Tornado Warnings, Lead Times, and Tornado Casualties: An Empirical Investigation

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ABSTRACT

Conventional wisdom holds that improved tornado warnings will reduce tornado casualties, because longer lead times on warnings provide extra opportunities to alert residents who can then take precautions. The relationship between warnings and casualties is examined using a dataset of tornadoes in the contiguous United States between 1986 and 2002. Two questions are examined: Does a warning issued on a tornado reduce the resulting number of fatalities and injuries? Do longer lead times reduce casualties? It is found that warnings have had a significant and consistent effect on tornado injuries, with a reduction of over 40% at some lead time intervals. The results for fatalities are mixed. An increase in lead time up to about 15 min reduces fatalities, while lead times longer than 15 min increase fatalities compared with no warning. The fatality results beyond 15 min, however, depend on five killer tornadoes and consequently are not robust.

1. Introduction

Tornadoes in the United States have become less deadly over the past 75 yr, with the annual national tornado fatality rate declining from 1.8 per million residents in 1925 to 0.11 per million in 2000 (Brooks and Doswell 2002). The National Weather Service's (NWS's) efforts to issue more accurate, reliable, and timely tornado warnings and to educate the public about tornado safety have surely contributed to this reduction. Conventional wisdom suggests that NWS warnings explain much of the decline and that improved warnings could further reduce tornado fatalities. Longer lead times allow for more residents to be warned of and take appropriate precautions for an approaching tornado.

Improved warnings are commonly perceived as an important safety benefit of current and future weather radars. The installation of a network of over 120 Next-Generation Weather Radars (NEXRAD) [Weather Surveillance Radar-1988 Doppler (WSR-88D)] was a major element of the modernization of the NWS in the 1990s. A National Academy of Sciences report on the future of weather radar concludes that, "The development of the WSR-88D . . . led to major improvements in capabilities of measuring winds, detecting tornadoes, tracking hurricanes, and estimating rainfall." (National Academy of Sciences 2006, p. 9). Simmons and Sutter (2005b) find that the mean warning lead time increased from 5.3 to 9.5 min after WSR-88D installation by the NWS. Furthermore, a new technology, phased array radar, promises further increases in lead time; a press release from the National Severe Storms Laboratory (2006, p. 2) suggests that once adapted for weather use, phased array radar, "has the potential to increase the average lead time for tornado warnings well beyond the current average of 11 minutes."

The link between warning lead times and tornado casualties, however, has never been empirically established. Although intuitively we expect that longer warning lead times should reduce casualties, this may not be the case. Either residents may need very little time to take protection against tornadoes, and current warnings may already provide sufficient lead time, or some residents may fail to receive the warning despite longer lead times. And even if improved warnings over the past 50 yr have reduced tornado casualties, the marginal benefit of increased lead time may now be low.

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Indeed, sufficiently long lead times might sometimes encourage dangerous behavior.

The impact of warning lead times on fatalities remains an open question[1] that must be answered before the benefits to society of longer tornado warning lead times can be quantified. We estimate a regression model of casualties based on more than 18 000 tornadoes in the contiguous United States between 1986 and 2002 to investigate the effect of warnings. The relationship between warnings and injuries is as expected: a warning in effect reduces expected injuries by 32%, and an extra minute of lead time on a warning reduces expected injuries by 1.1%. A warning in effect has almost no effect on expected fatalities—a statistically insignificant 1% decrease—while a 1-min increase in lead time *increases* expected fatalities by 0.6%. Further analysis indicates that a longer lead time reduces fatalities up to around 15 and 17 min, and that a 6–15-min lead time reduces expected fatalities by 41% and expected injuries by 47%. The apparent positive relationship between long lead times and fatalities is due to a handful of well-warned but highly deadly tornadoes.

Although our dataset contains more than 18 000 tornadoes, and in this respect is quite large, only a few tornadoes actually produce fatalities. In our sample, just over 300 tornadoes produced fatalities, and 15 tornadoes killed 10 or more persons. Consequently, the number of fatality-producing tornadoes is small. The potential for a few atypical tornadoes to affect our results must be acknowledged upfront.

2. Our method and dataset

Individual response to natural hazard warnings has been a topic of extensive research, although little research has examined tornado warnings specifically (Hammer and Schmidlin 2002). Existing studies examine the link between warnings and self-reported protective action, such as who responds to a hurricane or flood warning, and differences in response across population groups. Research on warning response often involves surveys of residents after a hazard event, which limits sample sizes and creates the potential that the results may not generalize beyond specific local conditions. Also, inferences about the effects of warnings on casualties are difficult because self-reported responses may be inaccurate and sample sizes may be too small to detect modest impacts of warnings.

We examine the link directly between warnings and casualties for tornadoes using a dataset of more than 18 000 tornadoes nationally over 17 yr. Society invests in hazard warning systems to reduce their impacts on society, and our study seeks to document this impact. But our large dataset comes at a price; namely, we lack measures of response to warnings at the storm level. Our investigation is one of the effectiveness of the warning system as a whole. A test of the impact of a tornado warning on casualties is a joint test of the effect of the warning and the response to the warning. Warnings may fail to reduce casualties in our regression because the warning or extra lead time does not allow extra precautions, or because the warning was not disseminated in a timely fashion, or because residents failed to respond properly to the warning. If analysis were to find that warnings did not reduce casualties, the result would require careful interpretation, since it may result from poor response to warnings for dangerous tornadoes.

Our dataset uses the Storm Prediction Center's (SPC's) national tornado archive, which reports state tornado segments beginning in 1950. The archive reports a number of different characteristics about each tornado, including the rating on the Fujita scale of tornado damage, time and day of touchdown, and counties struck by the tornado. The National Oceanic and Atmospheric Administration (NOAA) maintains tornado warning verification statistics dating back to 1 January 1986. We merged these two datasets to add information about the warning, if any, issued for each tornado. Thus, our dataset begins in 1986 and consists of all tornadoes in the contiguous United States through 2002. The verification records report whether a warning was issued for the tornado and the lead time of the warning in minutes (the number of minutes prior to touchdown that the warning was issued). The SPC archive reports one entry for each state tornado segment, while the NWS issues tornado warnings by county. Consequently, several warnings might be issued for a tornado that struck more than one county. We use the warning for the first county in the storm path to construct our warning variables. The warnings for the first county are used since they correspond to the alert that might be provided to residents *before* the tornado begins. The need to assign one value for the warning status variables (warning in effect, lead time on warning) for each tornado creates a potential problem. For longer-track storms, the lead time for residents farther

[1] Simmons and Sutter (2005b) found that Doppler radar installation by the NWS reduced expected fatalities 45% and expected injuries 40% and also improved tornado warning performance, but did not directly test the link between measures of warning performance and casualties. Some portion of the radar effect on casualties they identify may be a result of improved public response to Doppler-indicated warnings.

