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Improvements in Tornado Warnings and Tornado Casualties

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Doppler radar installation by the National Weather Service (NWS) improved tornado warning performance, raising the probability of detection and mean lead time while reducing the false alarm ratio. Research on tornado casualties has established that a warning reduces tornado injuries while lead times of up to fifteen minutes also reduce tornado fatalities. In this paper we estimate the decrease in tornado casualties attributable to the observed change in the distribution of warning lead times, and thus provide evidence on the benefit to society of weather warning systems. We find that increases in warning lead times accounts for 30-50 percent of the reduction in injuries but no more than 1/4 of the reduction in fatalities which occurred with the installation of Doppler radar by the NWS. Future improvements in warning performance to further reduce tornado fatalities by 18 percent and injuries by 24 percent.

Keywords: Tornadoes, Tornado Warnings, Fatalities, Injuries, Doppler Radar

Introduction

During the 1990s the National Weather Service (NWS) of the United States underwent an extensive modernization (Friday 1994). The modernization included a consolidation of Weather Forecast Offices, an increase in the proportion of professional meteorologists among NWS staff, and the deployment of the Advanced Weather Information Processing System. The most visible component of the modernization perhaps was the installation of new Doppler weather radars (WSR-88D) and the linking of these radars into a genuine national radar network, the NEXRAD network. The deployment of the Doppler radars was expected to improve warnings for severe thunderstorms and tornadoes, with the improved warnings reducing the societal impact of these storms (Crum and Alberty 1993). Doppler radars have indeed delivered on this promise: the percentage of tornadoes warned for increased from 35 percent to 60 percent; mean lead time on warnings increased from 5.3 to 9.5 minutes; and the false alarm ratio fell from .786 to .760. Tornado fatalities and injuries fell by 45 percent and 40 percent after Doppler radar installation (Simmons and Sutter 2005).

Improved warnings are a plausible means by which Doppler radar has reduced casualties, but NWS warnings comprise just one part of the warning process (Lindell and Perry 1987); communication and response also play a role because better weather warnings avert few casualties if people at risk do not receive or ignore the warning. In this paper we explore the relative contributions of improved warnings (specifically longer lead times) and response in the reduction in tornado casualties due to Doppler radar. Doppler radar allows forecasters to issue better tornado warnings but might also improve the public's confidence in and response to warnings.

Quantification of the societal benefits of meteorological services has become an important research and policy priority (Freebairn and Zillman 2002). This paper contributes to a growing number of studies on the benefits of weather hazard warning systems. Craft (1998), for example, documented a return to society in excess of 60 percent on the Weather Bureau's provision of storm warnings provided to shippers on the Great Lakes in the 1870s. Ebi et al. (2004) found that NWS summer heat advisories in Philadelphia avoided 117 heat related deaths between 1995 and 1998 and yielded a net benefit of $468 million. Carsell, Pingel and Ford (2004) estimated that a flood warning system for the Sacramento River basin could reduce expected annual flood damage by as much as 8 percent. And Escaleras and Register (2005) find that tsunami early warning systems have significantly reduced tsunami fatalities. We also provide a means to distinguish between improvements in warning performance and public response in reducing casualties. Tornado warnings have received relatively little attention in the hazard warning literature (Hammer and Schmidlin 2002), so this study particularly contributes to understanding the societal value of tornado warnings.

We find that the majority of the reduction in tornado casualties attributable to Doppler radar cannot be explained *merely* by the consequent increase in warning lead times. The observed increase in warning lead times accounts for 30-50 percent of the reduction in injuries and no more than one quarter of the reduction in fatalities. Much of the reduction in casualties due to Doppler radar appears attributable to improved public response to warnings, perhaps because Doppler radar images on television lead to greater public confidence in the warnings. The greatest reduction in fatalities and injuries occurs at lead times of 10 to15 minutes, and thus most of the benefit from improved warnings is from warnings for previously unwarned tornadoes. Our results suggest that further increases in the probability of detection and lead time for tornadoes with very short lead times will yield greater reductions in casualties than increasing lead times on currently warned tornadoes beyond 10 to 15 minutes.

