Reply

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We thank Brooks et al. (2008, hereafter BRO) for their interesting commentary on our article, Wurman et al. (2007, hereafter WUR). The major areas of discussion in the comment are 1) the probability of dying given that one is residing in a home destroyed in a tornado, 2) the persistence of violent winds in actual versus simulated tornadoes, 3) tornado warning lead times as they relate to fatality rates, and 4) what should be considered as a realistic worst-case event for emergency management planning.

THE PROBABILITY OF DEATH (POD) IN THE EF4/5 (F4/5) PORTIONS OF TORNADOES. BRO take issue with the assumption of POD = 0.1 in "catastrophic" tornadoes. A major part of the disagreement is due to BRO's misunderstanding of how WUR calculated fatalities in the simulated tornadoes. BRO states, incorrectly, that ". . . all residences in their hypothetical tornado face F4/F5 winds." While the total damaging wind swaths of the simulated tornadoes in WUR were quite wide, only small fractions of these paths contained winds in excess of 76 m s^{-1} (capable of causing the most extreme damage). The comparatively narrow extent and more focused impact of winds capable of causing EF4/5 damage is explicit in WUR's text, in their Figs. 9, 10, 13, and 14, and in their Tables 1 and 2. It is only in those regions, corresponding to the highest end of destruction to residential structures, suffering degrees of damage (DOD) = 9 and DOD = 10 (Marshall 2004), that WUR assigned a POD of up to 0.1. Outside that region, in the portions of the simulated damage paths subject to winds of 59–76 m s^{-1}, in which one would expect "destruction" of homes at DOD = 6–8, WUR assigned POD = 0. Elsewhere in the damage track, where winds were simulated to be 43–59 m s^{-1} (capable of causing substantial damage, but not completely destroying homes), POD was also set to zero. Our methodology is summarized in Table 1.

As a single illustrative example, in simulated tornado BC in Table 2 of WUR, 71 km^2 were impacted by tornadic winds in excess of 43 m s^{-1}, but only 23 km^2 by winds > 76 m s^{-1} (capable of EF4/5 damage; more precisely, DOD = 9–10, using the EF scale). While the extent of the areas impacted by these different wind thresholds varies depending on the intensity, translational speed, and steepness of the wind speed decrease away from the radius of maximum winds, as illustrated in Table 1 of WUR, it is typical that the ratio:

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Table 1. EF scale DOD and assumed POD versus simulated peak wind speed at individual structures.

Peak 3-s 10-m wind speed	Residences		High-rise apartments	
	DOD	POD	DOD	POD
43–76 m s^{-1}	4–8	0	4–8	0
76–102 m s^{-1}	9–10	0.1	9–10	0
102–135 m s^{-1}	10	0.1	10	0.01

$$\frac{\text{area}(> 43 \text{ m s}^{-1})}{\text{area}(> 76 \text{ m s}^{-1})} > 3,$$

meaning that less than 1/3 of the width of the "damage track" of the simulated tornadoes was associated with DOD = 9–10 (EF4/5) damage and with any estimated fatalities.

When comparing POD's in different tornadoes, it is critical to use consistent definitions concerning which residences to include in the calculation. Both BRO and WUR agree that the POD in the *F4/5 region only* of the Bridge Creek–Moore–Oklahoma City (OKC), Oklahoma, tornado on 3 May 1999 was in the range of 1%–3%. We have conducted a preliminary statistical analysis of the POD in the recent tornado that destroyed much of Greensburg, Kansas, on 4 May 2007 based on aerial and ground-level photography. Approximately 867 residences were damaged or destroyed, and 194 of these suffered DOD = 9–10 levels of damage. A preliminary estimate from a survey conducted independently by the Dodge City Weather Forecasting Office (WFO), based on aerial photography (J. Hutton 2007, personal communication), is that approximately 420 homes suffered DOD = 9–10 damage. The difference is likely in the aerial photography–based characterization of DOD = 8, wherein most walls collapsed, versus DOD = 9, wherein all walls collapsed, which is problematic. When our aerial photography versus ground photography intercomparison is complete, a more definitive value for the number of DOD = 9 and DOD = 10 residences will be available. Nine deaths occurred in structures in Greensburg, mostly clustered along a north–south axis on the west side of the town (Kansas Bureau of Investigation 2007, personal communication) in regions associated with DOD = 9 damage. Using the U.S. Census's residents per household value of 2.14 in Greensburg, we arrive at a POD in DOD = 9–10 structures of 9/(194 × 2.14) = 2.2%. (Using the Dodge City WFO value results in 1.0%.) WUR calculates, and BRO does not dispute, that POD to residents in the F3/4 portions of the Spencer, South Dakota, tornado of 30 May 1998 was 6%.