TABLE 1. Warnings in effect and casualties.

WARNING	Tornadoes	Fatalities	Fatalities per tornado	Injuries	Injuries per tornado
0	8984	235	0.0262	6131	0.682
1	9236	626	0.0678	11552	1.251

down the path may differ substantially from that for residents at the beginning of the storm path. Also, if the residents in the path of the storm are farther down the path, lead time for the start of the tornado may understate the effective lead time for the tornado. We would expect our WARNING and LEADTIME variables to most closely represent the effective warning status for short-path tornadoes. We will return to this issue in section 5.

We analyze two measures of warning quality, WARNING, a dummy variable that equals one if a tornado warning was issued for a storm and zero otherwise, and LEADTIME, the lead time on the warning in minutes. LEADTIME takes on integer values with a value of zero if no warning was issued for a tornado or a warning was issued after the tornado touched down. We also break the warning lead time down into categories to examine whether the marginal effects of lead time vary. To do so, we create dummy variables LEAD1–5, LEAD5–10, LEAD11–15, LEAD16–20, LEAD21–30, and LEAD31+, which, respectively, equal one if the lead time for the warning falls in the corresponding interval and zero otherwise.

We consider first the distribution of warning lead times and the bivariate relationship between warning performance and tornado casualties. Just over half of the state tornado segments in our dataset were warned for (50.7%), yet the warned storms account for over 72% of the fatalities and 65% of the injuries (see Table 1). The differences in fatalities per tornado and injuries per tornado for WARNING reported in Table 1 are statistically significant at better than the 99% confidence level in a test for a difference in means.

Lead times exhibit considerable variation, and just over 57% of tornadoes in our sample had no lead time (Table 2). But each lead time category has at least 5% of the storms in our sample, with over 950 storms in the category with the fewest (16–20-min lead time). Fatalities and injuries per tornado provide no evidence of a life-saving effect of longer lead times. The lowest fatality rate occurs for tornadoes with no lead time, 0.0315 fatalities per tornado, while the highest rate is nearly four times larger at the 16–20-min lead time range. The lowest injury rate, at about 0.75 injuries per tornado, occurs at a lead time of 11–15 min, while the highest, at 1.77, is for the 16–20-min range. Thus, the relationship of both fatalities and injuries with lead time is nonmonotonic and the expected negative relationship between casualties and warning lead time is not apparent.

3. Variable definitions and regression model

Conventional wisdom suggests that a longer lead time on a warning will reduce the lethality of a tornado, but this relationship is only valid if all other things are constant. An F5 tornado with a 20-min lead time will not necessarily be less deadly than an F1 tornado with no warning. Tornadoes do not occur in a laboratory setting where other factors can be controlled, and thus we estimate a regression model of tornado casualties. We define these variables, consider their expected effects on casualties, and discuss the econometric model employed in this section.

The storm characteristic variables are all taken from the SPC archive. The most important storm characteristic is the rating of the tornado on the Fujita scale (F scale) of tornado damage. The ratings take on integer values from 0 to 5, with 5 being the strongest. Technically the F scale is a measure of damage (Doswell and Burgess 1988), but it is widely reported as a measure of intensity and is the closest available proxy for storm

TABLE 2. Warning lead times and casualties.

Warning lead time (min)	Tornadoes	Fatalities	Fatalities per tornado	Injuries	Injuries per tornado
0	10395	327	0.0315	8562	0.824
1–5	1319	86	0.0652	1350	1.024
6–10	1387	75	0.0541	2001	1.443
11–15	1228	50	0.0407	929	0.757
6–20	957	107	0.1118	1690	1.766
21–30	1503	138	0.0918	2044	1.360
31+	1409	78	0.0554	1098	0.779

strength. We use categorical (or dummy) variables labeled F0, F1, F2, F3, F4, and F5 to represent the F scale. The variable F3, for example, equals one if a tornado was rated as a 3 on the F scale and zero otherwise. The use of dummy variables for each category instead of one integer variable does not impose any specific functional relationship between the F scale and casualties. Stronger tornadoes should produce more fatalities and injuries, but with categorical variables the regression model might indicate that F1 tornadoes are only slightly more deadly than F0 tornadoes, while F4 tornadoes might be much more deadly than F3 tornadoes. The dummy variable for F0 is omitted to allow estimation of the model, and thus the coefficients on the included F-scale variables indicate the effect of, say, an F2 rating relative to an F0 rating on casualties.

Other tornado characteristic variables include LENGTH, the tornado track length in tenths of miles. Longer-track storms have the potential to kill and injure more people, so we expect a positive sign on LENGTH. Previous research (Simmons and Sutter 2005b) has shown that time of day significantly affects casualties. We control for time of day with dummy variables DAY, EVENING, and NIGHT. DAY equals one if the tornado occurs between 0600 and 1759 LT, EVENING equals one if the tornado occurs between 1800 and 2359 LT, and NIGHT equals one for tornadoes between 0000 and 0559 LT. The regressions omit NIGHT so the coefficients on DAY and EVENING show the effects of tornadoes at these times relative to the late-night hours. Tornadoes at night are more likely to catch residents unprepared and produce more casualties, so we expect negative signs for DAY and EVENING. WEEKEND is a dummy variable equal to one if the tornado occurred on a Saturday or Sunday. Since work and commuting patterns differ on weekends, day of the week could easily affect tornado casualties, particularly for a late-afternoon tornado. We create a dummy variable SEASON to control for the month of the year of the tornado. SEASON equals one for tornadoes during March, April, May, or June and zero for tornadoes in any other month. We have no strong expectation regarding the signs of SEASON or WEEKEND.