Tornado Warning Performance, 1986-2002

We employ a dataset constructed from the Storm Prediction Center's (SPC) tornado archive, augmented by tornado warning records from NOAA. We first examine the improvement in tornado warning performance. The statistics we report are for state tornado segments, which is the unit of observation in the SPC archive. The tornado warning verification statistics reported by the NWS are for county warnings. Any tornado which tracks through two or more counties in the same state has one entry in the SPC archive and thus is one data point in our calculations. We assign the warning to the first county in the storm path for this tornado in our dataset and disregard the warnings for the subsequent counties; warnings for subsequent counties in the storm's path are included in the NWS calculations. Consequently the warning statistics reported here may differ slightly from official NWS warning performance statistics. Our dataset consists of all state tornado segments in the 48 contiguous United States, 1986-2002.

Figures 1 and 2 graph two important measures of warning performance by year: the percentage of storms warned for and the mean lead time in minutes. Improvement in both measures is readily apparent. The percentage of storms warned for increased from 31.4 in 1986 to 74.8 in 2002, while the mean lead time increased from 5.4 to 11.2 minutes. The improvement was not continuous over the period; for instance, both measures of performance fell in 1987 and 1988 compared to 1986.[1] A pronounced improvement in both measures occurs between 1994 and 1995, with the percentage of storms warned for jumping from just over 40 to just under 60 and the mean lead time increasing from around six to nine minutes. These marked improvements in performance occur when most tornadoes nationally began to be warned for by WFOs operating with Doppler radar. Simmons and Sutter (2005) established this link more formally by categorizing tornadoes by the Doppler radar installation status of the NWS WFO with warning responsibility for the storm. They found a statistically significant increase in both of these measures after Doppler radar installation.

We next consider the distribution of warning lead times. We use the following lead time intervals: zero minutes, 1 to 5 minutes, 6 to 10 minutes, 11 to 15 minutes, 16 to 20 minutes, 21 to 30 minutes, and 31 or more minutes.[2] Table 1 presents the percentage of tornadoes in each lead time interval for each year. The improvement in warning lead times is again apparent and consistent across the positive lead time intervals. The proportion of storms with a zero minute lead time

Figure 1: Percentage of Storms Warned For

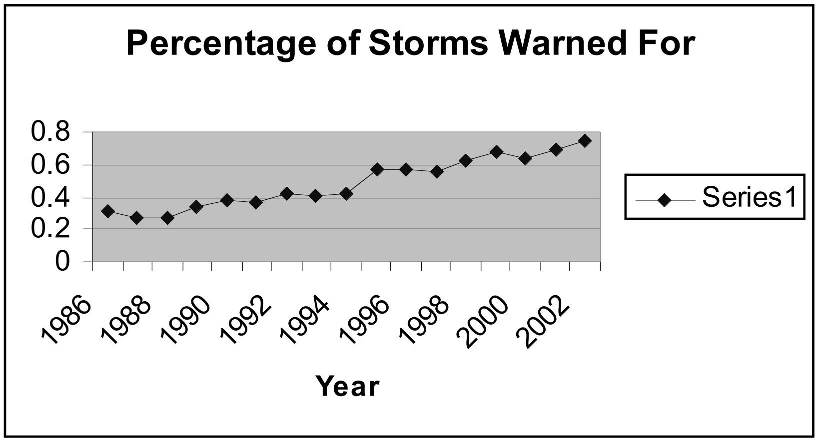
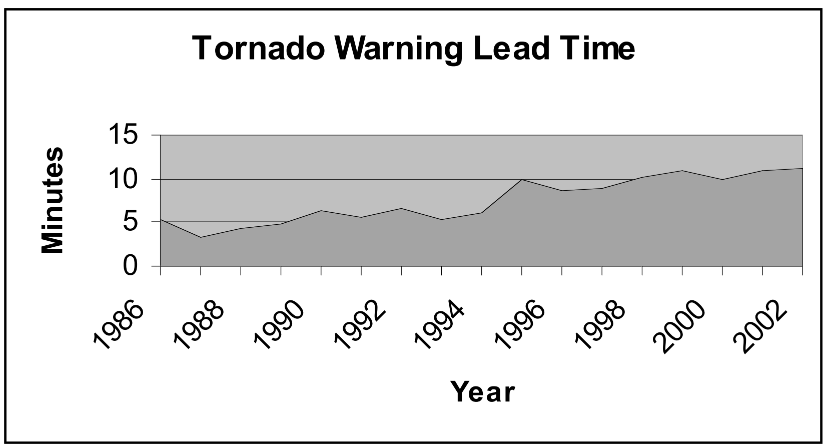


