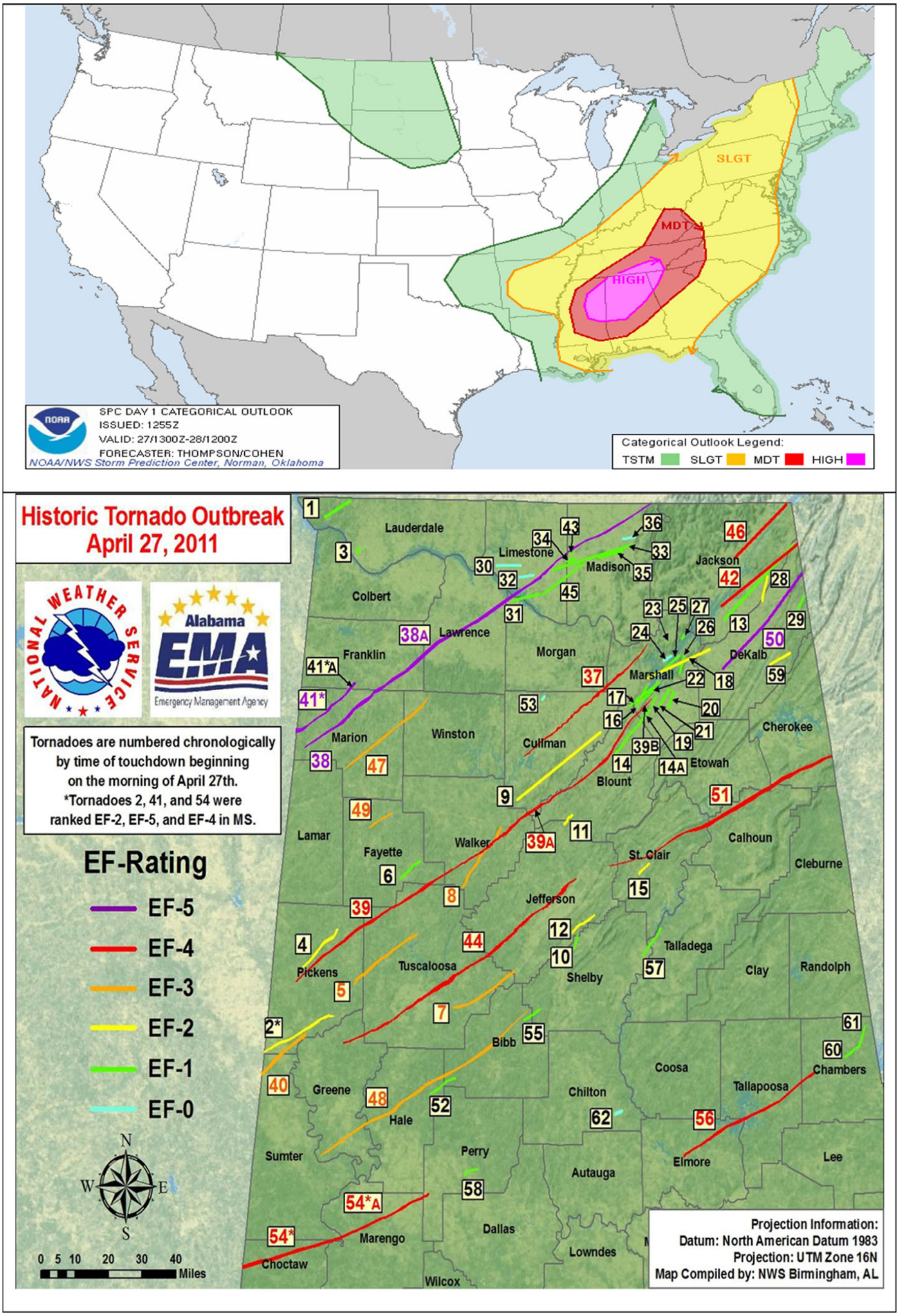


Fig. 1 (*Top*) Day 1 SPC convective outlook issued at 1255 UTC 04/27/2011 showing a rarely issued high risk for severe weather. (*Bottom*) Tornado tracks and ratings in the state of Alabama on 04/27/11 showing the accuracy of the SPC forecast. (SPC and NWS Birmingham, AL)

Successfully obtaining shelter and refuge for tornadoes depends on the intensity of the tornado, the amount of lead time and the availability of safer structures within walking or driving distance. These three primary factors help to define situational refuge, but residents under a tornado warning may not adequately consider the issue of safer refuge options depending on the situation. Instead, most residents (Senkbeil et al. 2012) follow common recommended refuge language found in many outlets if any plan is used at all. Recommended refuge plans are often not the wisest course of action on days when strong to violent tornadoes are likely.

In an effort to reduce future fatalities, this research seeks to perform the following:

1. Examine the language used in current tornado safety recommendations from various sources
2. Propose and discuss a system of classifying the tornado refuge adequacy of structures based on tornado intensity forecasts for each event
3. Examine the adequacy of refuge and shelter plans and locations from surveys of Tuscaloosa, Alabama residents following the April 27, 2011, EF4 tornado

