The Time Cost of Tornado Warnings and the Savings with Storm-Based Warnings

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ABSTRACT

The authors examine the cost of time spent under tornado warnings issued annually by the National Weather Service (NWS). County-based tornado warnings imposed substantial costs on the nation: an average of 234 million person-hours spent under warnings annually between 1996 and 2004, with a value of $2.7 billion (U.S. dollars) per year. Counties are large relative to tornado damage areas; therefore, county-based warnings overwarned for tornadoes, warning many persons a safe distance from the storm and not in immediate danger. In October 2007 the NWS introduced storm-based warnings (SBW) for tornadoes, which are expected to reduce the area warned by 70%–75%. SBW consequently will reduce the time spent under warnings by over 160 million person-hours per year, with a value of $1.9 billion. The time spent under warnings does not measure the full cost to society because many people do not respond to the warnings. Adjusting for warning response, this study estimates that SBW might save 66 million person-hours actually spent sheltering a year with a value of $750 million. Sensitivity analysis indicates that the value of time spent sheltering saved by SBW exceeds $100 million per year with a probability of 0.95.

1. Introduction

The National Weather Service (NWS) is charged with protecting lives and property. Tornado warnings issued by the NWS since 1948 have helped reduce the lethality of nature's most violent storms. The smoothed U.S. tornado fatality rate fell from an estimated 1.8 per million residents in 1925 to 0.11 per million in 2000 (Brooks and Doswell 2002); the NWS' efforts to educate and warn the public about tornadoes has undoubtedly contributed to this effort.[1] Installation of the Weather Surveillance Radar-1988 Doppler (WSR-88D) during the modernization of the NWS (Friday 1994) reduced tornado fatalities and injuries each by about 40% (Simmons and Sutter 2005). The greater lethality of nocturnal tornadoes (Ashley 2007; Ashley et al. 2008; Simmons and Sutter 2008) indirectly suggests the life-saving benefits of warnings and public response.

Deaths, injuries, and property damage are the obvious societal costs of tornadoes, but responding to tornado warnings is also costly because people must interrupt their daily activities to take shelter. Time spent sheltering in an interior room, basement, or storm shelter could be spent on other activities and represents a cost to society. We estimate the time cost of tornado warnings and find that this cost is not inconsequential: an average of 234 million person-hours were spent under warnings between 1996 and 2004, and the value of this time might be as much as $2.7 billion (U.S. dollars).

Tornado damage paths are small relative to counties; the average warned county has an area of around 1000 square miles, whereas the average tornado damage area is 0.43 square miles.[2] The NWS substantially reduced the time cost of warnings with the introduction of storm-based warnings (SBW) for tornadoes nationally in October 2007 (more information is available online at

[1] For details on these efforts see Doswell et al. (1999).

[2] Authors' calculations based on NWS tornado warning verification statistics for 1990–2004 and the Storm Prediction Center tornado archive for 1950–2006, respectively.

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http://www.spc.noaa.gov/archive/). In tests during 2004–05, SBW reduced the area covered by tornado warnings relative to conventional county-based warnings by 70%–75% (M. Looney 2006, personal communication; Jacks and Ferree 2007). The time spent under county warnings represents savings with SBW for tornadoes. If SBW reduces the area warned by 70%, this would reduce the time spent under warnings by 164 million person-hours annually and this time might be worth as much as $1.9 billion per year. Time under warnings does not measure time lost to society because warning response is less than 100%. Adjusting for warning response, we estimate that SBW can save perhaps 66 million person-hours actually spent sheltering per year with a value of about $750 million. Sensitivity analysis suggests that the value of time spent sheltering saved might be closer to $500 million and a 95% lower bound on the value of time saved annually is $109 million.

We also discuss other societal impacts of SBW. The area directly in the path of a tornado or radar indicated tornado will still be warned, so any effect of SBW on casualties will be due to second-order effects such as confusion on the part of the public, a reduction in lead times, and the potential for a tornado to veer out of the polygon warning area. But more significantly, SBW might improve warning response because of the heightened risk for the warned area. It is too early to test for an effect of SBW on casualties, but we suspect that improved warning response will end up reducing casualties. Ancillary investments by society will be needed to capture the full value of SBW. The National Oceanic and Atmospheric Administration (NOAA) weather radios and many public tornado siren systems will need to be upgraded, for instance, to warn residents based on the coordinates of the SBW polygon as opposed to counties. The value of the potential time savings documented here can be used to support making these ancillary investments.