We use three economic and demographic control variables that likely affect tornado casualties. The annual values of these variables for 2000 or earlier were estimated via linear interpolation from the 1980, 1990, and 2000 U.S. Census results for the counties in the storm path. For tornadoes that struck more than one county, the storm value averages the county values for the year in question. DENSITY is persons per square mile (in thousands) for the tornado path. The 2001 and 2002 values of DENSITY are based on the census's annual estimate of county population. We also interact DENSITY and LENGTH because a long-track tornado through a highly populated area may affect casualties differently than an increase in each variable separately. MOBILE is mobile homes as a percentage of the county housing stock. The susceptibility of mobile homes to damage from tornadic winds has long been recognized (Golden and Adams 2000; Schmidlin et al. 2001; Brooks and Doswell 2002), so we expect a positive sign for MOBILE in the casualty regressions.[2] INCOME is median family income in thousands of 1999 dollars.[3] Although nature does not care if a person is rich or poor, economists typically find that as people become wealthier, they will spend more to protect themselves against various risks (Viscusi et al. 2000, chapter 19). Higher-income individuals should be more likely to purchase houses affording greater protection against tornadoes, or own NOAA weather radios or other emergency alert systems. Wealthier communities should be more likely to have tornado sirens and more effective emergency management and rescue services. These factors are difficult to control for directly but should be associated with community income, so safety as a luxury good predicts that INCOME should have a negative sign. Indeed, recent studies by Anbarci et al. (2005) and Kahn (2005) confirm this negative relationship across countries for many natural hazards, including windstorms. Note, however, that Simmons and Sutter (2005b) found the opposite relationship—that higher income increased both fatalities and injuries in tornadoes.[4] Table 3 presents summary statistics for all the variables in our dataset.

We estimate the following regression models of tornado fatalities and injuries:

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[2] Mobile homes by county were not reported in 1980 U.S. Census publications, so the value of this variable for 1986–89 tornadoes is taken from the 1990 U.S. Census. Mobile home figures from the U.S. 2000 Census are used for 2001 and 2002 tornadoes.

[3] Nominal dollar values were converted to 1999 dollars using the Consumer Price Index for All Urban Consumers (CPI-U) price index. The change in real per capita personal income in each county since 1999 was used to produce values of this variable for 2000–02.

[4] Several other demographic variables failed to significantly affect casualties in preliminary regressions of OK tornadoes and thus were not included in the full dataset. The variables included median house price (as a proxy for housing quality), the percentage of male residents, the percentage of nonwhite residents, the percentage of residents with a college degree, the percentage of the population under 18, and the percentage of the population over 65.

$$\text{casualties} = f(\text{warning quality, F scale, DENSITY, INCOME, MOBILE, LENGTH,}$$
$$\text{LENGTH} \times \text{DENSITY, SEASON, DAY, EVENING, WEEKEND, YEAR}).$$

We estimate the models with year dummy variables, YEAR. An individual year variable, for instance YEAR99, is a dummy variable that equals one for tornadoes occurring in 1999 and zero otherwise. The year variables control for factors that vary across the entire nation yet are not captured by our other variables, for instance, the emergence of the Internet or cell phones. In addition, tornado casualties might exhibit year-to-year variation if, for instance, a year with few tornadoes lulls residents into a false sense of security the next year. The reported regressions omit the year variables to conserve space, but the full results are available from the authors.

Tornado fatalities and injuries take on integer values with a high proportion of zero observations, what econometricians call count data. Only 311 of the over 18 000 state tornado segments in our dataset produced one or more fatalities (with a maximum of 36) and 1799 produced one or more injury (with a maximum of 583). Ordinary least squares (OLS) estimation is inappropriate with count data because OLS does not account for the censoring of the dependent variable at zero (i.e., that casualties cannot take on negative values). Economists often employ a Poisson regression model for analysis of count data. The Poisson model assumes that the dependent variable y_i is drawn from a Poisson distribution with parameter λ_i, and that this parameter depends on the regressors, x_i (Greene 2000, 880–886). The Poisson model assumes equality of the conditional mean and variance of the dependent variable, and violation of this assumption is known as overdispersion. A generalization of the Poisson model known as the negative binomial model is recommended when count data exhibit overdispersion (Greene 2000, 886–888). Several tests (deviance, Pearson chi-square, and likelihood ratio) all indicated that tornado injuries but not fatalities exhibit overdispersion, and so we report a Poisson model of fatalities and a negative binomial model of injuries.

4. Casualty results

We report regression specifications of fatalities and injuries with WARNING and then LEADTIME as our warning quality variables (Table 4). A WARNING in effect reduces both fatalities and injuries, but the effects on fatalities are both quantitatively small—a 1% reduction in expected fatalities—and statistically insignificant in a two-tailed test (the 95% confidence interval is a 17% reduction to an 18% increase in fatalities). WARNING reduces expected injuries by 32% and the effect is statistically significant at better than the 1% level. The 95% confidence interval for injuries is a 22%–41% reduction in expected injuries. The effects of LEADTIME also differ for fatalities and injuries. For fatalities we have the unexpected result that a longer lead time on a warning makes tornadoes more deadly, everything else being equal. The point estimate, which is significant at better than the 10% level, implies that a 1-min increase in lead time increases expected fatalities by 0.6%, with a 95% confidence interval of a 0.07% decrease to a 1.2% increase. A 1-min increase in LEADTIME significantly (at better than the 1% level) reduces expected injuries by 1.1% with a 95% confidence interval of a 0.5%–1.6% reduction.