Figure 2: Tornado Warning Lead Time



fell from over three quarters in the first several years to just over one third in 2002. The proportion of tornadoes in the other lead time intervals increased from about 3 to 5 percent in the 1980s to 9 to 12 percent in each category in the last several years. Examination of the individual categories reveals that modest but steady increases in the 1 to 5 minute and 11 to 15 minute lead time categories occurred through 1999, while the other lead time categories experienced a pronounced jump between 1994 and 1995 as Doppler radar was being installed in the majority of NWS WFOs.

Table 1: The Distribution of Tornado Warning Lead Times by Year, 1986-2002

	Lead Time Interval						
Year	0	1 to 5	6 to 10	11 to 15	16 to 20	21 to 30	31+
1986	75.76	3.18	4.24	3.44	2.52	4.77	6.09
1987	81.30	3.55	4.02	3.40	2.01	2.47	3.25
1988	78.25	3.80	3.65	3.94	1.02	4.09	5.26
1989	75.26	3.95	4.65	3.48	3.37	4.41	4.88
1990	68.27	6.04	5.16	4.18	3.29	5.42	7.64
1991	70.61	5.82	4.75	3.67	3.49	5.29	6.36
1992	65.11	6.70	5.84	4.98	3.82	6.70	6.85
1993	67.90	5.59	6.80	4.82	3.70	6.80	4.39
1994	64.06	7.28	5.99	6.27	3.87	7.37	5.16
1995	49.46	7.54	10.23	6.29	5.78	10.23	10.48
1996	51.81	7.49	8.69	7.49	7.49	9.12	7.92
1997	51.82	8.97	8.18	7.48	5.28	8.53	9.67
1998	44.56	9.31	8.74	10.16	8.32	9.38	9.52
1999	40.34	10.10	10.83	10.10	7.15	11.58	10.69
2000	43.30	8.09	9.49	8.83	8.09	11.72	8.47
2001	39.56	9.46	10.77	10.52	5.79	13.54	10.36
2002	33.51	10.74	13.56	10.41	9.87	12.36	9.54
1986-88	78.29	3.50	3.98	3.59	1.87	3.83	4.94
2000-02	39.75	9.38	11.14	9.31	7.72	12.60	9.49

At first glance the lead time categories appear to have experienced roughly equal increases in the proportion of storms as the percentage of warned storms increased over time. To further explore this we calculated the percentage of storms with positive lead times for each interval category in each year. Thus, instead of dividing the annual totals in each category by the total number of tornadoes as in Table 1, we divide by the total minus the number of storms with a zero lead time. Dividing by the number of storms with positive lead times controls for the obvious increase in the percentage of storms warned for. If these percentages remained constant over time then the distribution of warning lead times would not have changed, with only a larger fraction of storms being warned for. To test for a change in warning time distribution, we regressed the percentage of tornadoes with positive lead times for each category on a linear time trend variable and a constant. For the 1 to 5, 6 to 10 and 11 to 15 minute intervals, the coefficient on the time trend was close to zero and not statistically significant, so we cannot reject the null hypothesis of no change over time in the proportion of warned storms for these categories. The time trend was positive and statistically significant for the 16 to 20 and 21 to 30 minute intervals and negative and significant for the over 30 minute interval, which indicates that fewer warned storms had lead times over half an hour and that 15 to 30 minute lead times have become more common. The distribution of lead times for warned storms has changed somewhat over the period.