The magnitude of the potential time under warnings savings with SBW might seem surprising. To provide perspective, we compare the value of time under warnings with other costs of tornadoes, including property damage and a monetized value of fatalities and injuries. Time spent under warnings had become prior to the implementation of SBW the largest, although certainly not the most visible, cost of tornadoes to the United States. More effective warning for tornadoes by the NWS and the public response to these warnings have reduced tornado lethality to such an extent that responding to warnings has become the largest component of the cost of tornadoes. An innovation reducing the cost of warnings without compromising safety thus could be most valuable in reducing the cost of tornadoes to society.

2. The cost of county tornado warnings

We begin by tallying the cost of county-based tornado warnings. We calculate the cost of tornado warnings exclusively based on the time spent under warnings, although warning response could impose several other costs. For example, Hammer and Schmidlin (2002) found that almost half of their survey respondents drove out of the path of the 3 May 1999 Oklahoma City F5 tornado, and more than 20% of manufactured home residents surveyed by Schmidlin et al. (2009) left their homes during a warning. Manufacturing plants, retail stores, and other businesses that shut down during a warning will take time to resume operations, and residents might use blankets or mattresses for protection, which need to be replaced after the warning. To begin to quantify the cost of tornado warnings, focusing on the time spent under the warnings seems like a reasonable approach.

The person-hours spent under warnings then measures the cost of tornado warnings. The NWS now issues about 3500 tornado warnings per year, up from about 1000 per year in the late 1980s (Fig. 1). The increase in the number of warnings issued coincides with the installation of the Next Generation Weather Radar (NEXRAD) network of WSR-88D radars, which was largely completed during 1995. Consequently, we calculate the time spent under warnings between 1996 and 2004.[3] The person-hours spent under an individual warning equals the estimated population of the warned county multiplied by the duration of the warning. County population uses the Census value for 2000, the linear interpolation of the 1990 and 2000 Census totals for 1996–99, and the Census annual population estimates for 2001–04 [Census Bureau population estimates for counties are available online at http://www.census.gov/popest/datasets.html.]. Here, we illustrate these calculations for three warnings issued for Oklahoma County, Oklahoma. A warning was issued 22 October 2000 at 1803 UTC and renewed until 1900 UTC, for a total warning time of 57 min (0.95 h). The population of Oklahoma County in the 2000 Census was 660 448, so this warning was in effect for 627 000 person-hours. The county was warned on 26 May 1996 from 1802 to 1900 UTC or 58 min (0.97 h). The 1990 Census population was 599 611, so the linear estimate of 1996 population places weights of 0.4 and 0.6 on the 1990 and 2000 Census totals for an interpolated estimate of 636 113 ($=0.4 \times 599\,611 + 0.6 \times 660\,448$); therefore, this

[3] Using the method employed by Simmons and Sutter (2005) to assign tornadoes to NWS Weather Forecast Offices, 99.1% of tornadoes in 1996–97 occurred in offices where WSR-88D radar had been installed. Radar installation was completed by the end of 1997.

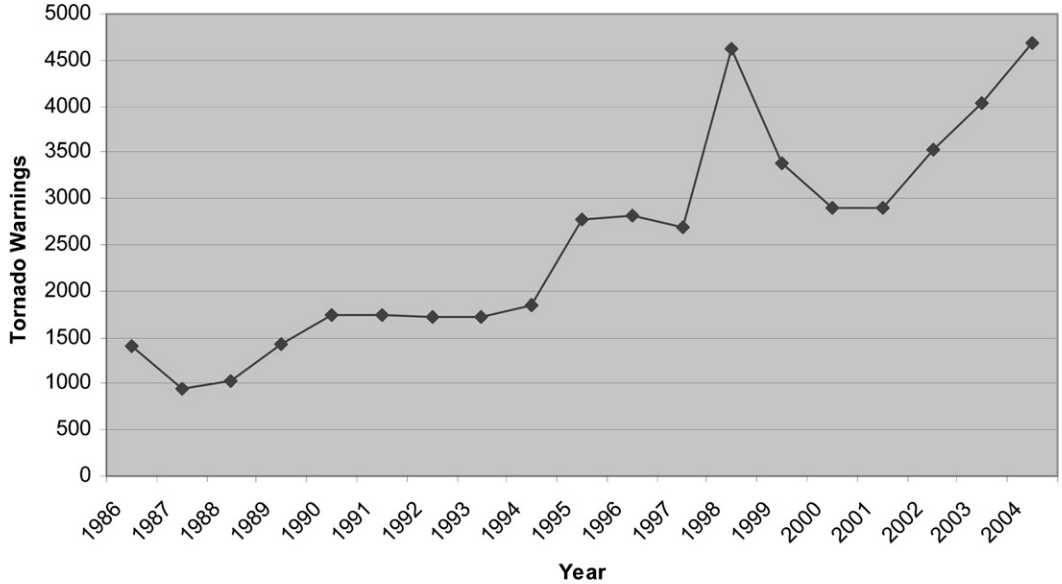

FIG. 1. Tornado warnings by year.

warning was in effect for 615 000 person-hours. Finally, the county was warned on 29 May 2004 from 1848 until 2100 UTC or for 72 min (1.20 h). The 2004 estimated population was 679 700, so this warning was in effect for 816 000 person-hours.