The relationship between the other control variables and fatalities and injuries, respectively, is not affected by the form of the tornado warning variable. Note that all of the control variables are significant at the 10% level or better for both fatalities and injuries and that the signs are consistent with the results of Simmons and Sutter (2005b). For fatalities, an increase in population density significantly increases expected fatalities, both directly and through the LENGTH × DENSITY interaction term. INCOME significantly increases expected fatalities, contrary to expectation. The effect is large as well, with a $1000 increase in median income increasing expected fatalities by 3.6%. As mentioned, considerable evidence supports the proposition that safety is a normal good, that as income increases people will spend more to protect themselves against life's many risks. Tornado safety appears not to follow this pattern, perhaps because upscale homes are not built substantially sturdier than more modest homes.[5] MOBILES has the expected sign; the effect of an increase in mobile homes as a percentage of the county population is both highly statistically significant and quantitatively large. If mobile homes compose an additional 1% of a county's housing stock, expected fatalities increase by about 6.6%. Longer-track storms are also more deadly, as the positive signs on LENGTH and LENGTH × DENSITY indicate. Expected fatalities are 15% lower for tornadoes that occur during the SEASON com-

[5] Simmons and Sutter (2005a) in a study of F5 tornadoes over a longer-time horizon found that higher income reduced tornado casualties.

Table 3. Summary statistics for regressions.

	Mean	Std dev	Min	Max
Fatalities	0.0473	0.726	0	36
Injuries	0.971	11.4	0	583
WARNING	0.506	0.500	0	1
LEADTIME	7.88	12.6	0	118
DENSITY	157.7	435.7	0.106	11 800
INCOME	39 500	9470	12 600	89 400
MOBILES	0.136	0.0818	0.000435	0.640
LENGTH	25.9	58.6	0	1600

pared with the offseason. Residents may be more aware of tornado risk during peak tornado months and, thus, alert to possible tornadoes. Time of day importantly affects fatalities. Expected fatalities are 64% lower for a DAY tornado and 40% for an EVENING tornado than for comparable storms occurring at night. Time of day effects provide strong, though indirect, evidence that tornado warnings save lives, if we assume that residents are more likely to receive a warning in time to take cover during the day or evening than at night. Expected fatalities are about 70% higher on a WEEKEND than a week day. The potential for fatalities for tornadoes during the afternoon rush hour certainly suggest that the opposite effect could have been plausible. The greater lethality of tornadoes at night and on weekends may be a result of residents being more likely to be home (which for some is a highly vulnerable mobile home) than at work or school. The F-scale variables are all highly significant, with the expected pattern that each F-scale category increases the lethality of tornadoes by at least a factor of 5, while an F5 tornado is 30 000 times more deadly than an F0 tornado.

All of the control variables in the injuries regression are statistically significant at better than the 1% level (except WEEKEND in the WARNING model, which is significant at the 10% level), and the direction of the effect is the same as with fatalities for each variable. DENSITY has a quantitatively greater effect on injuries than fatalities, with an increase of 100 persons per square mile increasing expected injuries by about 7%, or almost four times the impact on fatalities. A $1000 increase in INCOME increases expected injuries by just under 2%, so again we have the rather puzzling result that tornado safety may not be a normal good. A 1% increase in mobile homes in the county housing stock increases expected injuries by about 5%, which is less than the impact on fatalities. Expected injuries are 22% lower for tornadoes during the season than outside of the season. Time of day effects are again large, although smaller than for fatalities, with expected injuries 43% and 38% lower for tornadoes during the DAY and EVENING, respectively, than overnight. A tornado on a WEEKEND produces about 15% more injuries than a comparable tornado on a week day. Each category on the F scale significantly increases expected injuries, although the effect is somewhat smaller than for fatalities, with an F5 tornado expected to produce about 1500 times more injuries than an F0 tornado.[6]

We next report casualty models with lead time interval variables (Table 5). A warning reduces fatalities for short lead times. The point estimates of LEAD1–5, LEAD6–10, and LEAD11–15 are all negative and indicate 19%, 41%, and 19% reductions in expected fatalities, respectively, although only the LEAD6–10 variable is statistically significant at the 10% level. The signs of the LEAD16–20, LEAD21–30, and LEAD31+ interval variables are all positive, with point estimates of 60%, 37%, and 1% increases in expected fatalities, respectively, relative to no warning with the first two significant at better than the 1% level.[7] Thus, tornadoes with long lead times produced the positive sign for LEADTIME in Table 4, and the expected negative relationship between lead time and fatalities holds for the 79% of tornadoes in our dataset with lead times of 15 min or less.

The effect of lead time on expected injuries is consistently negative, with each variable significant at the 10% level or better and three (LEAD1–5, LEAD11–15, and LEAD31+) significant at better than the 1% level. The point estimates indicate reductions in expected injuries of 42%, 26%, 47%, 24%, 19%, and 41% (relative to no warning in each case) for LEAD1–5 through LEAD31+, respectively. The largest effect is at the 11–15-min interval, although the effect at a lead time of over half an hour is close in magnitude to this peak reduction. Thus, the relationship between injuries and warnings consistently conforms to expectations.[8]

The estimated impact of the control variables in the fatalities and injuries specifications are not affected by interval variables. Indeed, comparison of the point es-

[6] We examined the robustness of our time of day and year effects by estimating the model with month dummy variables and a finer time partition. The alternative specifications did not affect the significance of the WARNING or LEADTIME variables for either fatalities or injuries.

[7] The 95% confidence intervals for fatalities for the intervals are LEAD1–5, −38% to +5%; LEAD6–10, −55% to −22%; LEAD11–15, −41% to +11%; LEAD16–20, + 23% to +107%; LEAD21–30, + 9% to +71%; and LEAD31+, −23% to +31%.

[8] The 95% confidence intervals for injuries for the lead time interval variables are LEAD1–5, −45% to −25%; LEAD6–10, −42% to −5%; LEAD11–15, −60% to −31%; LEAD16–20, −43% to +2%; LEAD21–30, −37% to +3%; and LEAD31+, −55% to −29%.

TABLE 4. The effects of tornado warnings and lead time on casualties. The number of observations is 18 216. Standard errors are in parentheses. The significance of coefficients in the Poisson and negative binomial models is based on a chi-square test.

