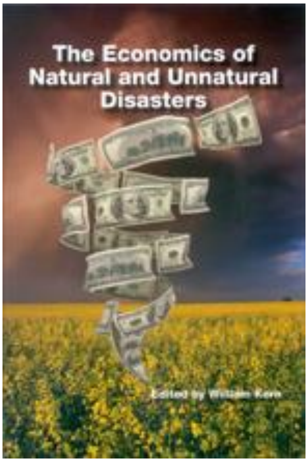
The Socioeconomic Impact of Tornadoes



Daniel Sutter
University of Texas-Pan American

Kevin M. Simmons
Austin College

Chapter 6 (pp. 103-132) in:
The Economics of Natural and Unnatural Disasters
William Kern, ed.
Kalamazoo, MI: W.E. Upjohn Institute for Employment Research, 2010
DOI: 10.17848/9781441678812.ch6

The Economics of Natural and Unnatural Disasters

William Kern
Editor

2010

W.E. Upjohn Institute for Employment Research
Kalamazoo, Michigan

Library of Congress Cataloging-in-Publication Data

The economics of natural and unnatural disasters / William Kern, editor.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-88099-362-3 (pbk. : alk. paper)
ISBN-10: 0-88099-362-6 (pbk. : alk. paper)
ISBN-13: 978-0-88099-363-0 (hbk. : alk. paper)
ISBN-10: 0-88099-363-4 (hbk. : alk. paper)
1. Disasters—economic aspects. I. Kern, William S., 1952– II. W.E. Upjohn Institute for Employment Research.
HC79.D45E25 2010
363.34—dc22
2010010590

W.E. Upjohn Institute for Employment Research
300 S. Westnedge Avenue
Kalamazoo, Michigan 49007-4686

Cover design by Alcorn Publication Design.
Index prepared by Diane Worden.
Printed in the United States of America.
Printed on recycled paper.

6

The Socioeconomic Impact of Tornadoes

Daniel Sutter
University of Texas–Pan American

Kevin M. Simmons
Austin College

Tornadoes are nature's most powerful and destructive storms, capable of producing winds in excess of 300 miles per hour, yet they are notoriously capricious, leveling one home and leaving the next undamaged. The United States experiences more than 1,200 tornadoes per year, and since 1900 over 15,000 lives have been lost in tornadoes. The deadliest tornado in U.S. history, the 1925 Tri-State Tornado, tracked across three states and killed 695 persons, devastating entire towns. Tornadoes have occupied a place in the national consciousness at least since the 1939 movie *The Wizard of Oz*, when a Kansas twister blew Dorothy and Toto to Oz. Every spring thousands of people spend weeks trekking across the Plains chasing tornadoes.

How can economists or social scientists contribute to our knowledge of tornadoes? While cloud dynamics and the technical properties of weather radars are outside these fields, economics can help us understand the impact of tornadoes on society. Economics can provide relevant evidence on several issues related to societal impacts:

- Have tornadoes become less deadly over time?
- If so, how much have the efforts of the National Weather Service (NWS) contributed to this?
- What measures offer the greatest potential to reduce casualties in a cost-effective manner?

An understanding of the causes is necessary to reduce the impacts of severe weather. Just as physicians must understand the causes of illness to successfully treat patients, meteorologists require information about societal impacts. Attempts to reduce casualties not founded on solid analysis could prove unsuccessful or incur excessive costs.

Tornadoes also provide evidence on some questions of significance to policymakers:

- People sometimes have difficulty making sense of small risks of death and either overestimate or underestimate these risks (Camerer and Kunreuther 1989; McClelland, Schulze, and Coursey 1993). Is misperception of risk a problem with tornadoes?
- Can an economic model of information help us understand peoples' reactions to hazard warnings?
- How prevalent is underpreparation for natural hazards? Hurricane Katrina has raised the issue of poor societal preparation for hazards to high salience for policy (Meyer 2006).

Because of the broad reach of tornadoes (they have occurred in all states), their impacts depend on the preparations and actions of essentially all Americans, a fact that underscores the importance of evidence regarding these events.

This chapter analyzes the impact of tornadoes on the United States and is organized as follows. The next section reviews the aggregate impact of tornadoes on the nation, including three main components: 1) the cost of casualties, 2) the value of property damaged or destroyed, and 3) the cost of responding to tornado warnings. Overall the monetized cost of tornadoes is $4.6 billion per year. We then discuss findings on the determinants of tornado casualties, and we use these findings to analyze how the impacts might be reduced. The final section offers a brief conclusion.

THE SOCIETAL COST OF TORNADOES

Tornadoes threaten life and limb, and they damage and destroy property. Tornado warnings are also costly, because people must disrupt their daily activities to take shelter during a tornado warning. To provide perspective on the impact of tornadoes, we monetize the value of casualties, damages, and sheltering costs, based on U.S. averages for 1996–2006. Damage is the easiest to monetize, and we use inflation-adjusted property damage as reported by the NWS, which averaged $1.07 billion annually (in 2007 dollars).[1] Note that 1996–2006 included the tornado with the greatest reported damage in U.S. history, the May 3, 1999, Oklahoma City F5 tornado.[2]

A total of 645 tornado fatalities occurred between 1996 and 2006, or 58.6 per year. Comparing fatalities with damage requires application of a dollar figure for the lives lost. The value of a statistical life as revealed in market trade-offs constitutes a reasonable way to value lives for such public policy purposes.[3] We use the value of a statistical life applied by the Environmental Protection Agency in a benefit-cost analysis of the Clean Air Act (EPA 1997). The EPA used a figure of $4.8 million in 1990 dollars, based on a meta-analysis of dozens of published studies. Adjusting this value for inflation yields a value of $7.6 million in 2007 dollars. The monetized value of tornado fatalities is thus $445 million per year.

Tornadoes injured an average of 999 persons annually. Values of statistical injuries have been developed using market data, and the EPA (1997) has applied monetary values for a variety of injuries. A difficulty arises in applying existing values to tornado injuries due to a dearth of information on the distribution of the severity of tornado injuries. Epidemiological studies in the aftermath of selected tornadoes provide some evidence on the severity of injuries, which overall are not very severe. Brown et al. (2002), for example, found that 76 percent of injuries in the May 3, 1999, Oklahoma tornado outbreak did not require hospitalization and that the average hospital stay was seven days. Carter, Millson, and Allen (1989) found that 83 percent of injuries in the May 31, 1985, Ontario, Canada, tornado outbreak were minor, with an average hospital stay of 12.5 days. Given this evidence, we follow Merrell, Simmons, and Sutter (2005) and use a value of a statistical injury equal to 1 percent of the value of a statistical life, or $76,000. The monetary value of injuries is then $76 million per year.

We turn next to the cost of tornado warnings, that is, the value of time spent under warnings. Although taking cover during a tornado warning can save lives, the disruption of business or leisure activities is costly. Between 1996 and 2004, the NWS issued around 3,500 warnings per year, which were in effect for an average of 41 minutes each.[4] We use the U.S. Census estimated population of the warned county and the duration of each warning to estimate person-hours spent under warnings. The average warned county had a population of 98,000, so an average of 234 million person-hours were spent under warnings annually. For members of the workforce, the hourly wage measures the opportunity cost of time. We use the average civilian nonfarm hourly wage of $17.42 in 2007 (BLS 2007) to value employed persons' time lost, and we value the time of individuals who are not employed, 52 percent of the population, at half this amount. The weighted average value of time is $12.89, and the annual value of time spent under warnings is $3.02 billion.