The 3500 warnings per year over the period were valid for an estimated 234 million person-hours annually. Table 1 reports the annual totals for each year from 1996 to 2004. The average warning was in effect for 41 min, which was reasonably constant over the period, and the average warned county had a population of 98 000. Although the annual totals vary substantially, the minimum person-hours under warnings in any year was 164 million in 1999.

Halting one's daily activities to take cover during a tornado warning is costly. All activities including leisure activities require time, and thus time spent sheltering has an opportunity cost for residents. Economists use the term utility to represent the value or satisfaction people get from consumption or other activities, and the cost of sheltering is the reduction in utility residents experience when sheltering instead of continuing their previous activity. In some cases, the opportunity cost will be monetary but in many cases it will not. Regardless of whether the cost is explicitly monetary, residents suffer a loss of utility when sheltering. That residents willingly incur the cost to reduce their chance of being killed or injured does not eliminate the cost.

Tornadoes occur at different times of the day and can affect individuals at work or play, as well as working adults, children, and the elderly. Consider these four cases of time and the value of time in each case:

1) Members of the workforce during their work hours. These persons' productive activities are disrupted to shelter during the warning. If a store or restaurant closes, a theater halts a movie, or a plant stops production, then the warning response disrupts economic activity.
2) Members of the workforce during their off-the-job hours. These persons lose scarce time for leisure activities; in general, people weigh the value of leisure time against hourly income in deciding how many hours to work.
3) Working age persons who are not employed. Although these persons do not lose time that would have been spent working when they shelter, these persons presumably have weighed potential income from working in their labor force participation decision, and have decided that their time is more valuable to them than the money they could potentially earn.

TABLE 1. Time spent under tornado warnings, 1996–2004.

Year	Person-hours under warnings (millions)	Average length of tornado warnings (in minutes)	Average person-hours per warning
1996	190.8	42.7	95 470
1997	202.4	45.1	99 990
1998	328.8	45.0	95 000
1999	164.2	42.1	69 010
2000	196.0	39.2	103 100
2001	187.9	38.8	100 100
2002	185.6	30.9	101 900
2003	292.3	41.2	105 900
2004	361.0	41.4	111 500

4) Persons who are not of working age or who would not be working under any circumstances. This would include young children, the elderly, and the severely handicapped.

The hourly wage represents a convenient, practical way to value time saved for benefit cost analysis, with leisure valued relative to working time. In the four cases laid out here, the hourly wage seems most applicable as the opportunity cost of time spent under warnings in the first case. Even if workers are not docked for time spent sheltering, the disruption of productive activities is costly to society, and this can be valued at an average wage. In the second case, if people can choose the number of hours they work, then they will work until the utility from the money earned from an extra hour working equals the utility from an extra hour to devote to leisure activities (including sleeping). Thus, some economists argue that leisure hours could be valued at the hourly wage, as this represents the opportunity cost of time (see the discussion in Smith et al. 1983). In the third case, people are not working at all, and thus the wage does not seem to represent an opportunity cost. Yet these persons could choose to work, and their potential earnings represent an opportunity cost. In the final case, we have individuals who would not be working under any circumstances and thus the wage seems an inappropriate opportunity cost for these persons' time. Yet we also must acknowledge that the young and old probably consider their time to be valuable and thus incur a cost when spending time sheltering, as opposed to continuing their daily activities.

Economists have addressed the question of valuing leisure time. The potential for multiple constraints complicates the valuation; that is, the value of leisure time can depend on constraints on the leisure activity (e.g., does it require daylight). Smith et al. (1983, pp. 264) conclude that "the opportunity cost of time is best treated as a nonlinear function of time". In some cases for tornado warnings, the opportunity cost of responding to a warning may in some cases be low, practically speaking zero. For example, residents may be able to undertake leisure activities like reading a book or magazine while sheltering in a basement or safe room. In fact, these may be the activities "disrupted" by the warning. But there are other leisure activities whose disruption would be quite costly, such as a high school graduation ceremony.