2 Current tornado safety recommendations and language

There are multiple sources of recommended action to take while under threat of a tornado, many of which are reviewed and discussed in Farley (2007). A publication from the National Weather Service (No Date) (Thunderstorms, Tornadoes, and Lightning: Nature's Most Violent Storms (http://www.nws.noaa.gov/om/severeweather/resources/ttl6-10.pdf)) outlines a hierarchy of tornado safety actions, beginning with an underground shelter, basement or safe room. If these are not available, the publication advises residents to choose an interior room on the lowest level of a sturdy building. Additionally, this webpage recommends driving if a person cannot quickly walk to a sturdy building. As a last resort, the recommendation is made to pull over and park if presented with flying debris while driving, with the seat belt on and head down below the windows, unless a person can get "noticeably lower" than the level of the roadway, in which case you should exit the car and lie in that area. A publication from the National Oceanic and Atmospheric Administration (NOAA) entitled "Tornadoes 101" (NOAA No Date (a) http://www.noaa.gov/features/protecting/tornados101.html) advises the public to seek underground shelter in a home or building, but if none is available, moving to an interior room or hallway on the lowest floor under a sturdy piece of furniture. This source also recommends abandoning vehicles and lying flat in a nearby ditch or depression. Additional advice is available from the SPC's tornado safety tips (Edwards 2012), which advises abandoning mobile homes for a storm shelter, sturdy building or lying flat on the ground away from mobile homes, trees and cars. Edwards (2012) and the SPC also address the vehicle issue by recommending people drive away from a tornado if it is far away and the traffic is light by moving at right angles to the tornado. This source also provides recommended actions if a tornado starts to hit your car, instructing the reader to "get as low as you can while staying in your seatbelt and leaning down and away from the windows and windshield as far as possible." The American Red Cross released a joint official tornado safety policy in conjunction with the NWS during 2009 which recommends seeking shelter in an underground shelter, basement or safe room immediately after hearing a tornado warning. It also recommends that if you are caught outdoors and are unable to reach one of these shelter options, you should get into a vehicle and drive to a shelter, unless your vehicle is hit by flying debris, in which case you should pull over, park, keep your safety belt on and cover your head with your hands, blanket, jacket or some other cushion. The advice goes on to recommend leaving your car if you can safely get "noticeably lower" than the level of the road, after which you should lie in that area, covering your head with your hands (American Red Cross 2009). Another webpage from NOAA (No Date (b)) (http://www.outlook.noaa.gov/tornadoes/q%26a.htm) recommends taking refuge in a basement or interior room under a sturdy piece of furniture and advises against trying to outrace a tornado; instead, advising residents to lie down in a ditch or depression. No mention is made of safe rooms in this NOAA publication or the NOAA publication referenced earlier, although underground shelters are mentioned; however, safe rooms are mentioned in the Edwards (2012) SPC source. Of particular importance to Tuscaloosa residents would be tornado safety advice found on the website for the Birmingham, AL NWS office, which advises residents to use basements or small, interior rooms on the lowest floor of homes or public buildings, but makes no mention of tornado shelters or safe rooms (Birmingham, AL NWS 2012).

The inconsistencies and ambiguities from these sources are evident. There are two salient points made in these recommendations that are either absent or contradicted in literature. The first, seeking refuge in a ditch or depression has never been shown to be safer than a vehicle (Brenner and Noji 1993; Schmidlin et al. 2002). There are multiple instances discussed in Farley (2007) where ditch refuge has resulted in death, either from being hit by a vehicle or other object. Also, in the case of the May 3, 1999, Oklahoma City tornado, abandoning a vehicle was found to be more dangerous than fleeing a tornado in a vehicle (Daley 2005). This recommendation for not abandoning a vehicle is also supported by research from Schmidlin (1997) and Schmidlin et al. (2002); however, the number of fatalities in vehicles has been higher than outside fatalities since 2004 (Table 1). Research by Hammer and Schmidlin (2000) also shows vehicle safety features are the most significant determining factor in vehicle deaths in tornadoes, further supporting the case for remaining inside a vehicle.

On the evening of April 27, 2011, an EF4 tornado struck the city of Tuscaloosa, Alabama, leaving an 80.68-mile (129.84 km) path, along with 65 fatalities and over 1,500 injuries. This tornado had an estimated maximum wind speed of 190 miles per hour (306 kph), with a maximum path width of 1.5 miles (2.4 km) The tornado formed at approximately 21:43 UTC and dissipated at approximately 23:14 UTC (Birmingham, AL NWS 2013).

Specifically in the case of Tuscaloosa, the entire precautionary/preparedness actions section of the tornado warning bulletin from the Birmingham, AL NWS, read:

> Take cover now. For your protection move to an interior room on the lowest floor of a sturdy building (Birmingham, AL NWS 2011).

The definition of sturdy is up to the discretion of the resident, and no specific examples are provided. Also, no distinction is made between the lowest floor of a sturdy building being a basement or the first floor. Although data from the Tuscaloosa tornado regarding fatalities do not specify whether the deceased individual was in a basement or on the first floor, it is assumed that taking refuge in a basement would increase one's likelihood of survival, though this option was omitted in the tornado watch and warning statements. This statement was issued at 21:47 UTC on April 27, 2011, and allowed for a lead time of approximately 65 min (FEMA 2012). The particularly dangerous situation (PDS) tornado watch was issued by the SPC for portions of Alabama, Georgia, Mississippi and Tennessee at 18:45 pm UTC on April 27, 2011, 4 h and 7 min before the tornado struck Tuscaloosa.

Table 1 Locations of tornado fatalities in the USA for the four major location categories through December 1, 2013

Year	Total	Homes or buildings	Percentage	Manufactured homes	Percentage
1991	39	5	13	16	41
1992	39	16	41	21	54
1993	33	10	30	13	39
1994	69	33	48	25	36
1995	30	9	30	11	37
1996	26	8	31	14	54
1997	68	27	40	30	44
1998	130	47	36	64	49
1999	94	45	48	36	38
2000	41	6	15	29	71
2001	40	18	45	17	43
2002	55	16	29	32	58
2003	54	24	44	25	46
2004	35	24	69	9	26
2005	38	3	8	32	84
2006	67	32	48	28	42
2007	81	27	33	49	60
2008	126	50	40	55	44
2009	22	8	36	12	55
2010	45	13	29	19	42
2011	553	322	58	112	20
2012	69	17	25	48	70
2013	51	29	57	13	25
Total	1,805	760	42	697	39