Table 6.1 summarizes the impacts of tornadoes quantified here. The cost is $4.6 billion per year, and the value of time spent under warnings accounts for nearly two-thirds of this total, property damage 23 percent, fatalities at just under 10 percent, and injuries less than 2 percent. Note that this total does not include societal impacts, such as business interruption, alternative living expenses, and external, community-wide impacts. Although tornado impacts on a metropolitan area are modest, major tornadoes can significantly impact small communities. In April 2007, a tornado heavily damaged the business district of Tulia, Texas (population 4,700). The town's only grocery store never reopened after the tornado, leaving residents with a 60-mile round trip drive to Amarillo for grocery shopping (Martinez and Ewing 2008).

Readers might find the large contribution of time under warnings to the total impact of tornadoes surprising. One way to put the costs of warnings in perspective is to consider how the cost of tornadoes would have differed in the 1920s. Brooks and Doswell (2002) estimate that the U.S. tornado fatality rate fell from 1.8 per million residents then to 0.11 per million in 2000. If the higher 1920s rate occurred today, the nation would experience an average of 960 fatalities per year, not the 59 actually observed since 1996. Applying the $7.6 million value of a statistical life yields a cost of fatalities of $7.3 billion annually; the NWS did not issue warnings in the 1920s, so there is no basis for comparing cost of time spent under warnings. The lethality of tornadoes has

Table 6.1 Annual Impact of Tornadoes

Impact	Amount	Monetized value ($ millions)	% of monetized impact
Property damage	—	1,070	23.2
Fatalities	58.6	445	9.7
Injuries	999	76	1.6
Time under warnings	234 million person-hours	3,020	65.5
Total		4,610	100.0

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

SOURCE: National Oceanic and Atmospheric Administration's (NOAA) tornado fatality location data, available from the NOAA by permission.

been so greatly reduced that responding to warnings now represents the largest part of the cost of tornadoes. The total cost is substantially lower today because tornadoes are less deadly.

WHAT ARE THE DETERMINANTS OF TORNADO CASUALTIES?

An analysis of tornado casualties reveals several significant patterns discussed in this section. The figures cited are from a regression analysis of tornado fatalities and injuries from 1986 to 2004. The data set has been constructed by the authors using the Storm Prediction Center's (SPC) national tornado archive, the NWS's tornado warning verification records, and U.S. Census data.[5] The unit of observation is the state tornado segment, because the SPC archive reports separate entries for multistate tornadoes. For simplicity we will usually just say tornadoes and not state tornado segments in the text. Appendix 6A discusses the details of the regression model and precise variable definitions, and Table 6A.1 reports the full results.

Most Tornadoes Are Not Killers

Only 347 of the almost 21,000 tornadoes in our data set resulted in one or more fatalities, and 1,988 resulted in one or more injuries. That is, 98 percent of tornadoes had no fatalities, and 91 percent caused no injuries. The risk to life and limb posed by tornadoes is quite concentrated in powerful storms. The most powerful tornadoes are rated F4 or F5 on the Fujita scale of tornado damage.[6] Nine of the ten F5 tornadoes and 42 percent of F4 tornadoes between 1986 and 2004 killed at least one person, and these tornadoes accounted for 43 percent of fatalities. The 41 tornadoes that resulted in five or more fatalities (less than 0.2 percent of the total) accounted for half of all fatalities.

Tornadoes rated F3 or stronger are much more likely to result in fatalities or injuries. Table 6.2, constructed from the regression analysis, reports fatalities and injuries by tornadoes of different F-scale ratings relative to an F0 tornado. Expected fatalities are about 27,000 times more likely with an F5 tornado than with an F0, and injuries are almost 2,000 times more likely in F5 tornadoes. Both fatalities and injuries increase fairly consistently with each F-scale category increase.

Location, Location, Location

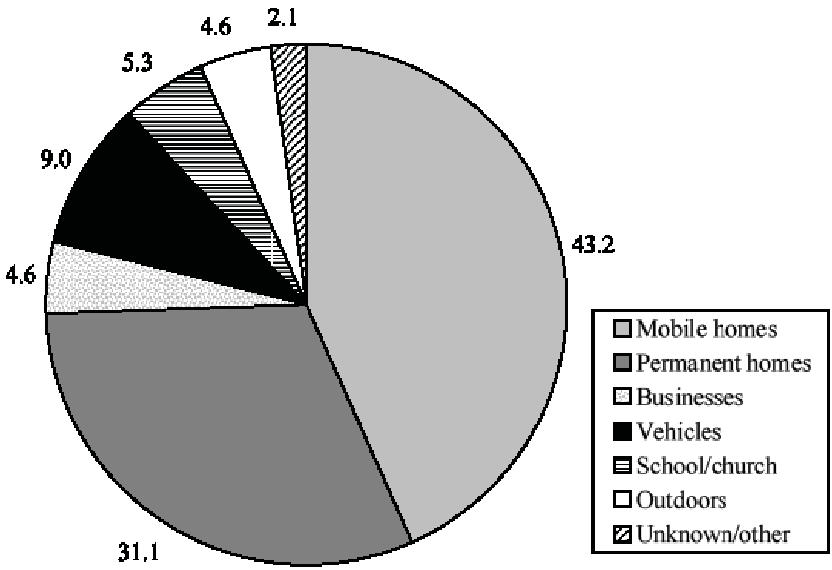
Many observers have noted the vulnerability of mobile homes to tornadoes (American Meteorological Society 1997; Brooks and Doswell 2002; Golden and Adams 2000; Golden and Snow 1991). Figure 6.1 reports tornado fatalities by location as tracked by the NWS for the years

Table 6.2 Tornado Casualties by Fujita Scale Rating

F-scale category	Fatalities	Injuries
F1	15	11
F2	105	65
F3	545	178
F4	2,644	692
F5	26,630	1,808

NOTE: The values in the table are the ratio of expected fatalities or injuries in a tornado of each F-scale category rating relative to an otherwise equivalent F0 tornado.
SOURCE: Authors' calculations.

Figure 6.1 Tornado Fatalities by Location (%)



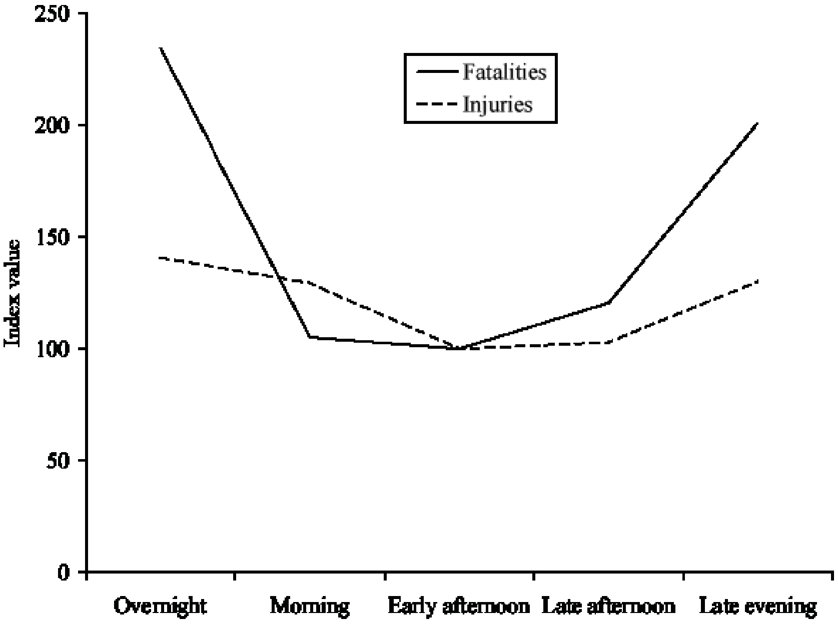
SOURCE: Authors' calculations from NOAA tornado fatality location data.

