WSR-88D Radar, Tornado Warnings, and Tornado Casualties

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ABSTRACT

The impact of the installation of Weather Surveillance Radar-1988 Doppler (WSR-88D) radars in the 1990s on the quality of tornado warnings and occurrence of tornado casualties is examined. This analysis employs a dataset of tornadoes in the contiguous United States between 1986 and 1999. The date of WSR-88D radar installation in each National Weather Service Weather Forecast Office is used to divide the sample. Tornado warnings improved after the installation of Doppler radar; the percentage of tornadoes warned for increased from 35% before WSR-88D installation to 60% after installation while the mean lead time on warnings increased from 5.3 to 9.5 min and the false alarm ratio fell slightly. A regression analysis of tornado casualties, which controls for the characteristics of a tornado and its path, reveals that expected fatalities and expected injuries were 45% and 40% lower for tornadoes occurring after WSR-88D radar was installed in the NWS Weather Forecast Office. This analysis also finds that expected casualties are significantly lower for tornadoes occurring during the day or evening than late at night throughout the sample, which provides indirect evidence of the life-saving effects of tornado warnings.

1. Introduction

A major part of the modernization of the National Weather Service (NWS) in the 1990s was the installation of a national network of Next Generation Radar [NEXRAD; Weather Surveillance Radar-1988 Doppler (WSR-88D)] weather radars.[1] The radars use a Doppler-pulse signal and were adapted for weather applications through a cooperative effort by the NWS, the Federal Aviation Administration (FAA), and the Department of Defense. The NEXRAD system consists of 159 radars deployed in the United States and overseas, with 121 of the radars installed at NWS Weather Forecast Offices (WFOs). The system is used to monitor and forecast severe storms and precipitation (including flash floods). In addition the FAA uses a Doppler-based radar developed as part of this cooperative government research effort in its Terminal Doppler Weather Radar (TDWR) system.

Improved tornado warnings have been promoted as one of the major benefits of the radars: "Doppler radar offered marked improvement for early and accurate identification of thunderstorm hazards, tornadoes, and squall lines" (Crum and Alberty 1993, p.1669; see also Serafin and Wilson 2000; National Academy of Sciences 2002). By improving the accuracy and lead time of tornado warnings, the new radar system should allow residents more time to take cover against an approaching tornado. Golden and Adams (2000, p.110) state the conventional wisdom on the relationship between warnings and casualties: "NWS seems to be moving from the era of 'detected' warnings (warnings based

[1] For details on the modernization of the NWS see Friday (1994).

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on detected existing tornadoes) to the era of 'predictive' warnings (warnings based on forecasts of tornado formation). This, combined with improvements in warning coordination and communication, has led to the reduction in morbidity and mortality for tornadoes."

In this paper, we examine the impact of Doppler radar on tornado warnings and tornado casualties. Previous studies have verified the impact of radar installation on improved warning verification statistics (Polger et al. 1994; Bieringer and Ray 1996), but employed warning statistics from only six WFOs and only for less than 10 yr. We use a dataset of all tornadoes in the contiguous United States between 1986 and 1999, consisting of nearly 15 000 tornadoes.

We also examine the impact of WSR-88D installation on tornado casualties. We offer a test of whether tornadoes produce fewer casualties after WSR-88D installation in a regression analysis of tornado casualties. We include control variables for the path of the tornado track and characteristics of the tornado in addition to a Doppler radar dummy variable in a regression model of tornado fatalities and injuries. Our method allows us to determine if Doppler radar has reduced tornado casualties and to estimate the number of tornado casualties avoided, which would be necessary to quantify the social benefits of the public investment in the NEXRAD system.

2. Variable definitions and dataset

Our dataset is taken from the Storm Prediction Center (SPC) national tornado archive, which includes all tornadoes beginning in 1950. We used all tornadoes in the contiguous United States between 1986 and 1999 to ensure an approximately equal number of tornadoes before and after radar installation. Our records are actually state tornado segments since the SPC archive contains separate listings for tornadoes that struck more than one state. We did not wish to include tornadoes that occurred too many years prior to Doppler radar installation because other factors varying over time might affect casualty rates and mask the impact of Doppler radar. Installation of WSR-88D radar was only one component of the modernization of the NWS during the 1990s. In addition to the NEXRAD system, the fraction of professional meteorologists and the amount of training offered to NWS employees has increased (Friday 1994, 50–51). We will return to the interpretation of our results in the concluding section.