Year	Total	Outside	Percentage	Vehicle	Percentage
1991	39	14	36	4	10
1992	39	0	0	0	0
1993	33	3	9	7	21
1994	69	5	7	3	4
1995	30	3	10	4	13
1996	26	1	4	3	12
1997	68	7	10	3	4
1998	130	3	2	16	12
1999	94	7	7	6	6
2000	41	2	5	4	10
2001	40	2	5	3	8
2002	55	3	5	4	7
2003	54	4	7	1	2
2004	35	0	0	2	6
2005	38	1	3	2	5
2006	67	0	0	7	10

Table 1 continued

Year	Total	Outside	Percentage	Vehicle	Percentage
2007	81	1	1	4	5
2008	126	3	2	18	14
2009	22	0	0	1	5
2010	45	6	13	7	16
2011	553	7	1	34	6
2012	69	2	3	2	3
2013	51	0	0	9	18
Total	1,805	74	4	144	8

On May 22, 2011, Joplin, Missouri was struck by an EF5 tornado with estimated maximum wind speeds in excess of 200 mph, causing 158 fatalities and over 1000 injuries. This tornado had a path length of 22.1 miles (36 km) and a path width ranging from .75 miles (1.2 km) to 1 mile (1.6 km). The tornado formed at 22:34 UTC and dissipated at 23:12 UTC (Springfield, MO NWS 2012). In comparison with the Tuscaloosa tornado warning statement, the warning statement for the Joplin, Missouri tornado contained the following precautionary/preparedness actions from the Springfield, MO Weather Forecast Office:

> The safest place to be during a tornado is in a basement. Get under a workbench or other piece of sturdy furniture. If no basement is available…seek shelter on the lowest floor of the building in an interior hallway or room such as a closet. Use blankets or pillows to cover your body and always stay away from windows.
>
> If in mobile homes or vehicles…evacuate them and get inside a substantial shelter. If no shelter is available…lie flat in the nearest ditch or other low spot and cover your head with your hands. (Springfield, MO NWS 2011).

In the case of the Joplin tornado, a tornado watch was issued at 18:30 UTC and effective until 21:00 UTC, 4 h and 4 min prior to the tornado impacting Joplin. The tornado warning was issued at 22:17 UTC and effective until 23:00 UTC. At approximately 22:34 UTC, the tornado touched down, allowing for about 17 min of lead time, with an additional 2 min until the tornado entered the Joplin city limits (Springfield, MO NWS 2012).

These two warning statements illustrate the trade-off between information content and statement length. Because tornado warning lead time currently averages 13 min (NOAA No Date (a) http://www.noaa.gov/features/protecting/tornados101.html), the seconds used by a longer statement are very valuable, and however, the statement should also contain enough information for a listener to choose their best available refuge location. The TWS seeks to address this dilemma by providing safety recommendations hours in advance of a tornado warning, providing ample time to consider all available refuge/shelter options.

The NWS may also issue a “tornado emergency,” which is broadcast in the same manner as a tornado warning and used to indicate a confirmed, likely strong or violent, tornado (NOAA No Date (c)). This statement also indicates a, “severe threat to human life and catastrophic damage from an imminent or ongoing tornado (NWS 2009).” This rare statement is meant to elicit precautionary actions from listeners in the warning area by providing an increased sense of urgency.

In addition to previously mentioned information sources, studies have shown that the media plays an important role in communicating weather warning and safety information to the public (Robinson and Levy 1986; Bartlett 2005; Sherman-Morris 2010). Findings from Mitchell (2004) show that the general public tends to trust local television more than any other news source. Particularly in central Alabama, a popular source for weather warning information is James Spann, a television meteorologist in Birmingham. Multiple participants in this research study mentioned Spann as their source of information for the April 27 tornadoes, as well as referencing him when given the opportunity for additional comments at the end of the survey, including responses such as:

> "James Spann was very informative. Showed us where it was heading and knew that we should take shelter, then saw it and took shelter," and "James Spann was great." One participant also provided his own recommendations, saying, "Watch James Spann and listen for the tornado sirens."

When contacted for comment via email on April 1, 2014, Spann provided the following information on his recommendations regarding tornado safety:

- Get to a small room, on the lowest floor, away from windows, and near the center.
- Wear some type of helmet if you can.
- Leave mobile homes and go to a more significant structure.
- Get out of cars and vehicles as quickly as possible (pull off at the next exit and go into a gas station, etc.).
- I have never said…
  - You won't survive unless you are underground.
  - Get in your car and drive away from the tornado.

I just don't believe those two statements are valid and can put people in a dangerous situation.

3 Methods

3.1 Survey design and implementation

In prior research (Senkbeil et al. 2012), surveys with Tuscaloosa residents were conducted for 2 weeks following the April 27, 2011, tornado. The response format of these surveys was mixed method, including both qualitative and quantitative responses. The types of questions posed in the survey included classification, behavioral, knowledge and perception (Bird 2009). In an attempt to achieve a higher response rate, face-to-face delivery mode was used in conducting the survey (Bird 2009). Because some members of the survey team did not record their response rate, an exact response rate is not available, but it is estimated to be near 67 % (2/3). The responses were recorded via Zoomerang survey (www.zoomerang.com) through use of an Apple iPad. A convenience sampling technique was used in the selection of participants, and the sample was representative of the population (Senkbeil et al. 2012). The participants were chosen from sites within the tornado damage swath at various shelter locations, relief stations, workplaces and neighborhoods. Residents were asked what their shelter plan was prior to the tornado where they took shelter during the tornado, and how or if they would change their shelter plan in the future. The term shelter was used during surveys instead of refuge because of its commonality in the safety recommendation nomenclature and to avoid confusion on behalf of the respondents. Results were used as the basis for statistical tests between the numbers of residents who sought adequate, questionable or inadequate shelter during the tornado and also for a possible future tornado.