Warning Lead Times and Changes in Casualties

We turn now to the impact of the increase in lead times on tornado casualties using the regression model of casualties in Simmons and Sutter (2006). The model uses state tornado segments as units of observation. The lead time for the tornado is the lead time for the warning for the first county in the storm's path. The regression model employs dummy variables for the lead time intervals reported in Table 1. Thus the lead 1 to 5 variable would equal one for tornadoes with lead times in this range and zero otherwise.

A tornado warning is only one factor affecting casualties and bigger storms will kill or injure fewer persons only when other determinants of casualties are controlled for. We will discuss only the impact of lead times on fatalities and injuries here, but the regression models in Simmons and Sutter (2006) contain many other variables which control for storm and storm path characteristics. For instance, the model contains a set of categorical variables to control for the rating of the storm on the Fujita scale of tornado damage, categorical variables for the time of day and the month of the tornado, whether the tornado occurs on a weekend, and the length of the tornado's path. All of these variables are constructed from the SPC archive. The model also contains three storm path characteristic variables from Census data based on the counties in the storm path, population density, mobile homes as a percentage of the housing stock, and median family income. Year dummy variables are also included. The number of persons killed or injured takes on nonnegative integer values, making ordinary least squares an inappropriate regression technique. Instead the models are estimated using a Poisson regression model because the dependent variable is a count variable. The Poisson model assumes the equivalence of the conditional mean and variance of the dependent variable, and violation of this assumption is known as overdispersion. Tornado injuries are overdispersed, and so the injuries models are estimated using a Negative Binomial regression model.[3]

We consider only the impact of warning lead time here; Simmons and Sutter (2006) present and discuss the full results. Table 2 reports several sets of results on the effect of lead time. In each case we present the proportional effect of the lead times in each interval instead of the regression coefficient. A lead time of zero is normalized to 1.00, so the numbers reported in Table 2 for the other categories represent the effect of an identical storm with a warning

Table 2: The Effect of Lead Time on Casualties

	Lead Time Intervals						
Regression Model	**0**	**1 to 5**	**6 to 10**	**11 to 15**	**16 to 20**	**21 to 30**	**31+**
Full Sample—Point Estimate							
Fatalities	1.000	.806	.590	.809	1.548	1.368	1.007
Injuries	1.000	.579	.739	.527	.761	.806	.586
Full Sample—Lower Bounds							
Fatalities	1.000	1.054	.776	1.110	2.066	1.714	1.315
Injuries	1.000	.750	.950	.692	1.023	1.032	.759
Full Sample—Upper Bounds							
Fatalities	1.000	.616	.448	.590	1.233	1.091	.771
Injuries	1.000	.448	.576	.402	.566	.629	.453
Outliers Omitted							
Fatalities	1.000	.966	.669	.784	.979	.955	.998
Injuries	1.000	.583	.746	.530	.763	.760	.589

Explanatory Note: the full sample is all state tornado segments in the 48 contiguous U.S. states between 1986 and 2002. The second sample omits five tornadoes with lengthy lead times and high fatality tornadoes identified as possible outliers. Fatalities and injuries with no lead time are normalized to 1.0 in each case and the other numbers represent the impact of a warning in the interval relative to a zero lead time.

in that range relative to a zero lead time. A value of .9 then indicates that expected casualties would be reduced by 10 percent relative to no warning. Results are reported for both fatalities and injuries.

The first two rows of Table 2 present our main calculations using the point estimates of the coefficients in Simmons and Sutter's full sample model. Warnings reduce injuries by 20 percent to 47 percent in each interval with the largest reduction in the 11 to 15 minute lead time range. Longer lead times do not produce additional reduction in injuries, because the effect of lead times in the 16 to 20 and 21 to 30 minute ranges is considerably less than the 1 to 5 or 11 to 15 minute ranges. The relationship between fatalities and lead times is not as expected. Warnings up to fifteen minutes reduce expected fatalities, with reductions of about 20 percent for 1 to 5 and 11 to 15 minute intervals and a 41 percent reduction in the 6 to 10 minute range. But lead times over 15 minutes *increase* fatalities relative to no warning, with lead times in the 16 to 20 and 21 to 30 minute ranges increasing expected fatalities by almost 60 percent and 37 percent respectively. A warning over 30 minutes has almost no effect on fatalities relative to no warning. The *positive* relationship between lead times and fatalities for long warnings is puzzling. The marginal value of lead time on a warning may become zero at some point once everyone in the storm's path has received the warning and taken cover, but more fatalities than no warning is difficult to rationalize. Anecdotes suggest that residents can make ill-advised, dangerous decisions with a long lead time on a warning. And some people may conclude after 15 minutes that the warning is a false alarm and leave their shelter too soon. However, such behavior would have to be fairly widespread to offset the people who do take cover to produce more fatalities than with *no* warning.