1985–2007.[7] More fatalities occurred in mobile homes (43 percent) than any other location. Permanent homes, which include single-family homes and apartments, rank second at 31 percent, followed by vehicles at 9 percent, schools and churches, businesses, and outdoor or other locations at about 5 percent each. The proportion of fatalities in manufactured homes is disproportionately high. These structures constituted only 7.6 percent of U.S. housing units in 2000 (U.S. Census Bureau 2000), but the fatality rate for manufactured homes is at least ten times that of permanent homes. Regression analysis confirms the dependence of casualties on the housing stock. An increase of one standard deviation in mobile homes as a proportion of county housing units increases expected fatalities by 36 percent and expected injuries by 26 percent.

Timing Matters

Timing significantly affects casualties, including time of day, day of the week, and month of the year. Tornadoes during the evening and overnight hours are significantly more likely to kill or injure people. Figure 6.2 reports an index for casualties by time of day based on the regression analysis. We divide the day into five time periods, the overnight hours (midnight to 6 a.m.), morning (6 a.m. to noon), early afternoon (noon to 4 p.m.), late afternoon (4 p.m. to 8 p.m.), and late evening (8 p.m. to midnight). The index sets fatalities and injuries from an early afternoon tornado equal to 100, and represents casualties from tornadoes at other times relative to an early afternoon tornado. Fatalities for overnight tornadoes exceed those of early afternoon tornadoes by a factor of nearly 2.5 and those for late evening tornadoes by a factor of

Figure 6.2 Time of Day and Tornado Casualties

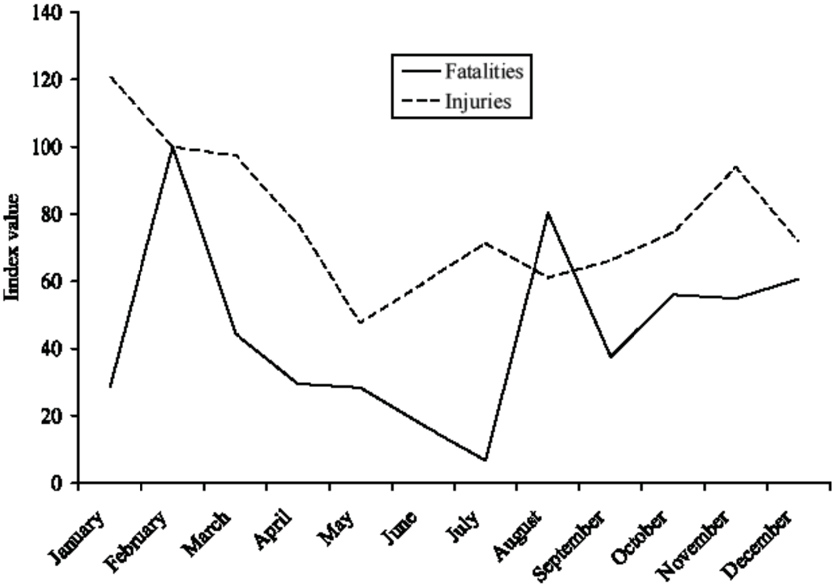


SOURCE: Authors' calculations from the NWS Storm Prediction Center's tornado archive.

more than 2. A similar pattern is observed for injuries, but the amplitude of the time of day effects are not as great; injuries are 43 percent and 32 percent higher overnight and in the late evening, respectively, than for a comparable early afternoon tornado.

Tornado casualties also vary widely by month. Figure 6.3 presents an index of fatalities and injuries by month derived from the regression analysis. The index equals 100 for both fatalities and injuries in February, the month with the deadliest tornadoes. The difference in lethality across months is quite substantial, as a tornado in February yields more than 14 times the fatalities of an otherwise equal tornado in July. Tornadoes are less deadly in the spring and summer months (with the exception of August) than tornadoes in the late fall or winter. Injuries exhibit the same basic pattern, except that again the variation is substantially less than for fatalities (injuries in January tornadoes exceed those in May tornadoes by a factor of 2.5). The low casualty rates

Figure 6.3 Tornado Casualties by Month



SOURCE: Authors' calculations from the NWS Storm Prediction Center's tornado archive.

in May, June, and July benefit the nation, since these months have the largest numbers of tornadoes, while the high lethality in November, December, January, and February applies to relatively few tornadoes. Although a difference in intensity of storms not fully captured by the F-scale variables may be thought to drive the result, the strongest tornadoes occur in the spring months. Hours of darkness might explain some of the variation over months, because tornadoes that occur after dark are more dangerous (see Ashley, Knmenec, and Schwantes 2008, who control for the exact time of sunset). But variation in casualties across months is much greater than the variation across the day, so darkness probably cannot explain much of the variation over the year. Surprise might drive this result; residents may not expect tornadoes during the winter, and thus are not alert for and ready to respond to a warning. In contrast, during the spring residents might suspect that an ominous thunderstorm could produce a tornado. Surprise would need to affect warning responses, since the regressions control for tornado warnings.

The day of the week also affects fatalities. Intuition suggests that casualties might be higher on either weekends or weekdays. On weekends people might be busy with recreation and leisure activities and not closely following the weather and weather warnings, while weekday tornadoes could occur during evening rush hour traffic jams. The regression analysis finds that weekend tornadoes are more dangerous: expected fatalities and injuries are 40 percent and 8 percent higher, respectively, than for tornadoes during the week, although only the fatalities result attains statistical significance.

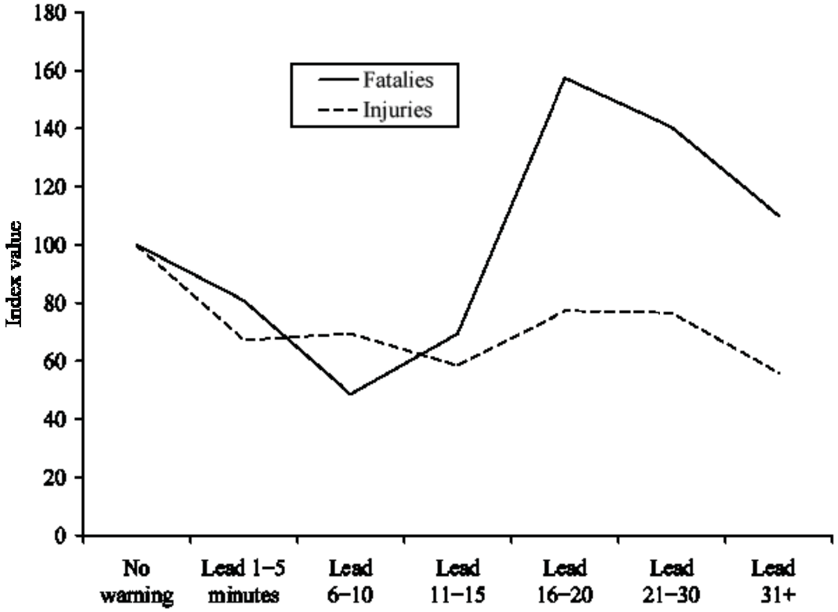
The Efforts of the National Weather Service

Protecting persons is part of the mission of the NWS, and tornado warnings have been issued since the 1950s to try to reduce casualties (Doswell, Moller, and Brooks 1999). The NWS installed WSR-88D (Doppler) radars at Weather Forecast Offices (WFOs) across the country between 1992 and 1997. The radars, adapted from military use, allow much better resolution of wind fields in severe storms. Viewers of weather coverage on television are probably familiar with the Doppler radar image of the “hook echo” of a tornado. Simmons and Sutter (2005) analyzed the effect of Doppler radar on tornado warnings and casualties by using the radar installation date for each WFO to determine which tornadoes occurred after installation of the new radars. Over the period from 1986 to 1999, Doppler radar increased the percentage of storms warned for from 35 to 60 percent and the mean lead time from 5.3 to 9.5 minutes; it also reduced the percentage of false alarm warnings from 79 to 76 percent. The new radars also reduced expected fatalities by 45 percent and expected injuries by 40 percent. We update the casualties analysis with these regressions, including more years of tornadoes and more county-level control variables.