	Fatality model		Injury model	
	Poisson regression		Negative binomial regression	
WARNING	−0.0097		−0.388**	
	(0.0912)		(0.0706)	
LEADTIME		0.0062*		−0.0106**
		(0.0028)		(0.0027)
DENSITY	0.178**	0.186**	0.696**	0.710**
	(0.0612)	(0.0609)	(0.0982)	(0.0992)
INCOME	0.0358**	0.0354**	0.0173**	0.0176**
	(0.0052)	(0.0053)	(0.0046)	(0.0046)
MOBILES	6.49**	6.42**	4.91**	5.09**
	(0.540)	(0.542)	(0.460)	(0.460)
SEASON	−0.155*	−0.158*	−0.248**	−0.259**
	(0.0826)	(0.0823)	(0.0679)	(0.0679)
DAY	−1.08**	−1.10**	−0.548**	−0.587**
	(0.117)	(0.117)	(0.124)	(0.124)
EVENING	−0.494**	−0.524**	−0.464**	−0.508**
	(0.119)	(0.119)	(0.130)	(0.129)
WEEKEND	0.531**	0.535**	0.146*	0.151**
	(0.0817)	(0.0815)	(0.0718)	(0.0718)
LENGTH	0.0006**	0.0006**	0.0033**	0.0029**
	(0.0002)	(0.0002)	(0.0007)	(0.0007)
LENGTH × DENSITY	0.0028**	0.0027**	0.0102**	0.0101**
	(0.0006)	(0.0006)	(0.0026)	(0.0026)
F1	2.84**	2.84**	2.48**	2.49**
	(0.399)	(0.399)	(0.0826)	(0.0824)
F2	4.77**	4.76**	4.18**	4.16**
	(0.388)	(0.388)	(0.105)	(0.104)
F3	6.44**	6.42**	5.31**	5.26**
	(0.386)	(0.385)	(0.160)	(0.159)
F4	7.91**	7.89**	6.65**	6.59**
	(0.389)	(0.389)	(0.273)	(0.272)
F5	10.4**	10.4**	7.28**	7.34**
	(0.402)	(0.401)	(0.904)	(0.903)
Intercept	−9.33	−9.32**	−4.38**	−4.40**
	(0.525)	(0.525)	(0.272)	(0.272)
Log likelihood	−881	−878	−8897	−9005
Pseudo R^2	0.593	0.594	0.864	0.864

* Significance at the 10% level.
** Significance at the 1% level.

timates indicates that the alternative specification of lead time has almost no effect on the magnitude of the effect of any of the control variables.

5. Further analysis of warnings and casualties

Our regressions in section 4 employed our entire dataset. We now extend the analysis by dividing our dataset and reestimating our casualty models including only certain types of tornadoes. Tornado warnings might affect casualties differently for different types of tornadoes, say for storms during the day versus at night. Splitting the sample provides a way to identify any such effects. We explore five divisions of our dataset and estimate the casualty models for each subset separately for the WARNING and LEADTIME variables. To conserve space, we report (Table 6) only the effects in percentage terms and statistical significance of the issuance of a WARNING and a 1-min increase in lead time of LEADTIME on expected casualties, but the full results are available from the authors.

We first divide the sample based on storm track length. The sample is split at the mean pathlength, 13.0 mi, and almost 96% of the tornadoes are short-path tornadoes using this criterion. This division of the dataset allows us to address the potential weakness in the definition of warning lead time mentioned early—that a given tornado is on the ground for 5 min as op-

Table 5. The effects of tornado warning lead time on casualties. The number of observations is 18 216. Standard errors are in parentheses.

	Fatality model	Injury model
	Poisson regression	Negative binomial regression
LEAD1–5	−0.216	−0.546**
	(0.137)	(0.132)
LEAD6–10	−0.528**	−0.302*
	(0.140)	(0.128)
LEAD11–15	−0.212	−0.640**
	(0.161)	(0.139)
LEAD16–20	0.468**	−0.273*
	(0.132)	(0.151)
LEAD21–30	0.313**	−0.216*
	(0.115)	(0.126)
LEAD30+	0.0065	−0.534**
	(0.136)	(0.132)
DENSITY	0.208**	0.703**
	(0.0594)	(0.0991)
INCOME	0.0330**	0.0175**
	(0.0054)	(0.0047)
MOBILES	6.38**	5.03**
	(0.546)	(0.461)
SEASON	−0.140*	−0.242**
	(0.0825)	(0.0681)
DAY	−1.08**	−0.556**
	(0.118)	(0.124)
EVENING	−0.520**	−0.469**
	(0.121)	(0.129)
WEEKEND	0.532**	0.0163**
	(0.0825)	(0.0718)
LENGTH	0.0007**	0.0030**
	(0.0002)	(0.0007)
LENGTH × DENSITY	0.0021**	0.0098**
	(0.0006)	(0.0026)
F1	2.84**	2.49**
	(0.399)	(0.0828)
F2	4.77**	4.19**
	(0.388)	(0.104)
F3	6.43**	5.31**
	(0.386)	(0.159)
F4	7.93**	6.64**
	(0.389)	(0.273)
F5	10.4**	7.36**
	(0.403)	(0.901)
Intercept	−9.29**	−4.42**
	(0.527)	(0.273)
Log likelihood	−853	−8990
Pseudo R^2	0.600	.864

* Significance at the 10% level.
** Significance at the 1% level.

Table 6. Effects of lead time on casualties in various data subsets. The percentage change in casualties based on the WARNING variable is reported first, followed by the effect of a 1-min increase in lead time calculated from the LEADTIME variable in a specification. Short-lead-time tornadoes are 17 min or less, and short pathlengths are 13.0 mi or less. NA indicates not applicable (all tornadoes with a warning lead time of 18 min or longer have a warning in effect).