3.2 Tornado refuge rubric

Tornado intensity is not classified before or during an event due to difficulties in radar wind speed extrapolation and preferred engineering analysis on damaged structures after an event. Without extensive meteorological knowledge, many residents take refuge actions with the assumption that every tornado is of the same magnitude. On days when violent tornadoes are expected, television meteorologists may show live video of a tornado on the ground using language such as "violent" or "destructive," even though the exact wind speeds cannot be quantified at that time. These video scenarios provide viewers with a heightened level of threat compared to a typical severe weather day without dramatic video evidence. Despite the heightened level of risk, the refuge plans of Tuscaloosa residents on April 27th, 2011, were almost exclusively lowest-floor, interior rooms. The adequacy of those plans is discussed later.

From 1950 through 2011, violent (EF4–EF5) tornadoes accounted for only 2.1 % of all tornadoes, but 62 % of tornado fatalities (NCDC 2012). With this fact in mind, the ultimate objective of this research was to develop a way of communicating the potential tornado risk for a given day in a manner that included safer refuge/shelter locations for a tornado watch area. To accomplish this, wind engineering data developed for use in the enhanced Fujita (EF) Scale by Texas Tech University's Wind Science and Engineering Research Center (TTU WiSE) (Texas Tech 2006) were used to develop a rubric of refuge/shelter locations based on potential tornado intensity for that day.

The current method for rating tornadoes, the enhanced Fujita (EF) scale, was adopted by the NWS in 2007 and used to replace the Fujita (F) scale (Fujita 1971). Its many advantages and shortcomings are discussed in Doswell et al. (2009) and Edwards et al. (2013). It is not the intent of this research to duplicate a lengthy EF scale discussion found in these two articles, but instead to discuss how previous research has informed the development of a tornado refuge rubric.

The EF scale is currently the best option available, despite its shortcomings, for estimating the wind speeds required to induce structural failure in the built environment (Doswell et al. 2009). The EF scale uses a damage-based rating system to apply an estimated wind speed to tornadoes and assigns each to a category on the scale (EF0–EF5) based on that wind speed (Texas Tech 2006). The EF scale rating is given to tornadoes in the days following an event by an individual or team of surveyors, usually trained in meteorology, engineering or both. To estimate the strength of a tornado, a field survey is done to examine the damage caused by the tornado using a list of damage indicators (DI) from the EF scale (e.g., farm outbuilding, one- or two-family residence). Each damage indicator lists degrees of damage (DoD) for each structure, corresponding to different ranges of wind speeds necessary for such damage (e.g., windows blown out, walls collapsed) to occur. These ranges of wind speeds include upper-bound (UB), expected (E) and lower-bound (LB) wind speeds to account for well-built, standard and poorly built structures, respectively. These ranges are determined using wind engineering experiments on different types of materials and different building practices (Texas Tech 2006).

Despite its specificity in ranges of speed and damage indicators, the EF scale allows for a rating of the failure point for wind damage or destruction while potentially ignoring the maximum potential wind that occurred (Doswell et al. 2009). Mobile Doppler radar velocities exceeding 140 m s^{-1} have been observed near ground level in tornadoes (Bluestein et al. 1993; Wurman et al. 2007), indicating it is possible that winds can greatly exceed the 90 m s^{-1} threshold for EF5 intensity on the EF scale. Often there are extreme gradients in damage assessment over very small distances. Houses only 50 meters apart can be rated 2 EF scale category differences or more. These damage discrepancies have many possible explanations due to changes in tornado vortex dynamics, structural integrity of houses, flying debris or a combination of reasons (Edwards et al. 2013). As more field surveys and investigations are completed, the EF scale will continue to evolve and improve by adding new damage indicators. Nevertheless, the EF scale represents a substantial downscaling in wind ranges when compared to the F scale, especially at the upper ranges of the F scale (Doswell et al. 2009). It is therefore a more conservative estimate of the winds at the failure point of structures with established damage indicators.

Given the motivation is to create an easily understood public rubric based on the forecast tornado strength class (weak, strong or violent) for a given day, the EF scale is an ideal template for proposing a rubric to classify tornado refuge adequacy. Ongoing research on this topic examines public preference and comprehension of a tornado watch scale linked to the tornado refuge rubric in this research. Using the EF scale, the 23 DIs which could be used as refuge locations were selected. The DoD for these damage indicators were then examined to identify the lower-bound wind speed for exterior wall failure or collapse. Lower-bound wind speed for exterior wall collapse was chosen as the threshold for shelter/refuge adequacy as a conservative estimate for the point at which the safety of a person seeking refuge inside would be compromised, albeit it is possible for flying debris to compromise a wall before wind loading. In addition to these 23 shelter options, categories were added for basements and vehicles because respondents commonly reported using these areas as refuge locations during tornadoes (Senkbeil et al. 2012). These categories are marked with asterisks due to considerable variability in basement construction and type, and the lack of formal damage indicators for basements (Table 2). Since some fatalities occurred in basements in Alabama in 2011, perhaps different styles of basement construction will be included as damage indicators in the future.

The vehicle option included in the rubric is intended to be used as a mobile alternative to evacuate a tornado watch area before a tornado warning is issued only if no other appropriate refuge is available, and thus, a vehicle is not given a wind speed rating. Using a vehicle once a tornado warning is issued may possibly work in rural areas if the individual can track the tornado visually or has a mobile device showing the tornado polygon and there is light traffic. Also, using a vehicle to evacuate from a large metropolitan area once a tornado warning is issued was shown to decrease risk of death and injury in the May 3, 1999, Moore, Oklahoma tornado (Biddle 2007), among other cases. However, this course of action is situationally appropriate and cannot be recommended in large metropolitan areas due to the possibility of extreme traffic congestion with a large-scale evacuation. Other complications with using a vehicle include the possibility of evacuating to an area that also is threatened with a tornado watch or a different tornado warning. Also, a reliable mobile device is essential to monitor changing weather and traffic conditions if a vehicle was used to evacuate a watch area or a tornado warning with long lead time.