The only practical approach to valuing time for many individuals is to use some fraction of the average wage rate. If employed persons choose how many hours to work (admittedly a debatable assumption for individuals, but certainly valid for individuals in the aggregate), the hourly wage represents the opportunity cost, so we will use the average hourly wage to value all of the time of persons in the labor force. The value of time for persons not in the labor force, including children, must be valued at less than the wage. Cesario (1976) argues that based on available evidence a value of between 25% and 50% of the hourly wage could be applied and recommends a value of one-third of the hourly wage, which we will use for persons not in the labor force. Our sensitivity analysis will apply a lower value of leisure in the calculation of the value of time.

We use the average civilian, nonfarm hourly wage of $17.42 in 2007 to value time under warnings (available online at ftp://ftp.bls.gov/pub/suppl/empsit.cseeb2.txt). Here, we apply a value of one-third this amount, $5.81, for persons who are not employed. Thus, we use a weighted average value of time, with weights based on the proportion of the population employed. In 2007, 48% of the U.S. population was employed, which yields an average value of time of 11.38 U.S. dollars ($=0.48 \times 17.42 + 0.52 \times 5.81$). The value of the 234 million person-hours spent under warnings annually between 1996 and 2004 is thus $2.67 billion.

3. The value of time sheltering saved with storm-based tornado warnings

SBWs are polygons based on the location of the potential tornado and typically are much smaller than an entire county. In trials during the 2004 and 2005 storm seasons, the area warned was reduced between 70% and 75% compared with traditional county warnings (M. Looney 2006, personal communication; Jacks and Ferrere 2007); in the February 2008 Super Tuesday tornado outbreak, the first major test of SBW in practice, the area warned was reduced by 61%.[4] We will use a 70% reduction in our calculations and assume that this reduction also applies to time spent under warnings.

The time spent under warnings does not measure the loss of time due to warnings because not all time under warnings is spent sheltering. An estimate of time savings for SBW must adjust for warning response. Time spent sheltering is less than the time under warnings for two reasons: some persons respond for only a portion of the valid period of the warning and others do not respond at all, because they either ignore or do not receive the warning. No evidence is available on the first question, and so we combine both factors into one response rate. Evidence on the response rate to tornado warnings is sparse (Sorensen 2000). Surveys of residents after tornadoes provide the available evidence. Table 2 lists surveys the authors have found on the response to tornado warnings. The reported response rates range from

[4] Authors' calculations based on the area-warned reduction reported in NWS (2009).

TABLE 2. Summary of the studies of tornado warning response.

	State(s)	Response rate	Notes
Studies directly asking about response			
Liu et al. (1996)	Alabama	29% without sirens 66% with sirens	Warned county
Balluz et al. (2000)	Arkansas	46%	
Paul et al. (2003)	Missouri	89%	Communities struck by tornadoes
Tiefenbacher et al. (2001)	Wisconsin	53%	Community struck by tornado but outside of damage path
Schmidlin et al. (2009)	Georgia, Illinois, Mississippi, Oklahoma	31%	Warned county
Studies with indirect information			
Hodler (1982)	Michigan	48%	Storm path
Legates and Biddle (1999)	Alabama	70%	Storm path
Hammer and Schmidlin (2002)	Oklahoma	87%	Storm path

just under 30% to almost 90%. Note that these are response rates and a further adjustment must be made for the portion of warning during which the residents shelter. Several additional studies listed in the bottom portion of Table 2 report information similar to a response rate. These latter studies typically asked residents where they were when a tornado struck, which does not indicate if residents were sheltering. We interpret locations consistent with NWS recommended response as indicating response in these studies. Consideration of these studies as a group is consistent with a 50% response rate or that 50% of time under county warnings was spent sheltering.[5]

The response rate relevant for estimating time spent sheltering saved with SBW will be less than 50%. The response rate to warnings is based on responses throughout the warning area. Many of the responses in the surveys in Table 2 would be from residents near the path of the tornado who could still be in the polygon of an SBW. To estimate the time spent sheltering saved with SBW, we need the response rate to warnings outside of the polygon, which is likely lower in the more remote parts of the previously warned counties. The theory of hazard warning response contends that people will seek to confirm and personalize a threat before responding (Mileti and Sorensen 1987). For tornadoes, this could involve seeking visual confirmation of the proximity of the tornado or wall cloud, which surveys often reveal people do (e.g., Hodler 1982; Schmidlin et al. 2009). Thus, the assumed 50% response rate averages the response rates within and outside the polygon, or, the response rate = 0.3 × (response rate in polygon) + 0.7 × (response rate outside the polygon) assuming a 70% area-warned reduction with SBW. The notes for the surveys listed in Table 2 indicate when possible whether the sample was drawn from an area in close proximity to the tornado or not, and thus whether the reported response would be inside the polygon or across the county. The available evidence still does not pin down a response rate, and thus we assume a response rate of 40% outside of the polygon, although in the sensitivity analysis we consider a rate as low as 10%.[6]