We also investigate the role of tornado warnings on casualties. Specifically, we focus on whether a longer lead time reduces casualties, or whether instead there is an optimal lead time for a warning. Although responding to a tornado warning does not take long, for example, in contrast with evacuation for a hurricane, issuing the warning is just one part of the warning process. The warning must be disseminated to residents in harm's way via television, radio, tornado sirens, the Internet, or other channels, including phone calls from friends or relatives. Dissemination takes time, creating a need for longer lead times. We can determine from NWS tornado warning verification records whether each tornado was warned for or not. We have explored several ways to model warnings, including an indicator variable for whether a warning was issued for the tornado and the lead time on the warning in minutes (Simmons and Sutter 2008a). Here we focus on a set of dummy variables for lead times in the ranges of 1 to 5, 6 to 10, 11 to 15, 16 to 20, 21 to 30, and 31 or more minutes. The lead time is specifically the number of minutes between the time the warning was issued and the beginning of the tornado.[8] Creating intervals allows the marginal effect of lead time to vary in a possibly irregular manner.

Figure 6.4 presents the effect of lead time on fatalities and injuries. We again use an index to display the effect, with the index set equal to 100 for tornadoes with no warning or a warning lead time of zero minutes. An index value less than 100 indicates that lead time reduces casualties. Tornado warnings reduce injuries at all lead time intervals, with the largest reductions occurring in the 11 to 15 and 31+ minute intervals—42 percent and 44 percent, respectively. The reductions in injuries in the other lead time intervals range from 23 to 33 percent, and although the lead time variables are statistically significant, the differ-

Figure 6.4 Warning Lead Time and Casualties



SOURCE: Authors' calculations from the NWS Storm Prediction Center's tornado archive.

ences between the intervals are not generally statistically significant. Thus warnings reduce injuries, but the marginal effect of lead time is essentially zero after 15 minutes.

The situation is different for fatalities. Lead times up to 15 minutes reduce fatalities by 19 percent, 51 percent, and 31 percent in the 1 to 5, 6 to 10, and 11 to 15 minute intervals, respectively. But lead times greater than 15 minutes increase fatalities relative to no warning, and by a sizable (and statistically significant) amount: 57 percent, 49 percent, and 11 percent for the 16 to 20, 21 to 30, and 31+ minute intervals, respectively. Some of these fatalities may occur because residents react to long lead times by taking actions that increase their risk relative to those taken when there is no warning. In addition, long lead times sometimes result when a warning is issued but not canceled and a tornado eventually occurs in the warning area; residents may not consider that such warnings convey the same degree of risk as those issued for an imminent tornado. As Simmons and Sutter (2008a) discuss, the increase in fatalities for long lead times reflects a handful of well-warned-of and particularly deadly tornadoes. A contributing factor is that powerful tornadoes tend to occur during large tornado outbreaks, and consequently are well warned of. We do not observe how many fatalities might result if the most powerful tornadoes occurred without warning. Furthermore, the warnings for some of these killer tornadoes may not have been disseminated to residents. For example, consider the 1987 Saragosa, Texas, tornado, which had a lead time of 22 minutes and resulted in 30 deaths. As Aguirre (1988) discusses, the fatalities occurred in an immigrant community where residents watched Spanish-language television networks that did not broadcast the warning, and thus they were effectively unwarned about the tornado.

While tornado warnings alert residents to danger, most warnings, because they are issued in advance of the tornado, turn out to be false alarms. The national false alarm ratio (FAR) was 0.744 in 2004, meaning that tornadoes did not occur in the warned county in three out of four cases. When warnings do not come to pass, the cry-wolf effect might apply: that is, residents might dismiss future warnings as false alarms, reducing the effectiveness of warnings that do precede tornadoes. A higher FAR reduces the value of the information contained in warnings, and should at some point reduce warning response. Yet a false alarm effect has been difficult to uncover: Barnes et al. (2007) find that "evidence for the cry-wolf effect in natural hazards research . . . has not been forthcoming" (p. 1142).

The extensive NWS tornado warning verification records allow a careful test of the effect of false alarms on tornado casualties, and by implication warning response. A complication arises because false alarms are nonevents, while tornadoes are events. It is not clear which tornado warnings, as regards both false alarms and verified warnings, should apply to constructing an FAR for different tornado events. If all warnings nationwide apply to all tornadoes, there will be no cross-sectional variation in FARs, and we would be forced to try to disentangle the effect of changes in the national FAR from a time trend. Warning performance, however, varies substantially across the nation as well as over time, and thus we use local, recent warnings to calculate an FAR in our analysis. Specifically, we use warnings issued in the state struck by a tornado over the previous 12 months to calculate an FAR that we use as a control variable in our regression analysis.[9]

We find strong evidence of a false alarm effect, consistent with economic models of the value of information. A higher state FAR significantly increases both fatalities and injuries. An increase of one standard deviation in the FAR (which is 0.117) increases expected fatalities by 10 percent and injuries by 9 percent. The national FAR declined after the NWS installed Doppler weather radars, so some of the reduction in casualties attributed above to Doppler radar (perhaps 10–20 percent of the 30–45 percent reduction) appears to have resulted from decreased false alarms. We have also calculated recent, local FARs using NWS Weather Forecast Office County Warning Areas and TV markets as defined by the A. C. Nielsen Company over one- and two-year intervals for robustness. We find a similar false alarm effect using these alternative FAR definitions (Simmons and Sutter 2009).

The dependence of casualties on time of day may constitute indirect evidence of the effectiveness of tornado warnings. Tornado warnings help reduce casualties only if people respond to them, and residents are probably less likely to receive warnings issued at night when they are asleep. Thus some portion of the lower fatalities and injuries for daytime tornadoes may be due to the lifesaving effects of tornado warnings.

The Demographics of Tornado Vulnerability

Economists have found that safety is generally a normal or luxury good: as people become wealthier and secure the necessities of life, they look to reduce risks of premature death. For natural hazards, Hurricane Katrina highlighted the converse of this proposition, the vulnerability of low-income households. Recent research has documented a negative relationship between income and natural hazards fatalities across countries (Anbarci, Escaleras, and Register 2005; Kahn 2005). Higher-income households could reduce tornado risk in several ways: by purchasing higher-quality homes (or not residing in manufactured homes), installing in-home tornado shelters, and purchasing NOAA weather radios or other emergency alert systems. Wealthier communities might be more likely to invest in tornado sirens and emergency management and emergency medical services.

Yet county-level income does not appear to reduce tornado fatalities or injuries. Our previous research (Simmons and Sutter 2005, 2008a) has shown that tornado paths through areas with higher median incomes have significantly greater fatalities and injuries, contrary to expectations. We include extra control variables in the regressions reported here, and the statistical significance of income is diminished, although an increase of one standard deviation in median income still increases expected fatalities and injuries by 8 to 9 percent. The income effect we found previously may be due to urbanization. Our previous and current regressions include population density, which as we would expect increases casualties since the number of persons in the path of a tornado affects the likelihood of casualties. Our regressions here also include the rural proportion of county population, as characterized by the Census Bureau; a larger rural population significantly reduces both fatalities and injuries. Urban areas have higher incomes than rural areas, and so the positive effect of income on casualties may be a residual consequence of a population effect.