After assigning the lower-bound wind speed for wall collapse to each damage indicator, this wind speed was converted into the corresponding EF scale rating (e.g., 120 mph/ 54 m s^{-1} = EF2). For each damage indicator, this EF rating was used as the threshold for inadequacy. A refuge location with a LB exterior wall collapse wind speed of 54 m s^{-1} would be inadequate on days with a potential for wind speeds greater than or equal to EF2

Table 2 Damage indicators (DIs) from the enhanced Fujita scale were analyzed to identify the lower-bound (LB) degree of damage (DoD) wind speed at which exterior walls would fail or collapse to determine a threshold of safety for a person taking refuge inside

	Damage indicator (DI)	LB DoD for exterior wall failure or collapse mph (m/s^{-1})	LB DoD for exterior wall failure or collapse EF rating	Weak event (EF0–EF1)	Strong event (EF2–EF3)	Violent event (EF4–EF5)
1	Small barns or farm outbuildings (SBO)	81 (36.2)	EF0	Inadequate	Inadequate	Inadequate
2	One- or two-family residences (FR12)	127 (56.8)	EF2	Adequate	Questionable	Inadequate
3	Manufactured home–single wide (MHSW)	87 (38.9)	EF1	Inadequate	Inadequate	Inadequate
4	Manufactured home–double wide (MHDW)	93 (41.6)	EF1	Inadequate	Inadequate	Inadequate
5	Apartments, condos, town houses (3 stories or less) (ACT)	138 (61.7)	EF3	Adequate	Questionable	Inadequate
6	Motel (M)	121 (54.1)	EF2	Adequate	Inadequate	Inadequate
7	Masonry apartment or motel building (MAM)	115 (51.4)	EF2	Adequate	Inadequate	Inadequate
8	Small retail building (fast food restaurants) (SRB)	120 (53.6)	EF2	Adequate	Inadequate	Inadequate
9	Small professional building (doctor's office, branch banks) (SPB)	123 (55)	EF2	Adequate	Inadequate	Inadequate
10	Strip mall (SM)	117 (52.3)	EF2	Adequate	Inadequate	Inadequate
11	Large shopping mall (LSM)	124 (55.4)	EF2	Adequate	Inadequate	Inadequate
12	Large, isolated retail building [K-Mart, Wal-Mart] (LIRB)	118 (52.8)	EF2	Adequate	Inadequate	Inadequate
13	Automobile showroom (ASR)	106 (47.4)	EF1	Inadequate	Inadequate	Inadequate
14	Automobile service building (ASB)	106 (47.4)	EF1	Inadequate	Inadequate	Inadequate
15	Elementary school [single story; interior or exterior hallways] (ES)	117 (52.3)	EF2	Adequate	Inadequate	Inadequate
16	Junior or Senior High School (JHSH)	121 (54.1)	EF2	Adequate	Inadequate	Inadequate
17	Low-rise building (1-4 stories) (LRB)	122 (54.5)	EF2	Adequate	Inadequate	Inadequate

Table 2 continued

	Damage indicator (DI)	LB DoD for exterior wall failure or collapse mph (m/s^{-1})	LB DoD for exterior wall failure or collapse EF rating	Weak event (EF0–EF1)	Strong event (EF2–EF3)	Violent event (EF4–EF5)
18	Mid-rise building (5–20 Stories) (MRB)	120 (53.6)	EF2	Adequate	Inadequate	Inadequate
19	High-rise building (More than 20 Stories) (HRB)	123 (55)	EF2	Adequate	Inadequate	Inadequate
20	Institutional building (hospital, government or university building) (IB)	127 (56.8)	EF2	Adequate	Questionable	Inadequate
21	Metal building system (MBS)	96 (42.9)	EF1	Inadequate	Inadequate	Inadequate
22	Service station canopy (SSC)	90 (40.2)	EF1	Inadequate	Inadequate	Inadequate
23	Warehouse building (tilt-up walls or heavy-timber construction) (WHB)	93 (41.6)	EF1	Inadequate	Inadequate	Inadequate
24[a]	Storm shelter (FEMA 320 or equivalent)	255 + (114 +)	NA	Adequate	Adequate	Adequate
25[a]	Fully underground basement	TBD	TBD	Adequate	Questionable	Questionable
26[a]	Partially underground basement	TBD	TBD	Adequate	Questionable	Inadequate
27[a]	Vehicle	NA	NA	Questionable	Questionable	Questionable

Four additional DIs were added because they are commonly reported as tornado refuge/shelter locations

Source Texas Tech University, 2006

[a] Additional categories frequently cited as tornado refuge/shelter locations by survey participants. Adequacy ratings may be adjusted if future wind engineering data become available. A vehicle is only intended to be used as a mobility device to evacuate the area during a tornado watch

tornadoes. This procedure was then applied to the 23 original DIs for which DoD were available. The exception to this classification was the placement of structures with an LB exterior wall collapse wind speed greater than 56 m s^{-1} (125 mph) into the “Questionable” category for strong tornadoes. These structures correspond to typical sturdy residential structures where most respondents report taking refuge, including permanent homes, apartments, condominiums and town houses less than three stories. The inclusion of “Storm Shelter” refers to a FEMA 320 or FEMA 361 storm shelter or safe room with a wind speed rating of 114 m s^{-1} (255+ mph), which would still be classified as adequate for violent events (FEMA 1999, 2000). These ratings were assembled into a table of tornado refuge adequacy ratings showing LB wind speed for exterior wall collapse, corresponding EF rating and whether the shelter is adequate, questionable or inadequate for weak (EF0–EF1), strong (EF2–EF3) or violent (EF4–EF5) tornadoes (Table 2). Using this ratings table as a basis, a tornado refuge rubric (Table 3) was constructed to provide an easily communicable means of displaying this information.