We can now adjust our time under warnings totals for warning response and estimate the time benefits for SBW. Each year an average of 234 million person-hours were spent under county warnings with a value of $2.67 billion. SBW will reduce these totals by 70%, which is 164 million person-hours worth $1.9 billion annually. With a 50% response rate, an estimated 117 million person-hours were spent sheltering under county warnings annually, with a value of $1.33 billion. Finally, 40% of the time spent sheltering under county warnings will be saved by SBW, so we estimate that SBW will save 66 million person-hours actually spent sheltering annually, with a value of $747 million.

4. Sensitivity analysis

The four annual estimates established previously—person-hours spent under county tornado warnings in the United States (234 million), the value of time spent

[5] One further qualification of the available evidence is that surveys are typically conducted after significant tornado events, and thus existing surveys may as a group be unrepresentative of responses to warnings in minor events or nonevents.

[6] The overall response rate and the portion of the population in the SBW polygon place a lower bound on the response rate outside of the polygon. For instance, if the overall response rate was 50%, then even if the response rate in the polygon was 100%, the response rate outside of the polygon would have to be almost 30%.

under county warnings ($2.67 billion), the value of time spent sheltering for tornadoes ($1.33 billion), and the time spent sheltering that might be saved with SBW for tornadoes ($747 million)—depend in total on four parameters. The time spent sheltering savings for SBW is a product of

$$\text{(Hours under Warnings)} \times \text{(Value of Time)} \\ \times \text{(Area Warned Reduction with SBW)} \\ \times \text{(Response Rate outside of the Polygon)}.$$

The other estimates also use one or more of the parameters. The parameters cannot be precisely estimated given the available evidence, which results in an uncertainty regarding our estimates of the time savings for SBW and other values. To examine the effect of this uncertainty on our estimates, we now undertake a sensitivity analysis. We begin by considering plausible ranges for each of the four parameters.

a. Hours under warnings

This component is estimated precisely given tornado activity between 1996 and 2004. The only uncertainty for this parameter arises from whether these 9 years represent a normal rate of tornado activity. We will cast a wide net with our range and take the minimum and maximum totals of person-hours under warnings over the period—164–361 million (see Table 1)—as our range.

b. Value of time

The average hourly wage reflects the opportunity cost for work time; however, uncertainty arises over the fraction of the wage to use for leisure time spent sheltering, given that some leisure activities can be undertaken while sheltering. As an upper bound for value, the wage arguably reflects the opportunity cost of the working age population between 18 and 65 years of age (62% of the U.S. population in 2000), regardless of whether they work, and the time of those not of working age could be valued at half of the average wage. These adjustments result in a weighted average value of $14.11 h^{-1}. As a lower bound, we could place no value on the time of the young and elderly and value the leisure time of working adults at 25% of the hourly wage. This results in a weighted average value of $4.79 h^{-1} or 27% of the hourly wage.[7]

c. Area-warned reduction with SBW

We use a 75% reduction in the early testing of SBW as an upper bound. In the 5–6 February 2008 tornado outbreak, the reduction for the Paducah, Kentucky, NWS Weather Forecast Office (WFO) relative to county warnings was 56.9%, which was the lowest of the six WFOs evaluated (NWS 2009). We use 55% as a lower bound for the area reduction.

[7] This calculation assumes that 33% of time under warnings for the employed population occurs on the job.

TABLE 3. Range of parameter values for sensitivity analysis.

Parameter	Base value	Lower bound	Upper bound
Time under warnings	234.4 million h	164.2 million h	361.0 million h
Value of time	$11.38 h^{-1}	$4.79 h^{-1}	$14.11 h^{-1}
Area-warned reduction	0.70	0.55	0.75
Response rate	0.40	0.10	0.60

d. Response rate outside of the polygon

The surveys found response rates from 29% to 89% (Table 2), but these studies do not focus on areas outside of the polygon. The response rate also accounts for the proportion of warning time that residents are sheltering. The choice of rates for sensitivity analysis is still arbitrary, and we will use 10% as a lower bound and 60% as an upper bound.