Tornadoes seem to run counter to several other common elements of natural hazards vulnerability. The elderly are considered an at-risk population, and this vulnerability might be particularly acute for tornadoes, as the elderly may have difficulty hearing sirens or an approaching tornado and quickly moving to shelter without assistance. Yet a larger proportion of county residents over age 65 are associated with significantly reduced fatalities and injuries. Injuries also decrease with larger portions of residents under 18 and male residents. Poverty is normally associated with greater vulnerability, and here we have mixed evidence: an increased county poverty rate increases (although not significantly) expected fatalities and reduces expected injuries. But poverty likely affects the propensity of a household to live in manufactured housing, and this definitely increases vulnerability. Education is also related to vulnerability. A low level of education as indicated by the proportion of residents over age 25 who did not graduate from high school increases both fatalities and injuries. But the proportion of persons with a four-year college degree does not affect casualties. Long commuting times might also affect vulnerability to tornadoes, particularly since many tornadoes occur during the evening rush hour. We find some evidence of the vulnerability of commuters, as a higher proportion of residents with a commute over 30 minutes significantly increases fatalities but does not affect injuries.

HOW MIGHT TORNADO IMPACTS BE REDUCED?

Our analysis of tornado impacts can assist in evaluating alternatives for reducing impacts. Economics provides numerous examples of policies that fail to achieve their goal or even have unintended negative consequences. Several options exist for trying to reduce tornado impacts, and our analysis can help evaluate the comparative advantages and possible interactions between these alternatives. Based on our analysis we offer four insights on reducing tornado impacts. Note that the potential gain in reduced casualties from one measure falls when other measures are simultaneously employed. For example, the United States currently experiences about 60 tornado fatalities per year. A measure that reduces fatalities by 25 percent would currently save about 15 lives per year. If another measure first reduces fatalities to 40 per year, the 25 percent reduction in fatalities now saves 10 lives per year, and so the benefits of the measure fall by one-third. Thus our statements about potential casualty reductions are all based on recent casualties and assume no other measures are employed.

Tornado Warnings

As previously discussed, the value of time spent under warnings represents a significant portion of the societal cost of tornadoes. A recent NWS innovation will significantly reduce the amount of time spent under warnings. The NWS introduced Storm Based Warnings (SBWs) for tornadoes (and other types of severe weather) nationwide in October 2007. SBWs warn for a polygon area near the tornado circulation, not an entire county. In tests the new warnings reduced the area warned by 70 to 75 percent compared with county warnings, with no compromise of safety since residents actually at risk from the possible tornado are still warned (Looney 2006; Jacks and Ferree 2007). The new warnings will significantly benefit society, although the savings of time sheltering depends on how many people actually responded to county warnings. Assuming a 50 percent response rate to county warnings and a 70 percent reduction in warned area, SBWs will reduce the value of time spent sheltering by $1 billion per year (Sutter and Erickson, forthcoming). SBWs could help reduce tornado casualties as well, since more precise and hence valuable information in the new warnings should improve response. Counties are large relative to tornado damage paths: the area of the typical county struck by tornadoes is about 1,000 square miles, compared to a mean tornado damage area of 0.3 square miles.[10] Thus the old county warnings provided relatively little detail on the location of a possible tornado. By conveying a higher level of risk for the warned area, SBWs might make residents more likely to abandon a manufactured home, as the NWS recommends, and increase the value of NOAA weather radios and commercial emergency alert systems. The technology exists to convey even more precise information on the location of a tornado—for instance, through street-level storm tracking currently provided by some television stations.

Improved lead time for unwarned tornadoes can also reduce casualties. An optimal warning lead time reduces fatalities and injuries by 50 percent and 42 percent, respectively, relative to no warning. Between 2000 and 2004, 46 percent of tornadoes occurred with a warning lead time of five minutes or less. These tornadoes are underwarned for, in that our analysis shows that longer lead times should reduce casualties. Optimal warning for these tornadoes would reduce fatalities and injuries by an additional 21 percent and 15 percent, respectively. Given current warning technology, these tornadoes could not be warned for without increasing the FAR, and that would increase casualties. Improving lead time performance without increasing the FAR would require new technology or algorithms that shift the trade-off between detection and false alarms (see Brooks 2004 for a depiction of this trade-off).

On the other hand, we find no evidence that increasing lead times beyond 15 minutes would benefit society. In fact, longer lead times perversely result in more fatalities than a tornado without a warning. Although we think that this result may be anomalous, it does not follow that we would be likely to find a further reduction in fatalities beyond that observed in the 6 to 10 minute interval. And for injuries the marginal benefit of lead time beyond the 11 to 15 minute interval is essentially zero. This diminishing return probably occurs because residents can respond to a tornado warning—take cover in an interior room or storm shelter if available—quite quickly. Time is needed to disseminate a warning, but our results suggest that everyone who is likely to receive a warning has received it within 10 or 15 minutes. Thus our analysis of casualties leads us to expect that increased lead times beyond 15 minutes would not yield significant benefits to society.

Tornado Shelters: Rarely Cost-Effective

Engineers have designed above-ground safe rooms and below-ground shelters capable of protecting residents from even the strongest tornadoes. Below-ground shelters retail for $2,000 to $2,500, while safe rooms cost in excess of $5,000. The Federal Emergency Management Agency (FEMA) included tornado shelters in its National Mitigation Strategy in the 1990s and issued performance criteria for shelters (FEMA 1999). FEMA and the state of Oklahoma collaborated on the Oklahoma Saferoom Initiative to provide rebates to homeowners installing a shelter or safe room.

The evidence suggests that tornado shelters are not a cost-effective way to reduce permanent home casualties. Merrell, Simmons, and Sutter (2005) and Simmons and Sutter (2006) calculated the cost per life saved for shelters using historical casualties, predicted casualties from a regression model, and casualties per home struck by tornadoes. All three methods yield fairly consistent estimates for permanent homes; for instance, the cost per life saved in Oklahoma, at the heart of Tornado Alley, was over $50 million, which greatly exceeds market-revealed values of a statistical life (typically under $10 million). We illustrate the arithmetic with the historical fatality totals for Oklahoma, which experienced 263 tornado fatalities between 1950 and 2007, or 4.5 per year. In-home shelters can be expected to prevent only the 31 percent of fatalities that occur in permanent homes (see Figure 6.1). If all permanent home fatalities could be prevented, shelters would prevent 1.4 deaths per year.[11] The cost of equipping all of the more than one million single-family homes in the state with a shelter (at $2,000 per shelter) is over

$2 billion. The resulting cost per life saved in this calculation is $57 million. As another way of understanding this result, 55 percent of permanent home fatalities occur in F4 and F5 tornadoes. Violent tornadoes occur too infrequently even in Tornado Alley to justify economically such an expenditure, regardless of the potentially fatal consequences. Hardening targets is an ineffective way to reduce permanent home fatalities.

Reducing Manufactured Home Vulnerability

Reducing the vulnerability of manufactured homes is crucial to reducing tornado casualties. Although tornado shelters are unlikely to be cost-effective in permanent homes, the cost per life saved for mobile homes is less than $10 million in the most tornado-prone states. And the cost per life saved could be even lower with cost-sharing for shelters in manufactured home parks. Schmidlin, Hammer, and Knabe (2001) report that manufactured home parks do in fact offer community shelters as an amenity for residents. Simmons and Sutter (2007) find that lots in parks in Oklahoma with shelters rent at a 5 percent premium, which approximately covers the cost of a community shelter as estimated by FEMA (2000). Thus tornado shelters may help with the mobile home problem, but they are only part of the answer, and will be less effective for the majority of homes not located in a park.

Manufactured homes can also be made more wind-resistant. The Department of Housing and Urban Development in 1994 amended the HUD code for manufactured housing to include wind load requirements in areas subject to high winds. Although intended to reduce hurricane-related damage (to which end the rule has been effective; see Grosskopf 2005), the wind load provisions appear to reduce tornado risk as well. Simmons and Sutter (2008b) examined the aftermath of the February 2007 tornadoes in Lake County, Florida, which killed 21 persons, all in manufactured homes. A key factor in fatalities was whether the home was totally leveled, as characterized by county officials: 16 of the 17 fatalities for which home condition could be ascertained occurred in leveled homes. Manufactured homes built to the wind load provisions were 79 percent less likely to be leveled than homes built before the HUD code went into effect. No fatalities could be documented in the newer homes, and the reduction in the probability of a home being leveled implies that in time fatalities could be reduced by as much as 70 percent. Of course, whether these results extrapolate to other tornadoes (either stronger or weaker) is an open question, but improved construction may help mitigate the mobile home problem.