4 Results and discussion

On April 27, 2011, in Tuscaloosa, Alabama, many fatalities resulted from residents who were likely following recommended refuge plans using interior rooms in residences or other permanent buildings (Fig. 2). The high number of fatalities in permanent homes and structures is disheartening if residents were following the recommended strategy of taking refuge in an interior room on the lowest floor of a sturdy building. This is especially true considering that only a small portion of the tornado path experiences the peak intensity of a tornado. In the case of the Tuscaloosa tornado, Prevatt et al. (2011) estimated that 92 % of damage surveyed in their study was at EF2 intensity or below, with less than 3 % experiencing EF4 intensity. While there are relatively inexpensive methods to reinforce residential structures with strong ties and other attachments, these reinforcements will not save the structure from failure in winds associated with the vortex of violent tornadoes.

In Alabama, mobile homes comprise 13.2 % of the housing stock, while permanent homes account for 86.8 % (US Census Bureau 2011). In 2011, 28 % of Alabama tornado fatalities with known locations occurred in mobile homes, compared to 53 % in permanent homes (NWS SPC 2012b). When comparing the number of mobile home deaths from tornadoes in Alabama in 2011 to that of permanent homes, a transition can be seen between EF3 and EF4 tornado strength, where the number of permanent home fatalities surpasses those occurring in mobile homes (Fig. 3). Because permanent homes make up a higher percentage of the housing stock, it would be expected that more fatalities would occur in permanent homes across the EF scale if both structures are equally likely to be destroyed by a tornado. However, this transition indicates that permanent homes only provide reliable refuge from a tornado at EF3 and weaker intensities.

Tuscaloosa County contains approximately 9,781 occupied mobile homes and 74,172 occupied permanent homes (US Census Bureau 2011). Using these data to normalize the number of fatalities during the Tuscaloosa tornado (42 in permanent homes and 8 in mobile homes), there were 6 deaths per 10,000 permanent homes and 8 deaths per 10,000 mobile homes. In the state of Alabama during 2011, these fatality rates drop to 0.5 fatalities per 10,000 permanent homes and 1.6 fatalities per 10,000 mobile homes. The increased rate of fatalities seen in Tuscaloosa is likely due to the higher population density along the tornado track.

During the survey, participants were asked where they sheltered during the tornado and whether they would change their shelter location in the event of another tornado (Senkbeil et al. 2012). Responses to these questions were then grouped into two categories. The first category, Shelter Before, indicates where the respondent took shelter or refuge during the tornado on April 27, 2011. The second category, Shelter After, represents the shelter or refuge intentions of the respondents in the event of a future tornado. Because no resident specified different shelter locations for tornadoes of varying magnitude or different levels of perceived danger, it was assumed that residents would use the same location for every tornadic event. Using this logic, the shelter environments in the Before and After categories were held constant, while rating their adequacy during a weak, strong or violent event using the tornado refuge rubric. For responses in the After category, many residents

Table 3 Using the ratings from Table 2 as a basis, a tornado refuge rubric was constructed to provide a simple method of communicating the adequacies of different structures based on tornado strength classes

Tornado refuge rubric						
Event type	EF Scale	Adequate refuge		Questionable refuge	Inadequate refuge	
Weak	EF–0, EF–1	Storm shelter/safe room One- or two-family home Apartments, condos, town houses[a] Small retail building Small professional building Strip mall Large stropping mall	Large, isolated retail building Elem., Jr., or Sr. High School Low-. mid-, or high-rise building Institutional building Motel Fully underground basement Partially underground basement	Vehicle (to evacuate during tornado watch)[b]	Mobile/manufactured home Farm outbuilding Automobile showroom Automobile service building Metal building system Service station canopy Warehouse building	
		Adequate		Questionable	Inadequate	
Strong	EF–2, EF–3	Storm shelter/safe room		One- or two-family home Apartments, condos, town houses[a] Institutional building Partially underground basement Fully underground basement Vehicle (to evacuate during tornado watch[b]	Mobile/manufactured home Farm outbuilding Motel Small retail building Small professional building Strip mall Large shopping mall Large isolated retail building	Automobile showroom Automobile service building Elem., Jr. or Sr. high school Low-, mid- or high-rise building Metal building system Service station canopy Warehouse building
		Adequate		Questionable	Inadequate	