Table 3 summarizes the range of values for each parameter used in the sensitivity analysis, along with the base values. Table 4 illustrates how our estimates of the value of time spent under warning and sheltering depend on each parameter. Each row examines the effect range of making the calculation with the minimum and maximum values for a parameter; for example, the value of time spent under county warnings ranges from $1.1 billion to $3.3 billion, based on the range of values of time. The value of time spent sheltering under county warnings ranges from $560 million to $1.7 billion depending on the value of time employed and from $270 million to $1.6 billion based on the response rate used in the calculations. The final four rows consider the time sheltering savings with SBW. The area-warned reduction produces the smallest variation, from $590 million to $800 million, whereas the response rate generates the largest range, from $190 million to $1.1 billion. Only for the value of time and the response rate do the estimated time sheltering savings from SBW fall below $500 million.

The ranges for each parameter allow us to explore the distribution of time sheltering savings from SBW based on variation of several parameters. To perform this analysis, we assume that each parameter is independently and uniformly distributed over the ranges displayed in Table 3. We then divided the range for each parameter into five equally sized intervals, which yields six values for each parameter; for instance, for the warning response rate, we have values of 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6. The six

TABLE 4. Sensitivity analysis using parameter ranges.

Calculation	Parameter	Value at minimum (U.S. dollars)	Value at maximum (U.S. dollars)
Value of time under tornado county tornado warnings	Value of time	$1.12 billion	$3.31 billion
Value of time spent sheltering under county warnings	Value of time	$561 million	$1.65 billion
Value of time spent sheltering under county warnings	Response rate	$267 million	$1.60 billion
Time sheltering savings from SBW	Time under warnings	$523 million	$1.15 billion
Time sheltering savings from SBW	Value of time	$314 million	$926 million
Time sheltering savings from SBW	Area-warned reduction	$587 million	$800 million
Time sheltering savings from SBW	Response rate	$187 million	$1.12 billion

values for each parameter yield 1296 ($=6^4$) different combinations and allow examination of the distribution of the time sheltering savings for SBW. Table 5 presents the summary statistics of the resulting distribution. The mean time sheltering savings is $565 million and the median is $473 million. Thus, the sensitivity analysis indicates that the estimate of $747 million with the baseline parameter values might be optimistic. The time sheltering savings across all of the parameter combinations ranged from $43 million to $2.3 billion. Ninety-five percent of the parameter combinations yielded benefits in excess of $109 million. Thus, SBWs are likely to produce substantial time savings for the United States of at least $100 million and quite possibly $500 million or more.

5. Further considerations

We have focused on the time under warnings saved with SBW, and thus our analysis does not comprise a complete assessment of the societal impacts of SBW. We consider here the effect of SBW on casualties. The area immediately threatened by a tornado will still be warned, so the SBW should not compromise safety (more information available online at http://www.spc.noaa.gov/archive/). The process of identifying a circulation on radar to warn for is unchanged, so the probability that a warning is issued should not go down. Consequently, any impact of SBW on casualties will depend on indirect or second-order effects.

Several factors might increase casualties, like the potential for a tornado to veer out of the polygon and into an unwarned area. Also, the smaller area of each warning and the time needed to prepare the warning (to describe the polygon warning area) could reduce warning lead times. The description of the warning area might confuse residents, who may fail to realize that they are under a warning. Barnes et al. (2007) note that warnings are often relayed by residents so a reduction in warning area may reduce warning transmission in this manner. Although these factors deserve consideration, they would likely have a small and temporary impact; for instance, because many U.S. residents do not know their county of residence, confusion is not a new problem for tornado warnings. Residents typically rely on a broadcast meteorologist, tornado sirens in their community, or NOAA Weather Radio to alert them that they are under a tornado warning. SBW will still be announced by a siren or alert from the Weather Radio, so as long as residents understand the meaning of the warning, they only need to respond when alerted. The extra time needed to describe a warning polygon should be minor with digitized maps. Finally, a modest reduction in lead times may have little effect on casualties. Simmons and Sutter (2008) examined the effect of warning lead time and found that the largest reductions in fatalities or injuries occurred for lead times of less than 15 min. Response by residents to a warning takes little time and, although a longer lead time provides more time to disseminate the warnings, the evidence suggests that the benefits of a longer lead time are captured by a 15-min advance notice.

SBW have considerable potential to improve warning response and thus reduce casualties. Tornado damage paths are small compared to counties, as mentioned previously. County warnings over warned for tornadoes, which is why SBW can substantially reduce warning areas. However, this also implies that county-based warnings conveyed a surprisingly low threat; the probability of damage at any location for an average-sized damage path and warned county was about 1 in 3000.

TABLE 5. Summary statistics from the sensitivity analysis. The statistics are for the value of time spent sheltering saved with SBW, based on 1296 parameter combinations.