Division of dataset	Fatality model	Injury model	Observations
Pathlength			
Short	−24.0%*	−40.0%**	17 464
	−0.26%	−1.2%**	
Long	+21.7%	−11.4%	752
	+0.62%	−0.92%	
F-scale rating			
F0, F1, F2	−31.5%*	−36.4%**	16 319
	−0.04%	−1.1%**	
F3, F4, F5	+10.8%	+2.8%	1897
	+0.83%*	−1.1%*	
Lead time			
Short	−4.9%	−35.1**	14 742
	−0.89%	−4.9%**	
Long	NA	NA	3474
	−2.8%	**	−1.9%*
Time of day			
Day	−5.4%	−43.3%**	16 319
	+0.49%	−1.0%**	
Evening, night	+10.3%	−26.9%**	1819
	+1.6%*	−0.87%	
Time of year			
Season	−6.9%	−26.5%**	11 168
	+1.3%*	−0.40%	
Offseason	+70.9%**	−41.4%**	7048
	+.55%	−2.3%**	

* Significance at the 10% level.
** Significance at the 1% level.

posed to 30 min. Residents near the end of a long-track storm could have longer to take cover even if the storm begins unwarned than would residents at the beginning of the path with a 10-min warning lead time. Warnings are indeed more effective for short-track storms. A WARNING reduces fatalities and injuries for short-path tornadoes by 24% and 40%, respectively, and both of these effects are statistically significant, while for long-path storms fatalities are 22% higher and injuries are 11% lower. LEADTIME is an insignificant determinant of fatalities for both short- and long-track storms, but the point estimate indicates that a 1-min increase in lead time reduces expected fatalities by 0.3% for short-track storms but increase expected fatalities by 0.6% for long-track storms. An extra minute of lead time reduces expected injuries more for short-track than long-track storms, a 1.2% reduction versus a 0.9% reduction, and the coefficient is significant at the 1% level for short-track storms but insignificant for long-track storms. The positive sign on LEADTIME in the full sample is due to long-track tornadoes. This also suggests that mismeasurement of the effective lead time by the official warning lead time could obscure evidence on the true effectiveness of lead times.

We next investigate the impact of warnings for weak versus strong tornadoes and estimate the models separately for tornadoes rated F0, F1, or F2 and those rated F3, F4, or F5. Warnings are more effective for weak tornadoes. For weak tornadoes a WARNING reduces expected fatalities by 32% and expected injuries by 36%, with both of these effects statistically significant. For strong tornadoes, fatalities and injuries are 11% and 3% higher, respectively, although neither effect is statistically significant. For fatalities, LEADTIME is insignificant with a negative point estimate very close to zero for weak tornadoes, but a 1-min increase in lead time increases fatalities by a statistically significant 0.8% for strong tornadoes. The effects of LEADTIME on expected injuries are virtually identical for strong and weak tornadoes, a statistically significant 1.1% reduction in injuries because of an extra minute of warning lead time in each case. The positive relationship observed in Table 4 between LEADTIME and fatalities seems to be due to the strongest tornadoes. Although stronger tornadoes produce the majority of the casualties, warnings appear to have more of an effect on reducing casualties in weak tornadoes. Note that stronger tornadoes have longer pathlengths than weaker tornadoes (the mean pathlength is 2.1 mi for F0–F2 tornadoes and 14.7 mi for F3 or stronger tornadoes), and thus our warning variables less accurately measure the effective warning for the stronger storms. In this respect the stronger impacts of warnings on weak tornadoes reinforce the pathlength results.

The next split of the data is based on the amount of lead time on the warning: short lead times of 17 min or less and long lead times of 18 min or more. A WARNING reduces expected fatalities by 4.9% for the short-lead-time tornadoes, although this effect is not statistically significant. LEADTIME decreases expected fatalities by 0.9% for short lead times, and by 2.8% for lead times of 18 min or more, although only the long-lead-time effect is significant. A 15-min lead time for a storm would reduce expected fatalities by 12.5% relative to no warning. A WARNING issued for a tornado reduces expected injuries by 35% (significant at the 1% level) for short-lead-time tornadoes. LEADTIME is a negative and significant determinant of expected injuries with short lead times, with a point estimate that a 1-min increase in LEADTIME reduces expected injuries by 4.7% and 1.9% for short- and long-lead-time storms, respectively, with both results statistically significant. A 15-min lead time would reduce expected injuries by 48% compared with no warning. Warnings are more effective in reducing casualties when only short-lead-time storms are considered, with a stronger effect of lead time on injuries and the expected negative sign for fatalities. Short-lead-time tornado warnings compose 80% of our sample and are the range where improvements in warning performance occurred during our study period.[9] LEADTIME is a negative and significant determinant of both fatalities and injuries for tornadoes with lead times of 18 min or greater. The negative signs for LEADTIME for both fatalities and injuries for long-lead-time tornadoes combined with the negative sign for lead times up to 17 min suggest that fatalities for tornadoes with lead times in the range of 18–20 min drive the overall positive sign on LEADTIME for fatalities in Table 4.

The response to warnings might differ by time of day, with residents less likely to receive and respond to a warning overnight. Combining warnings with different response rates could obscure a life-saving effect, so we estimate casualty models with DAY tornadoes and then with EVENING and NIGHT tornadoes. Comparison reveals that tornado warnings are more effective at reducing casualties during the day. A WARNING reduces fatalities by 5.4% during the day but increases fatalities by 10% at other times (although neither effect is statistically significant from zero), while for injuries a WARNING produces a 43% reduction during the day but only a 27% reduction during the evening or at night. LEADTIME is a positive determinant of expected fatalities in both regressions, although significant only for evening and night tornadoes. The point estimate indicates that a 1-min increase in lead time increases expected fatalities by 0.5% during the day and 1.6% in the evening and night. LEADTIME reduces expected injuries at both times, but the effect is larger (albeit slightly, -1.0% versus -0.9%) and statistically significant only for DAY tornadoes.

Finally, we split tornadoes by month, following the definition of SEASON. A WARNING for an in-season tornado reduces fatalities by 7% and injuries by 27%, while increasing fatalities by 71% and reducing injuries by 41% during the offseason. LEADTIME is a positive and significant determinant of fatalities in season, with a 1-min increase in warning increasing expected fatalities by 1.3% and is an insignificant determinant of injuries (although with a negative point estimate). For tornadoes during the offseason, LEADTIME is a negative and significant determinant of injuries, with a 1-min increase in lead time reducing expected injuries

[9] We varied the threshold number of minutes for short-lead-time tornadoes. LEADTIME had a negative sign for fatalities for all cutoff points up to 17 min, and LEADTIME was negative and significant at the 10% level or better for cutoff points up to 13 min. The sign on LEADTIME became positive when all tornadoes with lead time of 18 min or less were included, and positive and significant with a cutoff point of 19 min.

TABLE 7. Fifteen deadliest tornadoes in the United States, 1986–2002.