The next four rows of Table 2 report the effect of lead time with the lower and upper bounds of the 95 percent confidence interval for fatalities and injuries, which indicate the statistical significance of the point estimates of the lead time intervals. Rows 3 and 4 report the lower bounds, or the minimum reduction (or maximum increase) in casualties. Lead times decrease expected injuries in most categories with only the 16 to 20 and 21 to 30 minute intervals yielding slight increases (about 2 percent). The lower bound of the reduction in injuries is about 25 percent for the 1 to 5, 11 to 15 and over 30 minute intervals. Thus the point estimates of reductions in injuries are statistically significant at the 5 percent level or better except in the 16 to 20 and 21 to 30 minute intervals.[4] On the other hand, an increase in fatalities can be ruled out only in the 6 to 10 minute interval, and the 95 percent confidence interval includes a possible doubling of fatalities in the 16 to 20 minute interval. The upper bound or greatest statistically plausible reductions in fatalities and injuries exceed 50 percent—a 6 to 10 minute warning could reduce fatalities by 55 percent and an 11 to 15 minute warning could decrease injuries by 60 percent compared to a warning with no lead time. The upper bound shows that the increase in fatalities in the 16 to 20 and 21 to 30 minute intervals are statistically significant at the 5 percent level.

The last two rows report the point estimates of regressions which omit five tornadoes—out of more than 18,000 nationally over the period—identified as possible outliers. The five tornadoes all had particularly high death tolls and long warning lead times for their rating on the Fujita scale.[5] Omission of these storms significantly affects the fatalities results, particularly in the 16 to 20 and 21 to 30 minute ranges where warnings increase fatalities significantly with the full sample. With just five tornadoes omitted, fatalities are always lower than with no warning, albeit by less than five percent in some intervals. But the five tornadoes have little effect on injuries, with the change exceeding one percent only in the 21 to 30 minute interval. The implication that longer lead times *increase* fatalities relative to no warning is definitely premature since relatively few tornadoes kill people and a handful of particularly deadly but well warned storms can skew the results. About six times as many tornadoes produce injuries than fatalities, so the results for injuries are much less sensitive to a handful of tornadoes.

We are now ready to calculate the change in casualties attributable to the increase in warning lead times observed between 1986 and 2002. We estimate expected casualties in a year by combining the effect of warnings in each time interval category from Table 2 with the distribution of tornadoes by warning lead time category from Table 1. For example, if the distribution of warning lead times in a given year was .5 with a lead time of zero and .5 with a lead time of 1 to 5 minutes, expected fatalities in the year using the point estimates of the full model would be .903 (=.5*1.0 + .5*.806). The change in casualties due to the change in lead time distributions between two years is calculated using the change in expected casualties with the two distributions. This approach estimates a change in expected fatalities and injuries, since it uses only the proportion of storms with lead times in each category and not the individual storms. The actual change in casualties would depend on exactly which tornadoes had the better warnings. It might be that a violent tornado which would strike a densely populated county with many mobile homes would be warned due to the improvement in the distribution of lead times, with many lives saved. Or the better warned tornadoes might be weak and strike sparsely populated counties. Of course we have no way of knowing which tornadoes in 2002 would have gone unwarned if the distribution of lead times was unchanged from 1986.[6] We also consider a change in only the distribution of lead times and not the number of tornadoes. Thus our percentage change in expected casualties is based on no change in the level of tornado activity as warnings improve. A change in the number of tornadoes relative to the base year would increase the number of casualties avoided.