Mean	$564 million
Median	$473 million
Standard deviation	$393 million
Minimum	$43.2 million
Maximum	$2.29 billion
95% excedence value	$109 million
90% excedence value	$149 million

Drobot et al. (2007) found that an important predictor for whether people would drive into flooded roads is whether they take flood warnings seriously. Some residents might not have taken a tornado warning for their county seriously because of the relatively low risk. This could explain why surveys often find that residents seek visual confirmation of the tornado before responding. SBW will triple or quadruple the probability of damage within a warning area.[8] It is too early to assess the impact of SBW on casualties, but consideration of the various indirect channels suggests a likely reduction in casualties.

Fully exploiting the potential benefits of SBW will require further changes to the warning process, particularly refining methods of warning transmission. NOAA Weather Radio and tornado sirens might need upgrading to warn based on the coordinates of the polygon; otherwise, warnings might still need to be transmitted to entire counties. The cost of time spent under county warnings identified here is relevant in considering these expenditures. Consider, for example, Harris County (Houston), Texas, which was warned 104 times for a total of 79 h between 1996 and 2004. Harris County spent an average of 30 million person-hours with a value of $350 million under warnings annually. A one-time expenditure of, say, $5 million to install sirens capable of warning based on polygons would be quite modest relative to the cost of county-wide warnings.

6. Tornado warnings and the total societal cost of tornadoes

The value of time spent under warnings represents a considerable portion of the cost of tornadoes to the United States each year. To see this, we compare the time cost of warnings with the dollar value equivalent of tornado casualties and the value of property damage. Inflation-adjusted property damage (direct losses), fatalities, and injuries annually averaged $1.07 billion, 58.6, and 999, respectively, between 1996 and 2006. [Damage totals are taken from SPC (see online at http://www.spc.noaa.gov/archive/) and adjusted for inflation using the consumer price index (CPI) for housing (series CUUR0000JAA, available online at http://data.bls.gov/cgi-bin/surveymost?cu).] Loss data for natural hazards are subject to numerous biases, as described by Gall et al. (2009), who report that tornado losses in the United States between 1950 and 2005 vary by a factor of 2 across different publicly available databases. To compare the time under warnings and damage with casualties, we will need to put a dollar value on the risks to life and limb. Economists have developed the concepts of the value of a statistical life and the value of a statistical injury to facilitate such comparisons. These values are based on trade-offs between money and risk made in everyday life, such as deciding whether to purchase an optional automobile safety feature.[9] Economists have estimated the value of a statistical life implicit in various trade-offs, often focusing on wage premiums for risky jobs in the labor market (for surveys of this literature see Viscusi and Aldy 2003; Viscusi 2004). The Environmental Protection Agency (EPA) employed values of statistical lives and injuries in a cost benefit analysis of the Clean Air Act. The Agency used a value of a $4.8 million (in 1990 dollars) based on a meta analysis of dozens of published studies (EPA 1997). Adjusting for inflation produces a value of $7.6 million in 2007 dollars, yielding a value of tornado fatalities of $446 million annually. [The adjustment for inflation uses the CPI for all urban consumers (series CUUR0000SAO), available online at http://data.bls.gov/cgi-bin/surveymost?cu.] The same approach was applied by the EPA to injuries and illnesses, based on different values for various ailments. In applying this approach for tornado injuries, the limiting factor is a paucity of evidence on the severity of injuries. Some available epidemiological studies suggest that overall tornado injuries are not very severe. Brown et al. (2002), for example, found that 76% of injuries in the 3 May 1999 Oklahoma tornado outbreak did not require hospitalization, and hospital stays when required averaged seven days. Carter et al. (1989) found that 83% of injuries in the 31 May 1985 Ontario, Canada, tornado outbreak were minor, with serious injuries requiring an average hospital stay of 12.5 days. Based on this and values of statistical injuries reported in the economics literature, Simmons and Sutter (2006) value tornado injuries at 1% of the value of a statistical injury, or $76 000 in this case, for a total value of $76 million per year.[10]

The total cost of tornadoes in the United States depends on whether time under warnings or estimated time spent sheltering is used as the cost of tornado warnings. Table 6 presents a total monetized cost using

[8] The proportional increase in the probability of damage is 1/(1 − CAR), where CAR is the reduction in area relative to county warnings.

[9] For a further discussion of the values of statistical lives and injuries, see Viscusi et al. (2000).