Date	Location	F scale	Deaths	Lead time (min)	WARNING
3 May 1999	Moore, OK*	F5	36	19	1
8 Apr 1998	Birmingham, AL	F5	32	4	1
22 May 1987	Reeves County, TX*	F4	30	22	1
28 Aug 1990	Kendall, IL	F5	29	0	0
27 May 1997	Jarrell, TX	F5	27	35	1
22 Feb 1998	Osceola, FL*	F3	25	18	1
27 Mar 1994	St. Clair, AL	F4	22	2	1
15 Nov 1989	Madison, AL	F4	21	0	1
26 Apr 1991	Wichita, KS	F5	17	24	1
22 Feb 1998	Seminole County, FL*	F3	13	14	1
21 Nov 1992	Copiah County, MS	F4	12	31	1
20 Mar 1998	Hall County, GA	F3	12	0	0
16 Dec 2000	Tuscaloosa, AL	F4	11	14	1
13 Feb 2000	Mitchell County, GA*	F3	11	24	1
1 Mar 1997	Saline County, AR	F4	10	30	1

* A possible outlier storm as discussed in the text. These tornadoes are omitted from the regression models presented in Table 9.

by 2.3% and a positive but insignificant determinant of expected fatalities.

6. Long warning lead times and fatalities: A closer examination

We turn now to the apparent positive relationship between warning LEADTIME and fatalities in greater detail. While the marginal value of an *extra* minute of lead time might plausibly become zero or even negative at some point, it is difficult to understand why 20 or 30 min of lead time on a warning should make a storm *more* deadly than no lead time. Long lead times might encourage dangerous behaviors by some residents, but these would need to be quite prevalent to more than cancel out any protective actions taken by residents. We have already seen that long-path storms rated F3 or higher help drive this relationship. In this section we explore another element of the issue: that the deadliest storms in our dataset also happen to have long lead times. We do not observe how many fatalities would have resulted if the 1999 Moore, Oklahoma, or 1997 Jarrell, Texas, F5 tornadoes had occurred with no warning. A good warning performance on the potentially deadliest tornadoes could obscure the life-saving effects of warnings.

Analysis suggests that more dangerous tornadoes are better warned. Warning performance, for instance, is better for tornadoes rated higher on the F scale. Mean lead time for tornadoes rated F0, F1, or F2 ranged between 7.0 and 8.1 min and the percentage of storms warned for was between 46% and 54%. By contrast, for storms rated F3, F4, or F5—which produce the overwhelming bulk of fatalities—mean lead times were between 11.1 and 11.3 min and the percentage of storms warned for was between 71% and 80%. Consider further the 15 deadliest tornadoes in our sample, listed in Table 7, with their F-scale rating; whether a warning was in effect for the tornado; and the lead time in minutes. Thirteen of the 15 storms had a warning issued, compared with just over 50% of tornadoes in our sample, and the mean warning lead time for these storms was 15.8 min, with 10 having a lead time of at least 14 min, compared with a mean lead time of 7.9 min for the entire dataset.[10]

To further investigate this possibility, we examined F4 and F5 tornadoes to see if storm path characteristics differed for long- and short-lead-time storms. We sorted tornadoes in each category by lead time and divided the 10 F5 tornadoes into two groups and the 125 F4 tornadoes into quintiles. We calculated the mean values of DENSITY, MOBILE, and LENGTH within each group (Table 8). The differences between the F5 tornadoes with the longest and shortest lead times are unremarkable, with the paths of the longest-lead-time storms being shorter, with slightly higher density but fewer mobile homes. The F4 tornadoes with the longest lead times had the least populated storm paths and the highest percentage of mobile homes, although the difference in mobile homes was not great compared with the second, third, and fourth quintiles. The F4 tornadoes with the shortest lead times tracked through paths with much higher population densities and much lower fractions of mobile homes than the other F4 storms.

[10] Both of these differences are statistically significant at the 1% level.

TABLE 8. Storm path characteristics of F4 and F5 tornadoes by warning lead time. Means for each group of tornadoes reported in each case. Calculations based on 10 F5 tornadoes and 125 F4 tornadoes in the dataset.

	Storm path variable		
	DENSITY	MOBILE	LENGTH
F5 tornadoes			
Shortest lead times	152	7.95	360
Longest lead times	186	7.45	247
F4 tornadoes			
First quintile (shortest)	256	10.8	202
Second quintile	203	8.19	265
Third quintile	190	13.6	160
Fourth quintile	117	12.5	223
Fifth quintile (longest)	92.4	14.7	251

A regression model provides an alternative means of identifying tornadoes with the greatest lethality potential. We estimated a Poisson model of fatalities without any measure of tornado warning but with all of the other storm and path characteristics and ordered the dataset based on predicted fatalities from the restricted model. The mean lead time for the 15 tornadoes with the highest predicted fatality totals was 12.1 min, with 7 having a lead time of 15 min or more. So again, many of the deadliest tornadoes happened to have long lead times.

Finally, we identified five tornadoes with high death tolls relative to their F-scale rating, pathlength, and other characteristics, but also with long lead times. These five tornadoes are identified by an asterisk in Table 7. Reestimation of the casualties models from Table 5 with these five storms omitted demonstrates their impact (Table 9). The formerly positive and significant coefficients for LEAD16–20 and LEAD21–30 are now insignificant, with negative point estimates. Indeed, all six lead time interval variables have negative point estimates with the five storms omitted, although only one, LEAD6–10, is significant, and then only at the 10% level. Note that the point estimates of the LEAD1–5 and LEAD6–10 variables are reduced in magnitude compared to Table 5. By contrast, omitting the five storms does not affect the sign, significance, or magnitude of the lead time interval variables for injuries.[11] Omission of the five storms also has no effect on the sign, significance, or magnitude of the control variables for both fatalities and injuries. These regressions cannot be used to evaluate the effectiveness of warnings, since omitting observations to obtain results is hardly sound social science. But these results demonstrate that a conclusion that lead times over 15 or 17 min increase fatalities relative to no warning is unwarranted. Of the five tornadoes, Aguirre (1988) claims

[11] The point estimates of the reductions are all within 1% of those in Table 5 except for LEAD21–30; a warning in this range now reduces injuries by 24% compared with 19% with the full sample.