In contrast, BRO present much lower POD values from two other studies. However, these studies calculate the POD from all "destroyed" homes, not just the much lower number that suffer DOD = 9–10 damage. The Oklahoma Department of Emergency Management (ODEM) specifically includes all homes in which either walls or roofs fail or those for which repair is not economically feasible. This might correspond to homes suffering DOD = 6–10 as defined in the EF scale. The ratio of 3/19 between the Speheger et al. (2002) values (which at 1.9% are much closer to and validly comparable to those used in WUR) and the ODEM POD values is due to the different thresholds of damage used in the denominators of the POD calculation. The Daley et al. (2005) study counts structures that are "damaged or destroyed," including, presumably, a great number of structures that suffered much less than DOD = 9–10 damage. BRO present a value of POD = 1.1% in the Birmingham, Alabama, tornado from Legates and Biddle (1998), who also calculates POD in "destroyed" homes.

The difference in the two categories of calculations is the use of the following two different formulas for POD:

(deaths)/(No. of residences with DOD = 9–10), used in WUR, Wurman and Alexander (2005), and Speheger et al. (2002), and

(deaths)/(No. of residences destroyed, perhaps with DOD = 6–10), used in ODEM, Daley et al. (2005), and Legates and Biddle (1998).

This sparse historical record contains POD's in F3, F4, and F5 regions of tornado swaths ranging from 1% to 6%. WUR, while using POD = 10% in the DOD = 9–10 regions for many calculations, explicitly entertains that values of 1% are within the error bars of reason and would still result in potentially catastrophic levels of fatalities, potentially exceeding 1,000.

PERSISTENCE/COVERAGE OF INTENSE TORNADIC WINDS. BRO point out that Speheger et al. (2002) found that only 13% of the OKC tornado path area was associated with F4/5 damage. However, it is well known that *the documented damage intensity of tornadoes represents a lower bound of the damage that tornadoes might cause*. This lower bound is because the damage that tornadoes cause is due to the convolution of the distribution of near-surface winds and the distribution of structures/foliage for which damage intensity can be quantified.