The dates of WSR-88D installation at each WFO were provided by the Radar Operations Center in Norman, Oklahoma. Two dates could potentially be used for the availability of Doppler radar. The first are installation dates, defined as the date when the contractor who installed the radar left the office site and site personnel were able to use the radar to support forecast and warning operations. The second are commissioning dates, the date when the radar was officially commissioned and the old radar decommissioned. The first radar installation was at the Sterling, Virginia (Washington, D.C.), WFO on 12 June 1992 and the last installation was at the northern Indiana WFO on 30 August 1997. The first radar commissioned was at the Norman, Oklahoma, WFO on 28 February 1994 and the last on 4 December 1997 in the northeast Alabama (Huntsville) WFO. Polger et al. (1994) and Bieringer and Ray (1996) use installation dates in their analyses of the effect of Doppler radar on tornado warnings, and this study will follow their approach.

We assign tornadoes in the SPC archive to an NWS WFO and then use the date of WSR-88D installation for each office to create a dummy variable we named DOPPLER that serves as our treatment variable. Each NWS WFO is responsible for issuing tornado warnings for counties within their county warning area (CWA). The modernization of the NWS involved a consolidation of WFOs. The NWS provided us with a list of counties contained in each reorganized WFO's current CWA (as of 2003). The reorganization occurred prior to the installation of the WSR-88D radars, so the CWAs of the old WFOs are not required for the construction of our DOPPLER variable. We use the first county listed in the path of the storm in the SPC archive to identify the WFO where the tornado began. The dummy variable DOPPLER equals 1 if the WSR-88D radar had been installed in the WFO responsible for the county where the storm began on or before the day of the tornado, and equals 0 if the tornado occurred before installation. Thus, DOPPLER = 0 for all tornadoes in our dataset occurring before 12 June 1992 and DOPPLER = 1 for all tornadoes on or after 30 August 1997. Between these dates the value of DOPPLER depends on the date of WSR-88D installation providing data to the WFO with warning responsibility for the tornado.

Tornado warning verification statistics back to 1 January 1986 were provided by the National Oceanic and Atmospheric Administration (NOAA), which we use as the beginning date for our dataset. The verification records include whether a tornado warning was issued for the storm and the lead time of the warning in minutes (the number of minutes prior to touchdown that the warning was issued). For storms where the warning was issued after touchdown or no warning was issued, lead time equals zero. We matched the warning records with our tornado dataset to evaluate the impact of Doppler radar on three measures of the quality of tornado warnings, the percentage of storms (correctly) warned for, the mean warning lead time, and the false alarm ratio.

Our regression analysis uses several storm characteristics, which are taken from the SPC archives. The most

TABLE 1. Breakdown of tornadoes by F-scale classification and radar status. In addition, there were 64 tornadoes with a missing F-scale classification, denoted "−9" in the archive, 2 of which occurred prior to WSR-88D installation, which are included in the total. The assignment of tornadoes to the "before Doppler" and "after Doppler" categories is based on whether the tornado occurred before or after the date of WSR-88D installation in the relevant NWS WFO, as described in the text.

F scale	Total	Before Doppler DOPPLER = 0	After Doppler DOPPLER = 1	Percent with DOPPLER = 1
0	8527	4083	4444	52.1
1	4420	2633	1787	40.4
2	1416	862	554	39.1
3	429	248	181	42.3
4	113	67	46	40.7
5	10	5	5	50.0
All	14 979	7900	7079	47.3

prominent is the F-scale, which is the rating of the tornado on the Fujita damage scale (more information on the Fujita scale is available online at www.spc.noaa.gov/faq/tornado/f-scale.html). The ratings take on integer values from 0 to 5, with 0 being the weakest and 5 the strongest, although wind ranges are widely reported, the ratings are based on damages.[2] A tornado's F-scale rating by convention represents the maximum damage produced along its path. We separate records by F-scale category in our analysis of the impact of Doppler radar on tornado warnings. In our regression analysis of tornado casualties, we create a set of dummy variables to describe a storm's F-scale rating, F0, F1, F2, F3, F4, and F5, where F1 for instance is a dummy variable that equals 1 if the storm was rated F1 and 0 otherwise. The use of categorical variables for F-scale ratings as opposed to a single-integer variable does not impose any specific functional relationship between the F-scale and casualties. Note that although the Fujita scale is a damage scale, our control variables are intended to control for the strength of the tornado in our analysis.