Table 3 presents the change in casualties for each of the four sets of warning lead time impacts from Table 2. In each case we compare the first and last years of our sample, 1986 and 2002, and for the first and last three years, 1986-88 and 2000-02. Using three year averages for the start and end of our sample smooths out the effect of year-to-year variation in tornado activity and warnings. The improvement in the distribution of lead times reduced expected injuries by 14.8 percent when comparing 1986 to 2002 and 13.7 percent when comparing the three year distributions. The increase in lead times *increased* fatalities slightly, by just under 1 percent when comparing 1986 and 2002 and by 1 percent when comparing the three year totals. The increase in fatalities is due to the relatively larger increases in the percentage of tornadoes with lead times in the 16 to 20 and 21 to 30 minute intervals. Between 1986-88 and 2000-02 the percentage of tornadoes in the 16 to 20 and 21 to 30 minute intervals more than quadrupled and tripled respectively, while the percentages in the 1-5, 6-10 and 11-15 minute less than tripled.

Table 3: The Impact of Longer Warning Lead Times on Casualties

	Percentage Change	
Regression Estimates	**1986 to 2002**	**1986-88 to 2000-2002**
Full Sample—Point Estimates		
Fatalities	+.6 percent	+1.0 percent
Injuries	-14.8 percent	-13.7 percent
Full Sample—Lower Bounds		
Fatalities	+12.5 percent	+12.0 percent
Injuries	-5. percent	-5.1 percent
Full Sample—Upper Bounds		
Fatalities	-9.8 percent	-8.5 percent
Injuries	-22.9 percent	-20.8 percent
Outliers Omitted		
Fatalities	-5.5 percent	-5.1 percent
Injuries	-15.0 percent	-14.0 percent

The upper and lower bounds of the 95 percent confidence interval indicate the limits of the possible effect of the change in lead times. With the lower bounds injuries decrease by about 5 percent over the period, while fatalities increase by about 12 percent, again due to the large positive coefficients on the 16 to 20 and 21 to 30 minute intervals and the larger improvement in lead times in these intervals. The upper bound or maximal effect of improved warning lead times is a 9 to 10 percent reduction in fatalities and a 21 to 23 reduction in injuries.

Finally expected fatalities and injuries fall by about 5 percent and 15 percent respectively with the five outlier tornadoes omitted. Omitting these storms has almost no impact on injuries, while elimination of the increase (relative to no warning) in fatalities in the 16 to 20 and 21 to 30 minute intervals reduces expected fatalities by 6 percent.

Discussion

The installation of Doppler radar by the NWS decreased expected fatalities by 45 percent and expected injuries by 40 percent (Simmons and Sutter 2005). Our analysis here is based on three extra years of tornado records, and if Simmons and Sutter's regression model is estimated with these extra storms, the effect of Doppler radar is slightly reduced to a 37 percent reduction in fatalities and a 39 percent reduction in injuries.[7] One goal of this paper was to evaluate how much the improvement in warning lead times contributed to the casualty reductions. To do this we have used a regression model of fatalities and injuries with lead time interval dummy variables and then substituted the distribution of lead times in 2002 for the distribution in 1986. We have found, surprisingly, that the increase in lead times has had no discernable impact on fatalities, as the decrease in fatalities due to increased warnings in the 1 to 15 minute intervals is offset by increases in fatalities for the increase in warnings in the 16 to 30 minute intervals. Thus even though the percentage of storms with a warning lead time of zero minutes fell from 75 percent to just over 33 percent between 1986 and 2002, the increase in fatalities for tornadoes with lead times over 15 minutes and the increase in the percentage of warned storms with lead times in this range leads to no reduction in fatalities. The improvement in the distribution of warning lead times reduced injuries by 14-15 percent. The 95 percent confidence interval upper bound of the impact of improved warnings is a 10 percent reduction in fatalities and a 23 percent reduction in injuries. And with just five potential outlier tornadoes omitted, the impact of lead times on fatalities becomes negative, albeit a modest 5 percent reduction in fatalities.