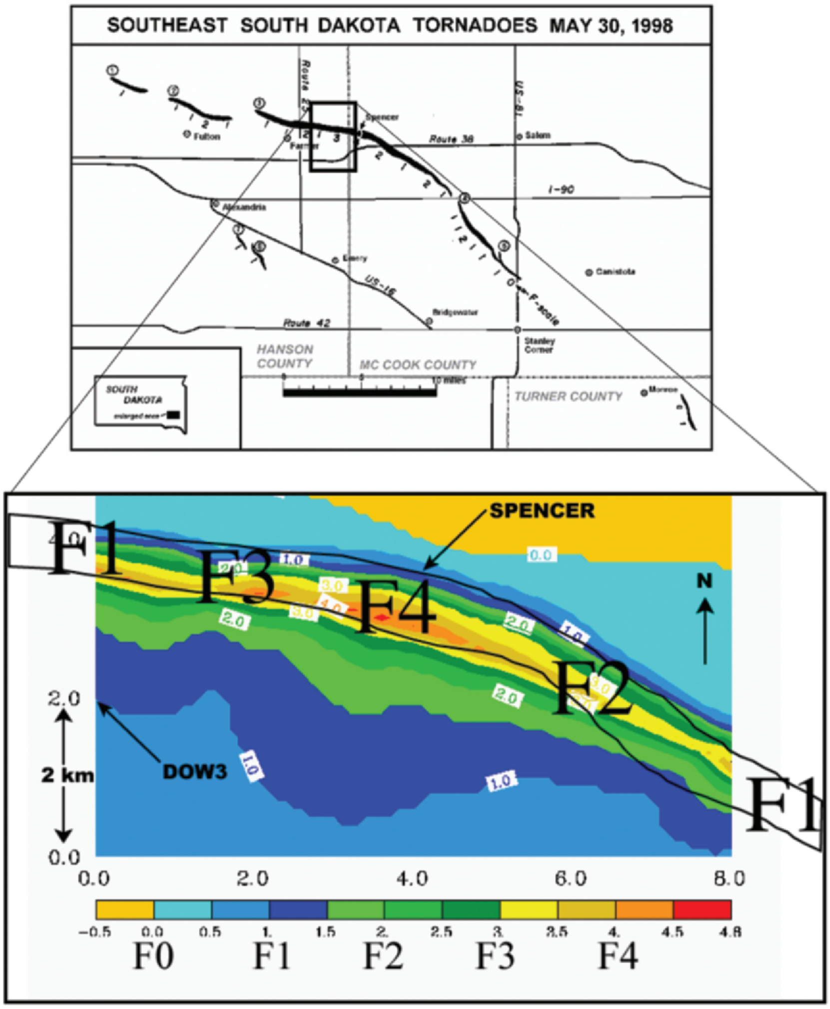

Fig. 1. F-scale equivalent of DOW-measured winds in the Spencer (1998) tornado compared with the National Weather Service Fujita-scale rating along the surveyed damage track. DOW-measured winds indicated that the tornado could have caused F4 damage along at least several kilometers of track west of Spencer. However, the damage survey indicated only F1–F3 damage in that area due to the lack of damage indicators. [Figure reproduced from Wurman and Alexander (2005). See also Alexander and Wurman (2005) for a time line of peak winds in the tornado prior to, during, and after its passage through Spencer.]

Wurman and Alexander (2005) document the striking difference between the extent of strong-to-violent measurement-constrained modeled near-surface tornado winds and the much smaller area of quantifiable damage caused by those winds [Fig. 1, reproduced from Wurman and Alexander's (2005) Fig. 12]. In the densely populated town of Spencer, South Dakota, the measured/modeled wind field corresponded very closely with the observed damage. But, just outside the town, where measured winds were nearly or equally intense, high-end damage was not documented. As can be seen in Fig. 1, and in Fig. 11g of Alexander and Wurman (2005), Doppler on Wheels (DOW)-measured winds corresponding to over 94 m s^{-1}, capable of causing extreme damage associated with either F4 or EF4/5 wind levels, were observed in the tornado during the several minutes before it crossed Spencer. However, observed damage ranged from F1 to F3. So, while the portion of the track of the Spencer tornado that was associated with surveyed high-end damage was small, the portion of the track of the Spencer tornado that could have caused high end, even EF5 damage had it been crossing a more substantial urban or suburban region, was considerably longer. The same is true of the Mulhall, Oklahoma (1999), tornado. Very intense winds were observed by a DOW to be occurring near the surface in this tornado for at least 18 min from 0310 UTC (when a violent tornado was already well underway) and 0328 UTC (Wurman 2002; Lee and Wurman 2006), when the tornado moved out of range of high-resolution DOW measurements. Preliminary damage surveys (corrected after consultation with the DOW data) suggested that this single violent tornado was two separate tornadoes. DOW observations suggested winds near 80 m s^{-1}, capable of causing EF4 damage, occurred in the gap between the two preliminarily surveyed tornadoes.

The invalidity of transposing damage-intensity patterns from one location to locations with different distributions of construction is a fundamental limitation of the technique used by Rae and Stefkovich (2000). Superposition of damage tracks from tornadoes that occurred over mostly rural areas to over more built-up areas will necessarily underestimate the damage potential of these tornadoes.

TORNADO WARNING LEAD TIMES AND THE IMPACT ON POD. WUR discuss that the low POD's in the OKC tornado were associated with better-than-average lead times. We stand by this statement. Overall, public-awareness of the tornadoes, in the regions where most fatalities occurred, was likely to have been above average.[1] Similarly, the recent Greensburg tornado was associated with above-average warning or public awareness lead times.[2]

We agree with BRO that large long-track tornadoes are likely to be well warned, but we note that this is likely only during the latter portions of their long tracks. The OKC tornado was notable in that it crossed Moore and Oklahoma City at the end of its lifetime, not at the beginning. Furthermore, as BRO agree, the relationship between the warning lead times and public perception is "complex." In our examination of worst-case scenarios, we note that tornadoes that either occur at night or impact urban populations that are less attuned to the tornado threat than those in Oklahoma City or Dallas, Texas, might be associated with less nimble public responses.

BRO claim that "few" housing units in Oklahoma City had below-ground or in-residence shelters. While this may be true, we have no reason to believe that the availability of shelters is any better in the suburban areas through which the simulated tornadoes in WUR passed.

REALISTIC WORST-CASE EVENTS FOR EMERGENCY MANAGEMENT PLANNING.