As mentioned earlier, it is desirable that our dataset include approximately as many tornadoes before and after WSR-88D installation. Table 1 presents a breakdown of the tornadoes in our sample by F-scale classification and by Doppler radar status in the WFO. Our sample is remarkably balanced before and after WSR-88D installation. Overall 47.3% of tornadoes in our dataset occurred after WSR-88D installation, and the breakdown within each F-scale classification is also balanced, ranging from a minimum of 39.2% for F2 to a maximum of 52.1% for F0. Thus our dataset should allow a good test of the impact of WSR-88D installation on casualties.

Our other defined storm characteristics are as follows. LENGTH is the tornado track length in tenths of miles. We create a dummy variable SEASON to control for the month of the year of the tornado. SEASON equals 1 for tornadoes in the months of March, April, May, or June and 0 for tornadoes in any other month. DAY, EVENING and NIGHT are dummy variables that control for the time of day of the tornado. DAY equals 1 if the tornado occurs between 0600 and 1759 local time (LT) and 0 otherwise, EVENING equals 1 if the tornado occurs between 1800 and 2459 LT and 0 otherwise, while NIGHT equals 1 for tornadoes between 1200 and 0559 LT and 0 otherwise.

We use three economic and demographic control variables that are likely determinants of tornado casualties. The annual values of these variables were estimated via linear interpolation from the 1980, 1990, and 2000 censuses. The values for these variables are based on the counties in the storm path, as reported in the SPC archive. For tornadoes that struck more than one county, the values for the storm average the values for each county in the year in question. DENSITY is the number of persons per square mile for the county containing the tornado path. INCOME is median family income in thousands of 1999 dollars for the county containing the tornado path. Income figures were converted to 1999 dollars using the national Consumer Price Index (CPI-U). MOBILE is the number of mobile homes as a percentage of total housing units for the counties struck by the tornado.[3] Other possible economic and demographic variables were considered as controls, but a preliminary analysis on Oklahoma tornadoes revealed that none of the other variables tested significantly affected fatalities or injuries and thus were not included for the full national dataset.[4]

[2] An estimated wind speed breakdown of the Fujita scale is as follows: F0, 40–72 mph; F1, 73–112 mph; F2, 113–157 mph; F3, 158–206 mph; F4, 207–260 mph; F5, 261–318 mph. Doswell and Burgess (1988) note that the F-scale is actually a damage scale although often treated as an intensity scale.

[3] Mobile homes were not reported as a percentage of housing units in the 1980 census, so we use the 1990 value of this variable for tornadoes between 1986 and 1989.

[4] The variables considered as candidates included males as a percentage of the population, the nonwhite population (as a percentage), the percentage of residents with a 4-yr college degree, the percent of the population under age 18 and over age 65, and median house price.

TABLE 2. Doppler radar and tornado warnings by F-scale category. The standard deviation of warning time is in parentheses.

F-scale category	Percentage of tornadoes warned for		Mean lead time (std dev) in min.	
	Before Doppler	After Doppler	Before Doppler	After Doppler
0	33.6%	58.6%*	5.18 (11.3)	9.45 (13.2)*
1	33.0%	56.4%*	5.04 (11.5)	8.77 (12.8)*
2	40.0%	68.4%*	5.54 (11.8)	10.9 (13.8)*
3	54.8%	86.7%*	7.60 (11.8)	13.9 (14.2)*
4	64.2%	93.5%*	8.61 (13.6)	15.0 (15.8)
5	80.0%	100%	11.7 (10.4)	16.2 (12.2)
Total	35.0%	59.7%*	5.28 (11.6)	9.53 (13.4)*

* Indicates that the value for this category with radar is statistically significantly larger than the nonradar value at the 1% level in a two-tailed test.