Only 30-50 percent of the reduction in injuries and no more than about 25 percent of the reduction in fatalities are attributable directly to the increase in lead times. If lengthened lead times do not explain the decrease due to Doppler, what does? One obvious candidate would be changes in communications technology over the period—pagers and the Internet as new channels for people to receive warnings, and cell phones and storm chasers to improve the reporting of tornadoes on the ground. But the regression model includes year dummy variables which should control for any changes like new technology that affect the nation as a whole at approximately the same time. Thus the Doppler radar effect cannot plausibly be attributed to these other factors.[8] Regression analysis cannot conclusively demonstrate what is responsible for the Doppler radar casualty impact, but by process of elimination the most likely remaining factor is improved public response to Doppler radar based warnings. Plausibly, as people see Doppler radar images of thunderstorms on television or the Internet, they might realize that Doppler is a powerful tool that NWS forecasters can use to identify potential tornadoes. Residents consequently might take the warnings more seriously and take cover when they receive a warning. Doppler radar may also contribute by better identifying the area of circulation within the thunderstorm which allows officials to confirm a tornado on the ground and identify the area most at risk.

The reductions in casualties attributable to longer lead times is basically due to providing a warning with some lead time for tornadoes and not increasing the percentage of tornadoes with longer lead times. To see this, the change in the distribution of warning lead times between 1986-88 and 2000-02 is decomposed as follows. Between 1986-88 and 2000-02, the percentage of tornadoes with no lead time decreased from 78.3 to 39.8. These warned storms had lead times throughout each of the intervals. But in the decomposition, assume that all these storms received a warning in the 1 to 5 minute interval. Call this decomposition "improved warnings, short leads." We then calculate the change in casualties between the actual 1986-88 lead times and the "improved warnings, short leads," and then the changes in casualties between the decomposition and the 2000-02 distribution. Providing short warnings for previously unwarned storms reduced expected fatalities by 7.5 percent and expected injuries by 17.5 percent, while lengthening of lead times from the 1-5 minute interval to the actual distribution over 2000-02 increased expected fatalities and injuries by 9 percent and 5 percent respectively.

Improvements in warning times could further reduce tornado casualties. To estimate the magnitude of potential gains from further improvements in warnings, we calculate the change in casualties which would result if all tornadoes with a zero or 1 to 5 minute lead time warning were warned optimally. That is, we compare casualties based on the actual distribution of lead times in 2000-02 to expected casualties when the lowest fatality rate, .590, and lowest injury rate, .527, are applied to tornadoes in the 2000-02 distribution in the 0 and 1 to 5 minute intervals. Technically the lowest fatality rate occurs in the

6 to 10 minute interval and the lowest injury rate in the 11 to 15 minute intervals, but we overlook this here. This hypothetical case shows the effect of providing optimal warnings for currently unwarned or very short lead time tornadoes. Comparison of actual casualties in 2000-02 with this hypothetical show that expected fatalities and injuries could be reduced an additional 18 percent and 24 percent each. Between 2000 and 2005 there were an average of 44 fatalities and 760 injuries from tornadoes per year. Thus improving warnings for the tornadoes with the shortest lead times could save about 8 lives and 180 injuries per year based on recent tornado experience.

Conclusion

The lack of evidence that warning lead times beyond 15 minutes reduce casualties is surprising because as Lindell and Perry (1987) discuss, the warning system is much more than just a warning issued by a government agency. The warning must be transmitted to residents, who may fail to receive or understand the warning, may not know how to respond to the warning, or seek independent confirmation of the threat. Thus a trade-off generally exists between time to disseminate a warning and response. With enough time, they point out that officials can go door-to-door to warn residents, resulting in little chance that residents who are home would fail to receive the warning or not know how to respond. Fifteen minutes seems like a short time to perfectly deliver a warning, so intuition suggests that the marginal value of additional lead time should still be positive. Certainly the recommended response to a tornado warning, namely take cover in a shelter or interior room or closet, takes only seconds. Perhaps informal warning processes, as Lindell and Perry discuss, work well in tornadoes, and residents may not be confused about how to respond to warnings.