Tornadoes after Dark

Tornadoes are significantly more dangerous at night than during the day. Casualties could be reduced if the lethality of nighttime tornadoes could be brought in line with tornadoes during the day. Between 1986 and 2004, 177 and 116 fatalities and 2,871 and 2,217 injuries occurred in late evening (8 p.m.–midnight) and overnight (midnight–6 a.m.) tornadoes, respectively. If these tornadoes were only as dangerous as early afternoon tornadoes, 155 fatalities and 1,308 injuries would have been avoided. Overall this would reduce fatalities by 16 percent and injuries by 7 percent.

A strategy to reduce this vulnerability depends on exactly why nighttime tornadoes are so lethal, which is an area of ongoing research. Three alternative explanations seem plausible. First, the warning process might be less effective for nighttime tornadoes. That is, fewer people might receive these warnings because they happen to be asleep, as mentioned above. Second, and closely related, the response to nighttime warnings could differ. For instance, people might seek visual confirmation of a tornado before reacting, and the difficulty of seeing tornadoes at night might make people less likely to respond. Finally, the nighttime effect might be a consequence of the greater vulnerability of manufactured homes, since residents are more likely to be at home at night than during the day.[12] If the vulnerability to tornadoes after dark is due to less effective warnings, emergency alert systems or more refined warnings might reduce this vulnerability. If nighttime fatalities are an extension of the mobile home problem, the HUD wind load provisions or tornado shelters in mobile home parks might address the problem.

CONCLUSION

Our investigation has identified several aspects of the distribution of tornado casualties and the relative likelihood of casualties. A handful of powerful (F3 or stronger) tornadoes, often clustered on super tornado outbreak days, account for a large fraction of total casualties. But the distribution of fatalities or injuries by F-scale does not tell us in which category society could most easily reduce casualties. We have found that tornadoes that strike mobile homes or after dark or on weekends or during the fall or winter months produce more casualties. If casualties in these circumstances could be reduced to the comparable rate in permanent homes for weekday tornadoes during the spring season, the toll from tornadoes would be reduced considerably. But overall casualties are not currently the largest component of the societal cost of tornadoes. Because tornadoes have become less deadly over the years, property damage and the cost of responding to warnings now account for the bulk of their societal impact. The introduction of Storm Based Warnings by the NWS will reduce time spent under warnings by perhaps 70 percent.

Our quantitative, large data set analysis also reveals some promising directions for qualitative, survey, or case study analysis. Large data set statistical analysis excels at identifying patterns in vulnerability but does not necessarily allow us to pinpoint the cause of the vulnerability. A relatively small number of tornadoes account for many of the fatalities and injuries that drive our regression results; detailed case studies could help reveal whether special circumstances or details about the dissemination of warnings not readily captured by control variables contributed to the loss of life. Future qualitative research could help to address some of the casualty disparities. For instance, surveys could explore whether people respond differently to tornadoes at night or during the fall and winter months. Additional quantitative and qualitative research will be needed to reduce the societal impacts of tornadoes in a cost-effective manner.

Notes

We are grateful for continued financial support from NOAA's National Severe Storms Laboratory, the Institute for Catastrophic Loss Reduction, and the Natural Hazards Center at the University of Colorado.

1. Information on property damage, and on injuries and fatalities resulting from tornadoes in the following paragraphs, is from NOAA's National Weather Service Storm Prediction Center (SPC) Historical Severe Storm Database, http://www.spc.noaa.gov/wcm/index.html#data.
2. Brooks and Doswell (2001) present damage totals for past tornadoes adjusted for inflation, population growth, and changes in national wealth. The May 3, 1999, F5 tornado ranks eleventh in their adjusted damage calculations.
3. For a discussion of the concept of a statistical life and a survey of estimates from the market, see Viscusi, Vernon, and Harrington (2000).
4. National Oceanic and Atmospheric Administration (NOAA) Tornado Warning Verification Archive (StormDat), available from NOAA by permission.
5. The SPC archive can be accessed online at http://www.spc.noaa.gov/archive.
6. The Fujita scale rates tornado damage from F0 (weakest) to F5 (strongest). An F0 is a minimal tornado that causes light damage; an F5 tornado causes "incredible" damage, including well-built homes swept off their foundations and cars thrown more than 100 meters. A description of the Fujita scale and the Enhanced Fujita scale can be found at http://www.spc.noaa.gov/faq/tornado/f-scale.html.
7. National Oceanic and Atmospheric Administration (NOAA) Tornado Fatality Locations, available from NOAA by permission.
8. By convention, the NWS counts a case where a tornado warning is issued after the tornado is on the ground as a warned tornado with a lead time of zero. We had previously separated out zero lead time tornadoes as an extra category, but the effect of a zero lead time warning was very close to (and statistically indistinguishable from) no warning.
9. These regressions omit tornadoes for which no warnings were issued in the state in the prior 12 months, since the FAR in these instances is undefined.
10. Authors' calculation using NOAA's National Weather Service Storm Prediction Center (SPC) Historical Severe Storm Database, http://www.spc.noaa.gov/wcm/index.html#data.
11. And even then shelters would prevent all in-home fatalities only if residents always take shelter before the tornado hits.
12. Note that residual mobile home vulnerability could also explain the greater lethality of tornadoes on weekends.

Appendix 6A

The impacts on tornado casualties discussed throughout this chapter are from a regression analysis of casualties. This appendix describes the details of the regression models. Fatalities and injuries take on nonnegative integer values; that is, the number of persons killed in a tornado can equal 0, 1, 2, or more, with a large number of zero observations. Ordinary least squares regression fails to take into account the truncation of casualties at zero, and thus instead a Poisson regression model is applied to this count data. The Poisson model (Greene 2000, pp. 880–886) assumes that the dependent variable y_i is drawn from a Poisson distribution with parameter λ_i, or

$$\text{Prob}(Y_i = y_i) = e^{-\lambda i} \times \lambda_i^{yi}/y_i!,\ y_i = 0, 1, 2, \ldots$$

The parameter λ_i of the distribution is assumed to be a log-linear function of the independent variables x_i, or $ln(\lambda_i) = \beta' \times x_i$. The Poisson regression model assumes equivalence of the conditional mean of y_i and its variance; violation of this condition is known as overdispersion. The negative binomial regression model (Greene 2000, pp. 886–888), a generalization of the Poisson model, is recommended when the data exhibit overdispersion. Diagnostic tests consistently indicate that injuries but not fatalities are overdispersed. Consequently we estimate fatalities with Poisson models and injuries with negative binomial models.

Our models include three categories of variables, describing characteristics of the tornado, the tornado path, and NWS efforts to reduce casualties. The models also include, but we do not report, year dummy variables. The year variables control for nationwide changes over time, such as the advent of the Internet as a channel to communicate warnings, and any possible year-to-year variation in warning response. The tornado characteristic variables are as described in the text, and model the rating of the tornado on the F-scale of tornado damage, the time of day, month, and whether the tornado occurred on a weekend. We also include the length of the damage path in miles.

The storm path variables control for the economic and demographic characteristics of the area struck by the tornado. The variable labels in Table 6A.1 are self-descriptive. The variables are constructed using census data for the counties reported as in the storm path. For a tornado that struck more than one county, the tornado path variables average the observations for each county in the storm path. The path variables for a specific year are based on linear interpolation from the decennial censuses. For tornadoes after 2000, population density is calculated using the census annual population estimates, while other variables use linear interpolation with county data from the 2006 American Community Survey when available. Mobile homes as a proportion of housing units by county was not reported in census publications prior to 1990, so for 1986–1989 tornadoes, the values from the 1990 census are used. We also include an interaction term between path length and population density, because a long-track tornado through a highly populated area might affect casualties differently from an increase in either of these variables separately.