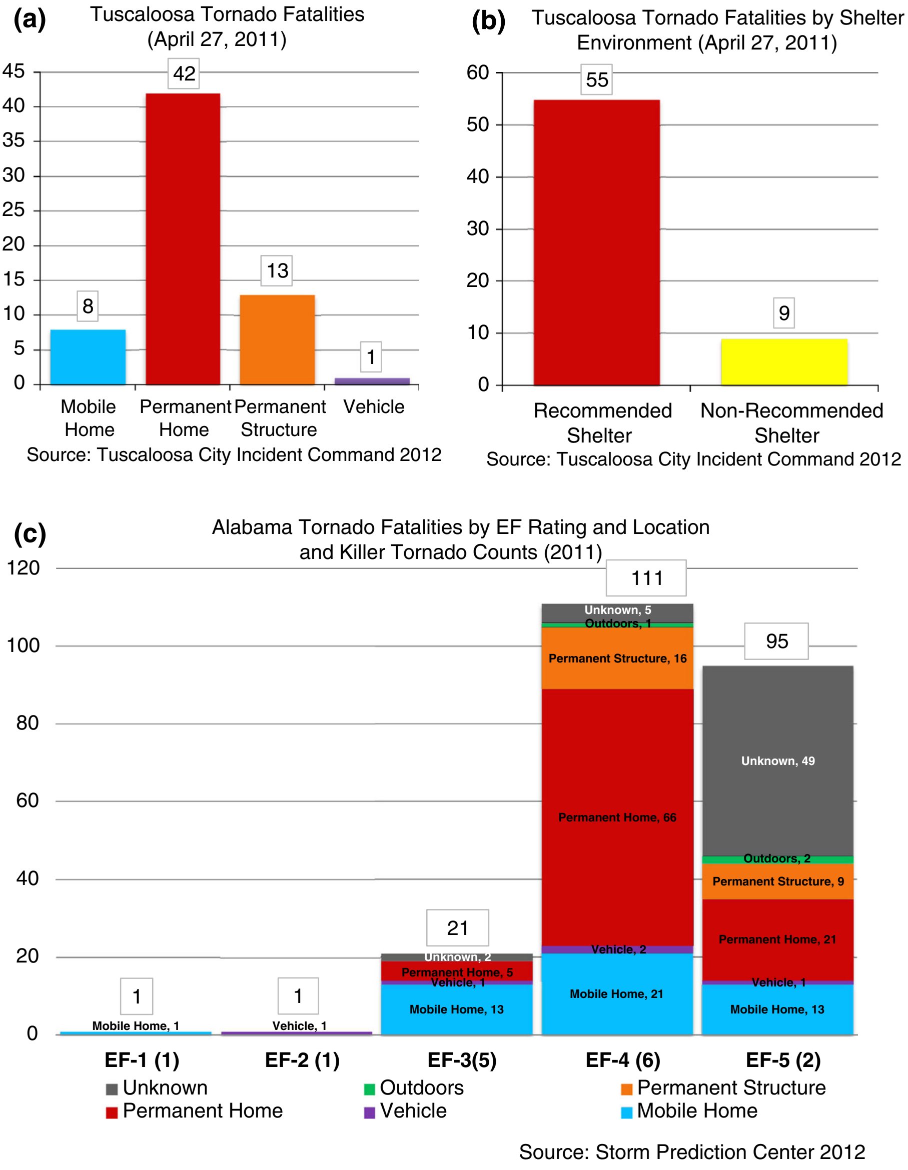
Table 3 continued

Tornado refuge rubric					
Event type	EF Scale	Adequate refuge	Questionable refuge	Inadequate refuge	
Violent	EF-4, EF-5	Storm shelters sale room	Vehicle (to evacuate during tornado watch)[b] Fully underground basement	One- of two-family home Mobile/manufactured home Apartments, condos, town houses[a] Farm outbuilding Motel Small retail building Small professional building Strip mall Large shopping mall Partially underground basement	Large isolated retail building Automobile showroom Automobile service building Elem, Jr. or Sr high school Low-, mid-, or high-rise building Institutional building Metal building system Service station canopy Warehouse Building

All refuge locations should be in an interior room on the lowest level of the structure, away from windows

[a] Apartments, condos and town houses three stories or less

[b] Evacuation should be done during a tornado watch, out of the watch area, before a tornado warning is issued



Source: Tuscaloosa City Incident Command 2012

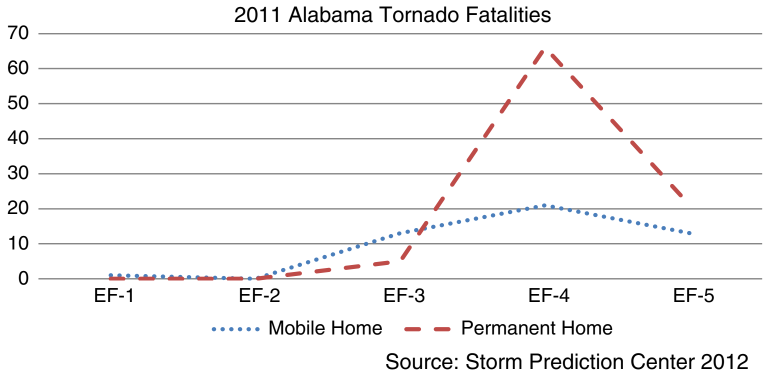
Source: Tuscaloosa City Incident Command 2012

Source: Storm Prediction Center 2012

Fig. 2 **a** April 27, 2011, Tuscaloosa tornado fatalities by location. **b** Tuscaloosa tornado fatalities, by shelter location recommendations. **c** Locations of tornado-related fatalities in Alabama during 2011, grouped by EF rating. Peak-estimated intensity ratings along the tornado track are used for classification. (Tuscaloosa City Incident Command (2012) and SPC (2012))

were unsure of where they would seek refuge in the event of another tornado; these responses were grouped into the category unsure. These included responses such as “no idea,” “somewhere secure” and “go to the safest place the news tells us to go.”

Other common responses to this question included, “Go to a basement,” “Find a storm shelter,” and, “Get in my car and drive away.” Responses occurring less often, but illustrating some of the shortfalls in understanding of appropriate tornado safety actions



Source: Storm Prediction Center 2012

Fig. 3 Comparison of Alabama tornado fatalities in mobile homes and permanent homes during 2011, by peak EF rating of tornado

include “Get in a hole or ditch” and “I would go to a large store like Wal-Mart or the mall,” possibly in reference to a popular news story in the preceding weeks of customers surviving inside a large home improvement store in Sanford, NC, which was hit by a tornado on April 16, 2011. One participant also reported he would, “Head to the grocery store for the freezer unit,” likely in response to the story of a local Tuscaloosa restaurant in which workers and customers survived inside the walk-in freezer while the store was destroyed by the April 27 tornado.