We acknowledge that historical tornadoes have not caused the level of fatalities estimated in WUR. However, considering that tornadoes are relatively rare and that dense population in urban and suburban neighborhoods in the United States is a relatively recent but growing phenomenon, the historical record is too short to indicate the range of possible events. Analogously, the sparse historical record of terrorist attacks before 11 September 2001 could have suggested, incorrectly, that an attack resulting in >200 deaths was unlikely.

BRO note that the actual OKC tornado resulted in far fewer fatalities than the one in WUR's simulation. We agree. The path of the simulation was chosen to cross a far greater length of suburban neighborhoods. Furthermore, unlike the actual OKC tornado, which narrowed and weakened prior to impacting OKC itself, the simulated tornado crossed suburban neighborhoods of OKC at maximum intensity. The purpose of the simulation was to show the potential impact if the OKC tornado, at its maximum strength, crossed through large tracts of suburban housing. We stand by the conclusion in WUR that a large number of fatalities would be possible. The number of fatalities might be only 627 using the historical death rate in the 3 May 1999 tornado of 1.9%. Or, if the worst-case POD = 0.1 is accepted for the possible scenarios mentioned previously, the number of fatalities might be as high as 3,300, as calculated in WUR.

High-resolution radar observations from DOWs indicate that persistent violent winds can occur in tornadoes and that previous damage survey–based estimations of violent wind persistence are underestimates. If a persistently violent tornado passed through many kilometers of medium-density suburban neighborhoods, many thousands of fatalities could occur. As admitted by BRO, the relationship between public perceptions, and by implication, public response, to any particular tornado threat is complex. In the absence of substantial corroborating data, it is unclear whether 1%, 3%, 6%, 10%, or more of the residents in structures completely destroyed at the DOD = 9–10 level by the worst portions of these tornadoes containing winds > 76 m s^{-1} might die, particularly, if these tornadoes struck at night.

The number of fatalities caused by a tornado could, in the worst cases, greatly exceed the number that have occurred historically. That the number of fatalities might be daunting is not a reason to avoid planning for these scenarios. Emergency managers in earthquake-prone urban areas have had to contend

[1] BRO point out that the warning times for the OKC tornado were in the 50th percentile for Oklahoma County and in the 85th percentile for Cleveland County. We note that the formal warning time for the nearest towns to Bridge Creek were slightly above the 50th percentile (warning at 2340 UTC, tornado passage through Bridge Creek at 2354 UTC). We note that Grady County, in which Bridge Creek is located, was under several tornado warnings beginning at 2147 UTC, over 2 hours before the fatalities occurred. Furthermore, at 2307 UTC, a tornado warning was issued for Chickasha, to the southwest of Bridge Creek, for "multiple tornadoes," "moving northeast." A reasonable conclusion is that the residents of Bridge Creek had above-average awareness that tornadoes were in their county, possibly threatening their neighborhood, well before the 2340 UTC warning. Nevertheless, 12 died. Eleven fatalities occurred in Moore, despite 32-min lead time.

[2] The tornado impacted Greensburg from about 0245 to 0254 UTC. A tornado warning for a "large and extremely dangerous tornado" was issued for Kiowa County, specifically mentioning Greensburg, at 0219 UTC, giving 30–39-min formal lead time. Tornado sirens were activated at about 0225 UTC, about 20 min before the tornado struck. While only gathering anecdotal evidence concerning the impact of these long warning lead times on fatality rates, one of us (J. Wurman) spoke to several surviving residents of Greensburg who had time to get to basements or other shelter because of the ample warning/awareness lead times.

with worst-case scenarios far more severe than those envisioned in WUR. Urban ports receiving shipments of liquid natural gas have considered scenarios involving unprecedented, but possible, devastation. Similarly, post–11 September emergency managers in large urban areas have had to plan for contingencies involving mass casualties, even some involving large, contained crowds in stadiums as mentioned by BRO. In order to avoid causing unwarranted alarm, WUR specifically avoided constructing unrealistic "hyper–worst case" scenarios involving contorted tornado tracks (even though a looping track did occur recently near Greensburg), rush hour traffic, tornado damage–related industrial catastrophe, or high-rise building collapse. WUR avoided simulating the effects of the largest, most violent tornadoes in less-tornado-prone urban areas. We believe that it would be wise for emergency managers to consider that reasonable worst-case tornadoes could be associated with scenarios much more severe than those that have occurred in the past and avoid complacency based on the absence of such events in the short historical record.

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