The NWS variables are a dummy variable for tornadoes that occurred after installation of Doppler radar and tornado warning. The Doppler variable equals 1 if the tornado occurred on or after the date on which Doppler radar was installed in the NWS Weather Forecast Office with warning responsibility for the first tornado in the storm's path. Since warnings are issued by county, a tornado that strikes several counties may yield several valid warnings. We apply the warning for the first county in the storm path. The tornado warning variables are dummy variables that indicate whether the lead time in minutes for the warning (if any) for the first county in the storm path was in this interval. The False Alarm Ratio (FAR) variable is the proportion of warnings issued in the state struck by the tornado in the prior 12 months that were false alarms (i.e., that did not verify, as defined by the NWS). Table 6A.1 reports one specification of the casualties regressions with the Doppler radar variable but no warning variables, and one specification with the warning variables but not the Doppler variable. The Doppler radar specifications test for an impact of radar installation on casualties, which could be due to better warning for tornadoes or improved warning response.

Table 6A.1 reports the raw regression coefficients and standard errors. To interpret the coefficients as discussed in the text, the antilog of the coefficient must be taken. Thus to calculate the marginal effect of a dummy variable with coefficient β_k from the table, the percentage change in expected casualties is $100 \times (\exp[\beta_k] - 1)$. The percentage change in expected casualties due to a one standard deviation increase in variable k, σ_k, in variable k is $100 \times (\exp[\beta_k \times \sigma_k] - 1)$. Note that for a set of mutually exclusive categories (F-scale categories, day parts, months of the year), one of the dummy variable categories must be omitted for the model to be estimated. The impact of the included variables is then measured relative to that of a tornado in the excluded category: overnight for day parts, July for month, and F0 for F-scale. Table 6A.1 also indicates the statistical significance of each of the coefficient estimates at two different levels, 10 percent and 1 percent, in a two-tailed test of the null hypothesis that the coefficient is zero.

Table 6A.1 Regression Analysis of Tornado Fatalities and Injuries

	Fatalities (Doppler, no warning)[a]	Fatalities (warning, no Doppler)[a]	Injuries (Doppler, no warning)[a]	Injuries (warning, no Doppler)[a]
Doppler		−0.354* (0.240)		−0.581*** (0.174)
FAR	0.784* (0.353)		0.702*** (0.262)	
Lead 1–5 min.	−0.223* (0.134)		−0.396*** (0.123)	
Lead 6–10 min.	−0.727*** (0.145)		−0.363*** (0.119)	
Lead 11–15 min.	−0.369* (0.160)		−0.538*** (0.127)	
Lead 16–20 min.	0.446*** (0.132)		−0.257* (0.137)	
Lead 21–30 min.	0.336*** (0.114)		−0.265* (0.119)	
Lead 31+ min.	0.0879 (0.134)		−0.582*** (0.124)	
Morning	−0.808*** (0.174)	−0.903*** (0.174)	−0.0882 (0.144)	−0.0536 (0.140)
Early afternoon	−0.846*** (0.132)	−0.891*** (0.131)	−0.359*** (0.126)	−0.436*** (0.123)
Early evening	−0.664*** (0.124)	−0.592*** (0.121)	−0.323*** (0.121)	−0.386*** (0.118)
Late evening	−0.154 (0.133)	−0.147 (0.131)	−0.0816 (0.137)	−0.161 (0.134)
Weekend	0.334*** (0.0847)	0.313*** (0.0836)	0.0793 (0.0704)	0.0853 (0.0688)
January	1.45*** (0.391)	1.03*** (0.352)	0.521*** (0.192)	0.536*** (0.186)
February	2.70*** (0.366)	2.19*** (0.323)	0.332 (0.210)	0.372* (0.201)
March	1.89*** (0.353)	1.42*** (0.311)	0.305* (0.161)	0.236 (0.154)
April	1.49*** (0.348)	0.993*** (0.307)	0.0702 (0.140)	0.0554 (0.136)

(continued)

Table 6A.1 (continued)

	Fatalities (Doppler, no warning)[a]	Fatalities (warning, no Doppler)[a]	Injuries (Doppler, no warning)[a]	Injuries (warning, no Doppler)[a]
May	1.44***	1.12***	−0.408***	−0.473***
	(0.341)	(0.298)	(0.129)	(0.125)
June	0.944*	0.506	−0.187	−0.226*
	(0.375)	(0.336)	(0.132)	(0.129)
August	2.48***	2.07***	−0.161	−0.0645
	(0.366)	(0.323)	(0.169)	(0.162)
September	1.68***	1.05***	−0.0892	−0.109
	(0.420)	(0.387)	(0.172)	(0.168)
October	2.16***	1.60***	0.0360	0.0064
	(0.393)	(0.357)	(0.173)	(0.169)
November	2.10***	1.70***	0.269*	0.317*
	(0.354)	(0.313)	(0.153)	(0.150)
December	2.20***	1.74***	0.0023	0.0795
	(0.392)	(0.355)	(0.241)	(0.234)
Density	0.000251	0.0000	0.0029***	0.0003***
	(0.000995)	(0.0001)	(0.0007)	(0.0001)
Mobiles	3.67***	4.04***	2.79***	3.07***
	(0.660)	(0.654)	(0.529)	(0.526)
Income	0.00865	0.0118	0.0077	0.0159*
	(0.00915)	(0.0091)	(0.0083)	(0.0081)
Rural	−1.40***	−1.57***	−0.598***	−0.616***
	(0.212)	(0.218)	(0.155)	(0.153)
Nonwhite	−0.898*	−1.03***	0.657*	0.593*
	(0.367)	(0.363)	(0.313)	(0.306)
Male	2.42	2.17	−6.54***	−6.59***
	(2.47)	(2.40)	(2.02)	(1.99)
Under 18	1.53	1.53	−5.19***	−5.83***
	(1.81)	(1.74)	(1.37)	(1.34)
Over 65	−3.94*	−5.56***	−5.54***	−5.59***
	(1.69)	(1.65)	(1.11)	(1.08)
Commute 30+ min.	2.19***	2.30***	0.361	0.0932
	(0.413)	(0.458)	(0.351)	(0.381)
No high school	1.81*	1.45*	3.07***	3.63***
	(0.791)	(0.786)	(0.662)	(0.646)

Table 6A.1 (continued)

	Fatalities (Doppler, no warning)[a]	Fatalities (warning, no Doppler)[a]	Injuries (Doppler, no warning)[a]	Injuries (warning, no Doppler)[a]
College	−0.244	−1.41*	−0.0540	−0.0097
	(0.840)	(0.836)	(0.694)	(0.683)
Poverty rate	1.48	1.75	−2.43*	−2.06*
	(1.16)	(1.27)	(1.03)	(1.01)
Length	0.1002***	0.0008***	0.347***	0.0032***
	(0.0214)	(0.0002)	(0.0592)	(0.0006)
Length × density	0.0006	0.0000	0.0072***	0.0001***
	(0.0008)	(0.0000)	(0.0020)	(0.0000)
F1	2.73***	−10.5***	2.40***	0.672
	(0.374)	(1.71)	(0.0810)	(1.30)
F2	4.65***		4.17***	
	(0.365)		(0.101)	
F3	6.30***		5.18***	
	(0.364)		(0.154)	
F4	7.88***		6.54***	
	(0.368)		(0.255)	
F5	10.19***		7.50***	
	(0.387)		(0.867)	
Intercept	−10.5***		0.282	
	(1.83)		(1.35)	
# observations	20,605		20,605	
Log likelihood	−1,797		−9,400	

NOTE: Fatality estimates use Poisson regression models and injuries use negative binomial models with standard errors in parentheses. *significant at the 0.10 level (two-tailed test); ***significant at the 0.01 level (two-tailed test).