New radar technologies, particularly phased array radar, offer the potential for significant improvements in average lead times in the future (NSSL 2003, p.2). Our analysis shows that the reductions in casualties due to longer lead times that we can document result from warning for tornadoes which otherwise would be unwarned. Also, increasing the lead times for tornadoes with less than a five minute warning yields benefits. Warning optimally for currently unwarned or underwarned tornadoes could reduce fatalities by about 18 percent and injuries by 24 percent. We have been unable to document that increasing lead times beyond 15 minutes yields additional casualty reductions. Thus in the development of new technology and efforts to improve warnings, meteorologists would benefit society by focusing on increasing the probability of detection and lengthening short warnings.

Would an investment to increase the warning lead time for tornadoes beyond fifteen minutes produce benefits to society? Analysis to date provides no evidence of this. Nonetheless, three factors suggest that longer lead times may yield benefits. First, the inability to document a casualty reduction for lead times over 15 minutes may be due to data limitations. Violent tornadoes (rated F4 or F5) are rare; and those tracking through highly populated areas even rarer; violent tornadoes are also better warned than average. We do not observe the number of casualties that might have occurred in the Jarrell, Texas or Moore, Oklahoma F5 tornadoes if these storms had occurred without warning. With additional data, a life saving impact of long lead times may yet be documented. Second, long lead times on tornado warnings have been quite infrequent in the past, so residents may not have taken long lead times seriously. Between 1986 and 1988, only about 10 percent of tornadoes occurred with warnings of 16 minutes or more, and nearly half of these warnings had lead times of 31 minutes or more. Given that over 75 percent of tornado warnings are false alarms, residents might reasonably have dismissed warnings not followed promptly by a tornado as likely false alarms. As longer lead time warnings become more common, residents might have greater confidence in warnings and respond better. Finally, recommended warning response has always been for residents to shelter in their homes. Provided that this is how people respond, an increase in lead times merely gives residents more time to do what they have always done for a tornado warning. An extra ten minutes provides little benefit (and only increases sheltering time) for residents who quickly receive and responded to the warning. At some point longer lead times coupled perhaps with a lower false alarm ratio or greater specificity about the exact location of the tornado might make different response options feasible. Residents might be willing and able to take other actions besides going to the safest place in their home. It may become possible for residents to go to a neighbor's or relative's shelter or flee the tornado path. Casualties from past tornadoes are a function of residents responding as they always have to tornadoes. If residents eventually respond to longer lead times with better response options, longer tornado warnings might yield casualty reductions impossible to extrapolate from the historical record.

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Notes

1. Brooks (2004) similarly finds several apparently discontinuous improvements in tornado warning performance.

2. The verification statistics report a lead time of zero minutes when a warning is issued for a tornado at or after the time of touchdown. Hence the percentage of tornadoes with zero lead time in the first column of Table 1 does not equal one minus the percentage of storms warned for in Figure 1.

3. For details on the Poisson and Negative Binomial regression models and overdispersion see Greene (2000, pp.861-868).

4. The reductions for 16 to 20 and 21 to 30 minutes are significant at the 10 percent level.

5. The omitted tornadoes (with deaths and lead times in parentheses) were: Moore, Oklahoma, 5/3/99 (36, 19); Reaves County, Texas, 5/22/87 (30, 22); Ocala, Florida, 2/22/98 (25, 18);

Seminole County, Florida, 2/22/98 (13, 14); and Mitchell County, Georgia, 2/13/00 (11, 24).

6. As Scanlon (1988) notes, both disasters and public policy toward disasters are likely to produce winners and losers, and improvement in tornado warnings is no exception. Areas of the country which experienced greater tornado activity in the latter years of our sample were the winners in experiencing less tornado impact.

7. The Simmons and Sutter model did not include the weekend variable, which takes away a portion of the fatality impact previously attributed to Doppler.

8. New technologies not introduced evenly throughout the nation would tend to be used first in wealthier communities but Simmons and Sutter (2005, 2006) find that income increases fatalities and injuries, which provides further evidence that new technologies do not explain the Doppler radar casualties effect.

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