TABLE 9. The effect of tornado warning lead time on casualties, outliers omitted. The number of observations is 18 211. Standard errors are in parentheses.

	Fatality model	Injury model
	Poisson regression	Negative binomial regression
LEAD1–5	−0.0351	−0.540**
	(0.136)	(0.131)
LEAD6–10	−0.402*	−0.293*
	(0.141)	(0.127)
LEAD11–15	−0.243	−0.634**
	(0.163)	(0.138)
LEAD16–20	−0.0215	−0.271*
	(0.173)	(0.151)
LEAD21–30	−0.0462	−0.274*
	(0.137)	(0.128)
LEAD30+	−0.0022	−0.530**
	(0.138)	(0.132)
DENSITY	0.261**	0.696**
	(0.0625)	(0.0988)
INCOME	0.0426**	0.0182**
	(0.0054)	(0.0047)
MOBILES	6.82**	4.97**
	(0.568)	(0.461)
SEASON	−0.327*	−0.246**
	(0.0852)	(0.0680)
DAY	−1.05**	−0.558**
	(0.120)	(0.124)
EVENING	−0.619**	−0.483**
	(0.121)	(0.129)
WEEKEND	0.521**	0.0159**
	(0.0872)	(0.0719)
LENGTH	0.0011**	0.0032**
	(0.0002)	(0.0007)
LENGTH × DENSITY	0.0010	0.0097**
	(0.0007)	(0.0026)
F1	2.84**	2.49**
	(0.399)	(0.0828)
F2	4.78**	4.18**
	(0.388)	(0.104)
F3	6.32**	5.25**
	(0.387)	(0.159)
F4	7.74**	6.52**
	(0.391)	(0.275)
F5	10.2**	7.25**
	(0.411)	(0.999)
Intercept	−9.42**	−4.42**
	(0.530)	(0.273)
Log likelihood	−1020	−8950
Pseudo R^2	0.566	0.853

* Significance at the 10% level.
** Significance at the 1% level.

that only two residents of Saragosa, Texas, received the warning for the Reeves County tornado despite the 22-min lead time, and two others were part of the February 1998 Florida outbreak, which occurred at night in areas without tornado sirens. Thus, warning dissemination might well have failed for these storms.

7. Conclusions

Common sense suggests that longer lead times on tornado warnings should reduce tornado casualties. Systematic evidence does not exist though on the relationship between warnings and lead times and tornado casualties, and this study represents a first contribution on this topic. The relationship between warnings and fatalities is not as intuition suggests. A lead time up to 15 min reduces fatalities; a warning in the range of 6–10 min reduces expected fatalities by 41% compared to a similar tornado with no warning. Longer warnings than 15 min increase fatalities compared to no warning. Warnings in effect and longer lead times reduce injuries compared to a storm with no warning, but the greatest reduction in injuries occurs with a lead time of between 11 and 15 min, with a 47% reduction in expected injuries, and that beyond this time frame the marginal benefit of longer lead times becomes negative.

Further analysis provides several insights regarding the relationship between long-warning tornadoes and casualties. Long-track, powerful tornadoes appear to drive the result. For long-track storms and tornadoes rated F3 or stronger, which have longer tracks, our definition of warning lead time is ambiguous. Residents down the path of a long-track tornado might be warned well in advance even if the tornado began unwarned. One number must be assigned for a tornado if the tornado event is to be used as a data point. We find that warnings significantly reduce fatalities for short-track and weaker tornadoes, consistent with our tornado warning variables providing a better approximation of the effective lead time for these storms.

Injuries are less concentrated than fatalities, with almost six times more tornadoes producing at least one injury than at least one fatality, and the results for injuries conform with intuition. Omitting only five deadly tornadoes with long lead times produces negative (although not generally statistically significant) coefficients for all of the lead time interval variables, while barely affecting the results for injuries. A conclusion that a warning with a lead time greater than 15 min makes a tornado more dangerous than no warning is not, in our judgment, supported by the data.

We do not get to observe casualties that would occur if a specific deadly tornado occurred without warning. But regression analysis with a large dataset gets around this problem by including control variables that affect the potential lethality of a tornado. Differences in warning performance do exist even for the tornadoes with greater lethality potential as indicated by our control variables: there were unwarned F3, F4, and F5 tornadoes in our sample, and of the 1000 tornadoes with the most densely populated, longest, and highest concentration of mobile homes storm paths, 60%, 31%, and 53%, respectively, occurred with no warning. Our control variables, however, will always be an imperfect measure of potential lethality. Notably, our demographic and economic control variables are based on the counties struck by the tornado and not the exact storm path. This creates a source of error, although not necessarily bias (sometimes tornadoes will strike the one town in a sparsely populated county, and sometimes an undeveloped portion of an urban county). *If* potential lethality is not adequately captured by our control variables and the tornadoes with the greatest potential lethality are well warned, we could get a spurious apparent positive relationship between lead time and casualties.

Our results for fatalities and injuries both indicate that the effectiveness of warnings declines when lead times exceed 15 min. This may occur because residents discount warnings with long lead times. That is, if a tornado does not begin shortly after a warning is issued, people might dismiss the warning as a false alarm. About 80% of the tornadoes in our dataset had lead times of 15 min or less. The false alarm ratio for tornado warnings during the time period of our study is just over 0.75, but the false alarm ratio, conditional on no tornado within 15 min of issuance, is around 0.95. Conventional wisdom holds that a high false alarm ratio should negatively affect casualties. The reduced effectiveness of warning lead times greater than 15 min might be evidence of a false alarm problem. Lead times in excess of 15 min have historically been rare, although they are becoming more frequent over time. The percentage of tornadoes with a lead time of 16 min or more increased from 13.4% in 1986 to 31.8% in 2002, so the false alarm ratio conditional on no tornado within 15 min of warning was even higher than 0.95 in the not too distant past. Twenty years ago, residents might reasonably dismiss a warning when a tornado did not begin quickly after the issuance. It may take time for residents' perceptions of warning accuracy to catch up with improvements. If so, warnings with longer lead times might become more effective in the years to come.

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