[a] See Appendix 6A for the distinction in the two calculations of fatalities and injuries.

SOURCE: Authors' calculations from SPC, NWS, and U.S. census data.

References

Aguirre, Begnino E. 1988. "The Lack of Warnings before the Saragosa Tornado." *International Journal of Mass Emergencies and Disaster* 6(1): 65–74.

American Meteorological Society. 1997. "Policy Statement: Mobile Homes and Severe Windstorms." *Bulletin of the American Meteorological Society* 78(5): 850–851.

Anbarci, Nejat, Monica Escaleras, and Charles A. Register. 2005. "Earthquake Fatalities: The Interaction of Nature and Political Economy." *Journal of Public Economics* 89(9–10): 1907–1933.

Ashley, Walker S., A.J. Knmenec, and Richard Schwantes. 2008. "Vulnerability Due to Nocturnal Tornadoes." *Weather and Forecasting* 23(5): 795–807.

Barnes, Lindsay R., Eve C. Gruntfest, Mary H. Hayden, David M. Schultz, and Charles Benight. 2007. "False Alarms and Close Calls: A Conceptual Model of Warning Accuracy." *Weather and Forecasting* 22(5): 1140–1147.

Brooks, Harold E. 2004. "Tornado-Warning Performance in the Past and Future: A Perspective from Signal Detection Theory." *Bulletin of the American Meteorological Society* 85(6): 837–843.

Brooks, Harold E., and Charles A. Doswell III. 2001. "Normalized Damage from Major Tornadoes in the United States: 1890–1999." *Weather and Forecasting* 16(1): 168–176.

———. 2002. "Deaths in the 3 May 1999 Oklahoma City Tornado from a Historical Perspective." *Weather and Forecasting* 17(3): 354–361.

Brown, Sheryll, Pam Archer, Elizabeth Kruger, and Sue Mallonee. 2002. "Tornado-Related Deaths and Injuries in Oklahoma Due to the 3 May 1999 Tornadoes." *Weather and Forecasting* 17(3): 343–353.

Bureau of Labor Statistics (BLS). 2007. *Establishment Data, Historical Hours and Earnings: B-2. Average Hours and Earnings of Production and Nonsupervisory Employees on Private Nonfarm Payrolls by Major Industry Sector, 1964 to Date*. Washington, DC: Bureau of Labor Statistics. ftp://146.142.4.23/pub/suppl/empsit.ceseeb2.txt (accessed December 9, 2009).

Camerer, Colin F., and Howard Kunreuther. 1989. "Decision Processes for Low Probability Events: Policy Implications." *Journal of Policy Analysis and Management* 8(4): 565–592.

Carter, A.O., M.E. Millson, and D.E. Allen. 1989. "Epidemiologic Study of Deaths and Injuries Due to Tornadoes." *American Journal of Epidemiology* 130(6): 1209–1218.

Doswell, Charles A. III, Alan R. Moller, and Harold E. Brooks. 1999. "Storm Spotting and Public Awareness since the First Tornado Forecasts of 1948." *Weather and Forecasting* 14(4): 544–557.

Environmental Protection Agency (EPA). 1997. *The Benefits and Costs of the Clean Air Act, 1970 to 1990*. http://www.epa.gov/airprogm/oar/sect812/index.html (accessed December 9, 2009).

Federal Emergency Management Agency (FEMA). 1999. *Taking Shelter from the Storm: Building a Safe Room Inside Your House*. 2d ed. Publication 320. Washington, DC: Federal Emergency Management Agency.

———. 2000. *Design and Construction Guidance for Community Shelters*. Publication 361. Washington, DC: Federal Emergency Management Agency.

Golden, Joseph H., and Christopher R. Adams. 2000. "The Tornado Problem: Forecast, Warning, and Response." *Natural Hazards Review* 1(2): 107–118.

Golden, Joseph H., and John T. Snow. 1991. "Mitigation against Extreme Windstorms." *Reviews of Geophysics* 29(4): 477–504.

Greene, William H. 2000. *Econometric Analysis.* 4th ed. Upper Saddle River, NJ: Prentice Hall.

Grosskopf, Kevin R. 2005. "Assessing the Effectiveness of Mitigation: A Case Study of Manufactured Housing and the 2004 Hurricane Season." *Journal of Emergency Management* 3(5): 27–32.

Jacks, Eli, and John Ferree. 2007. "Socio-Economic Impacts of Storm-Based Warnings." Paper presented at the 2d Symposium in Policy and Socio-Economic Impacts, held in San Antonio, TX, January 15–18.

Kahn, Matthew E. 2005. "The Death Toll from Natural Disasters: The Role of Income, Geography, and Institutions." *Review of Economics and Statistics* 87(2): 271–284.

Looney, Michael. 2006. "Polygon Warnings: The Sharp Focus on Service." Presentation to the Central Regional Managers' Conference, held in Kansas City, MO, March 7.

Martinez, Maribel, and Bradley Ewing. 2008. "A Look at the Economic Impact of Tornado Induced Damage in Tulia, Texas." Paper presented at the 2008 Hazards and Disaster Researchers Meeting, held in Broomfield, CO, July 15–16.

McClelland, Gary H., William D. Schulze, and Don L. Coursey. 1993. "Insurance for Low-Probability Hazards: A Bimodal Response to Unlikely Events." *Journal of Risk and Uncertainty* 7(1): 95–116.

Merrell, David, Kevin M. Simmons, and Daniel Sutter. 2005. "The Determinants of Tornado Casualties and the Benefits of Tornado Shelters." *Land Economics* 81(1): 87–99.

Meyer, Robert J. 2006. "Why We Under-Prepare for Hazards." In *On Risk and Disaster: Lessons from Hurricane Katrina*, Ronald J. Daniels, Donald F. Kettl, and Howard Kunreuther, eds. Philadelphia: University of Pennsylvania Press, pp. 153–173.

Schmidlin, Thomas W., Barbara Hammer, and Jodanna Knabe. 2001. "Tornado

Shelters in Mobile Home Parks in the United States." *Journal of the American Society of Professional Emergency Planners* 8: 1–15.

Simmons, Kevin M., and Daniel Sutter. 2005. "WSR-88D Radar, Tornado Warnings, and Tornado Casualties." *Weather and Forecasting* 20(3): 301–310.

———. 2006. "Direct Estimation of the Cost Effectiveness of Tornado Shelters." *Risk Analysis* 26(4): 345–354.

———. 2007. "Tornado Shelters and the Manufactured Home Parks Market." *Natural Hazards* 43(3): 365–378.

———. 2008a. "Tornado Warnings, Lead Times, and Tornado Casualties: An Empirical Investigation." *Weather and Forecasting* 23(3): 246–258.

———. 2008b. "Manufactured Home Building Regulations and the February 2, 2007, Florida Tornadoes." *Natural Hazards* 46(3): 415–425.

———. 2009. "False Alarms, Tornado Warnings, and Tornado Casualties." *Weather, Climate and Society* 1(1): 39–53.

Sutter, Daniel, and Somer Erickson. Forthcoming. "The Value of Tornado Warnings and Improvements in Warnings." *Weather, Climate and Society.*

U.S. Census Bureau. 2000. *Historical Census of Housing Tables—Units in Structure*. http://www.census.gov/hhes/www/housing/census/historic/units.html (accessed December 9, 2009).

Viscusi, W. Kip, John M. Vernon, and Joseph E. Harrington Jr. 2000. *Economics of Regulation and Antitrust*. 3d ed. Cambridge, MA: MIT Press.