[10] A recent study of the Federal Emergency Management Agency (FEMA) mitigation projects (Multihazard Mitigation Council 2005) provides an alternative means to value tornado injuries. This study assumes tornado casualties are geometrically distributed across a 5-point severity scale, with monetized values of injuries ranging from $6000 to $2.4 million, and it yields a value of a statistical injury for tornadoes of about $40 000. Given that injuries account for about 2% of the monetary impact of tornadoes, the cost per injury would need to substantially exceed the $76 000 figure to materially affect the total.

TABLE 6. The annual impact of tornadoes. Damage and casualties are averages for 1996–2006 and time under warnings an average for 1996–2004. The valuation of lives lost, injuries, and time under warnings is discussed in the text.

Impact	Average annual total	Monetized value (U.S. dollars)	Percent of impact for time under warnings	Percent of impact for time spent sheltering
Property damage	$1.07 billion	$1.07 billion	25.2	36.6
Fatalities	58.6 persons	$445 million	10.5	15.2
Injuries	999 persons	$75.9 million	1.8	2.6
Time under warnings	234 million person-hours	$2.67 billion	62.3	
Time spent sheltering	117 million person-hours	$1.33 billion		45.6
Total time under warnings		$4.25 billion	100.0	
Total time spent sheltering		$2.92 billion		100.0

both figures. Both totals indicate that tornado warnings are the largest component of the cost of tornadoes and are 3–6 times greater than the monetized cost of fatalities. Using time under warnings, warnings compose 62% of the total cost of $4.3 billion per year. If time spent sheltering is used, the total cost is $2.9 billion, with warnings accounting for 46% of the total. Of course, the same caveats discussed previously apply in valuing time and estimating warning response. Even if further adjustments are made, the point that county-based tornado warnings constitute an important portion of the total cost of tornadoes in the United States remains valid.

Readers might find the cost of tornado warnings and thus the potential benefits from SBW surprising. The large contribution of tornado warnings results from two factors: the installation of Doppler weather radars in the 1990s that led to a large increase in the number of warnings issued annually (see Fig. 1) and the success of NWS efforts to reduce the lethality of tornadoes (Doswell et al. 1999). To illustrate this latter point, Brooks and Doswell (2002) estimate that the smoothed, 25-yr U.S. tornado fatality rate declined from 1.8 per million in 1925 to 0.11 per million in 2000. An average of 59 tornado fatalities occurred per year between 1996 and 2006; if not for the proportional reduction in the fatality rate observed by Brooks and Doswell, the United States could have experienced 960 fatalities annually. The monetized value of 960 fatalities a year using a $7.6 million value of a statistical life is $7.3 billion. If no tornado warnings were issued today and the 1925 fatality rate prevailed, the fatality cost would be $7.3 billion but there would be no warning cost. Instead, the total cost of tornadoes today is substantially less, but warnings compose the largest component of that cost.

7. Conclusions

Over warning refers to warning people who do not end up at risk in a hazard. Imperfect understanding of hazards, constraints on technology, and the time needed to respond make overwarning inevitable. The high cost of evacuation has highlighted the overwarning problem for hurricanes but to date little has been noted about the cost of tornado warnings. County tornado warnings, however, were quite costly, with an average of 234 million person-hours spent under tornado warnings annually between 1996 and 2004. We estimate the value of this time at $2.7 billion, and the cost of time spent sheltering for these warnings might have been as much as $1.3 billion per year. SBW for tornadoes have the potential to reduce these totals by possibly 75%, with the time under warnings reduced by 164 million person-hours per year and the value of time spent sheltering reduced by $747 million per year. The estimate of the value of time spent sheltering relies on several imprecisely estimated parameters. Sensitivity analysis places a 95% confidence bound for time sheltering savings at just over $100 million annually. Thus, SBW will substantially reduce the societal impact of tornadoes. SBW still warn the areas closest to the tornado, so there should be no direct impact on tornado casualties, but casualties could be affected indirectly. Casualties might increase because of confusion about the new warnings or the potential for a tornado to move out of the polygon warning area. However, the warning response should improve because the smaller warning area will convey to residents a greater threat.

The imprecision of the parameter estimates indicate areas for future research. We have too little evidence on response to warnings, and the issue of how long people shelter when they respond has not been addressed by the existing studies. The average tornado warning over our period of examination was around 40 min, so whether people actually shelter for 40 min or more for a tornado warning is a relevant open question. Also, we have identified several issues regarding an assessment of the impact of SBW in the future. The time spent sheltering savings will in many cases require auxiliary investments to refine the precision of warning transmission, and these investments may not be made. SBW will convey a much higher level of risk relative to the average risk across a warned county, so the response rate should increase, particularly in large counties; eventually, the impact of the new warnings on casualties should be investigated once SBW have been issued for enough years to allow a statistically significant analysis.

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