Of particular interest is the number of participants (62) who were unsure of where they would take refuge or shelter in the event of another tornado. This represents nearly one-third of all responses (29.4 %). Results of Pearson chi-square tests for differences in the adequacy of shelter locations Before ($x^2 = 752, p < .01$ (4)) and After ($x^2 = 290, p < .01$ (6)) were both highly significant (Table 4). This statistical significance is due mainly to most respondents indicating refuge in an interior room of a permanent structure, which would be adequate refuge for a weak tornado, questionable refuge for a strong tornado and inadequate refuge for a violent tornado.

Using the included tornado refuge rubric (Table 3), it is evident that the refuge location (permanent structure, interior room) most commonly chosen by Tuscaloosa residents during the EF4 April 27 tornado would have been inadequate refuge in the tornado vortex. The locations of fatalities within the Tuscaloosa city limits are shown in Fig. 2a and reflect this distribution of inadequate refuge (Tuscaloosa City Incident Command 2011). If these permanent homes and structures are classified as sturdy buildings, the death toll is exceptionally high for what is to be considered recommended refuge from a tornado (Fig. 2b). This same pattern can be seen in all tornado fatalities in Alabama during 2011 where a high number of fatalities from EF4 and EF5 tornadoes occurred in permanent homes or permanent structures (Fig. 2c), where many NWS tornado warning call-to-action statements recommend taking refuge if a storm shelter or basement is unavailable. In Tuscaloosa, many older homes were affected that were clearly not compliant with modern building codes.

The results from Tuscaloosa show that there is a highly significant difference in whether refuge/shelter locations are appropriate for weak, strong or violent tornadoes. This significance is explained by most residents reporting seeking shelter in an interior room on the lowest level of a sturdy building, which is adequate for weak tornadoes, questionable for

Table 4 Chi-square analysis of respondent tornado refuge/shelter locations during the April 27, 2011, Tuscaloosa, AL tornado (Before) and intended refuge/shelter locations in the event of a future tornado (After)

Event type	Refuge/shelter adequacy				
		Adequate	Questionable	Inadequate	
Pearson chi-square test for April 27, 2011, tornado shelter locations (before)					
Weak (EF0, EF1)	Count	189	3	19	
	Expected count	72.3	51	87.7	
Strong (EF2, EF3)	Count	14	147	50	
	Expected count	72.3	51	87.7	
Violent (EF4, EF5)	Count	14	3	194	
	Expected count	72.3	51	87.7	
Chi-square tests	Pearson chi-square	752.260a	Critical value @ 0.001		18.46
	Degrees of freedom	4	*p* value		0.000

Event type	Refuge/shelter adequacy				
		Adequate	Questionable	Inadequate	Unsure
Pearson chi-square test for April 27, 2011, tornado shelter locations (after)					
Weak (EF0, EF1)	Count	119	4	6	82
	Expected count	64.3	27	37.7	82
Strong (EF2, EF3)	Count	37	73	19	82
	Expected count	64.3	27	37.7	82
Violent (EF4, EF5)	Count	37	4	88	82
	Expected count	64.3	27	37.7	82
Chi-square tests	Pearson chi-square	290.367a	Critical Value @ 0.001		22.46
	Degrees of freedom	6	*p* value		0.000

Because residents did not indicate changing refuge/shelter plans based on tornado intensity or perceived danger, locations were held constant and evaluated for adequacy during weak, strong and violent tornado events using the tornado refuge rubric

strong tornadoes and inadequate for violent tornadoes according to the procedures used to create the tornado refuge rubric used in this research. One possible explanation for this might be the language used in most tornado warning statements, which often recommends sheltering in a lowest level, interior room of a sturdy building, as seen in the Tuscaloosa tornado warning statement. The vast majority of residents (92 %) who had a shelter plan for the April 27, 2011, tornado indicated their plan was a lowest-floor, interior room such as a bathroom, closet or basement (Senkbeil et al. 2012). Many provided additional details saying that a lowest-floor, interior room is what you are supposed to do. Another contributing factor in the decision to seek refuge in lowest-level, interior rooms is likely convenience and the limited availability of basements and public storm shelters.

5 Conclusions and recommendations

The tornado refuge rubric discussed in this research integrates the meteorological threat of potential tornado intensity with recommendations for refuge and shelter actions based on structure resiliency determined by wind speed ranges developed by engineers and meteorologists. Evidence presented from Tuscaloosa suggests that residents followed a “one size fits all” recommended protective action policy by seeking refuge in a lowest-floor, interior room during the April 27, 2011, tornado. These recommended actions are normally a wise protective strategy, but this strategy is not as safe on days when violent EF4 and EF5 tornadoes are expected. The devastation in Tuscaloosa caused many residents to evaluate their future refuge plans, many of which chose a safer option; however, many did not know what to do or they chose options that will not be safe in another violent tornado. By suggesting a revision to recommended tornado refuge/shelter guidelines, it is hoped that a more uniform, comprehensive set of tornado safety guidelines can be communicated to the public through use of a tornado refuge rubric or a similar product.

Ultimately, it is hoped that some form of a rubric will be used in addition to tornado watches issued by the SPC, allowing for a weather forecast office’s coverage area to receive a general forecast of maximum tornado intensity on a given day, which is currently addressed in the form of probabilistic tornado guidance from the SPC, which either contains a significant (EF2+) area or not. Using this rubric when a tornado watch is issued, rather than a tornado warning, would be advantageous because many people must travel to an appropriate shelter during a tornado warning, which would be very difficult, dangerous or impossible for storms with short or negative lead times. Using the included tornado refuge rubric as a basis, this research aims to set a foundation for a probabilistic-to-categorical conversion of existing SPC products into a tornado watch scale, which will be addressed in future research focusing on the public approval and comprehension of a revised tornado watch system.

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