3. Doppler radar and tornado warnings

In this section, we examine the effect of Doppler radar installation on three measures of the quality of tornado warnings, the percentage of storms warned for, the mean lead time, and the false alarm ratio. Two previous studies have made before-and-after WSR-88D radar installation comparison of tornado warnings and they both documented an improvement in warning quality with Doppler radar. Polger et al. (1994) found that the percentage of tornadoes warned for (with a tornado warning) increased from 46% for the 3 yr prior to Doppler radar installation at six WFOs to 72% after radar installation. Bieringer and Ray (1996) using a slightly longer time series for these same WFOs found that radar installation increased the percentage of tornadoes warned for from 61% to 73% and mean lead time on warnings from 8 to 13 min. Polger et al. (1994) also found that the false alarm rate fell for these six offices after WSR-88D installation as well, so an increase in the probability of detection was not achieved merely by more aggressive warning of potentially tornadic thunderstorms. In addition, Crum et al. (1998) show that the national mean lead time for tornadoes rose from 4.7 min in 1986 to 9.9 min in 1996, consistent with improvements due to Doppler radar. But the national averages they report combine tornadoes occurring in WFOs with and without WSR-88D radar in the years 1992–96, and thus we cannot be sure of the longer lead times from warnings issued using Doppler radar.

Our dataset allows calculation of these three measures of tornado warning quality for the entire nation for 14 yr, and thus provides a more extensive test of the impact of Doppler radar installation. Table 2 displays the percentage of storms warned for and mean lead time broken down by F-scale category for tornadoes occurring before and after WSR-88D installation; the before and after Doppler columns correspond to values of 0 and 1 of our DOPPLER variable defined above. The table reports both the mean warning lead time as well as the standard deviation of lead times for each category. The improvement in warning performance is easily apparent. For all tornadoes, the percentage of storms warned for increased from 35.0% before WSR-88D installation to 59.7% with Doppler, while the mean lead time increased from 5.28 to 9.53 min. The increase in both of these statistics is significant at the 1% level in two-tailed tests for the difference in ratios and means, respectively.

Warning performance improved within each F-scale category as well. The percentage of storms warned for increased by at least 20% in each category after WSR-88D installation. For each category the percentage of storms warned for exceeded 55% with Doppler radar, a percentage attained only for F4 and F5 tornadoes prior to WSR-88D installation. The increase in percentage of storms warned for is significant at the 1% level for every category except F5, which is not significant at the 10% level, due most likely to the small sample sizes. Over 85% of storms rated F3 or higher—the most dangerous storms—were warned for after WSR-88D installation. The average lead time increased by at least 3.73 min in each F-scale classification after WSR-88D installation. The mean warning lead time increased by over 6 min for F3 and F4 tornadoes, while in percentage terms the increases ranged from a doubling of mean warning lead time for F2 tornadoes to a 38% increase for F5 tornadoes, which already had a mean lead time over 11 min prior to WSR-88D installation. The differences in mean lead times for F0–F3 are statistically significant at the 1% level, but the differences for F4 and F5 tornadoes are not significant at the 10% level.[5]

[5] We also calculated tornado warning performance using the commissioning date for WSR-88D in the WFO. With this date, 37.6% of tornadoes were warned for prior to radar commissioning with a mean lead time of 5.64 min, while after commissioning 61.0% of tornadoes were warned for with a mean lead time of 9.87 min. Both of these differences were statistically significant at better than the 1% level in a two-tailed test.

False alarms cannot be broken down by F-scale and thus we can only examine the overall performance of this measure. Before Doppler radar installation, there were 2888 verified tornado warnings and 10 576 warnings not verified, for a false alarm ratio of 0.786. After Doppler radar installation, there were 4208 verified warnings and 13 290 warnings not verified, for a false alarm ratio of 0.760. The decrease in the ratio after radar installation is significant at better than the 1% level in a one-tailed test for a decrease in ratios. Since all three measures of warning quality have improved, we can conclude that the installation of Doppler radar has improved the quality of tornado warnings. To examine whether improvements in these measures of warning quality produced societal benefits, we now turn to an analysis of tornado casualties before and after Doppler installation.

4. Doppler radar and tornado casualties

We now estimate a model of tornado casualties to investigate the impact of radar installation directly on casualties. Intuition suggests that improved tornado warnings should reduce casualties, but intuition does not prove radar's efficacy. The societal benefits from the NEXRAD system would depend on demonstrable safety effects. Examination of the raw national casualty totals before and after WSR-88D installation does not indicate that NEXRAD has reduced casualties. An average of 97.3 fatalities and 1578 injuries per year for 1997–99, compared to averages of 39.5 fatalities and 946 injuries per year over 1986–96. But Doppler radar is only expected to reduce casualties holding all other determinants of casualties (e.g., strength, location, and time of the tornado) constant, which the annual totals fail to do. A regression model controls for other factors affecting casualties. To our knowledge, our study is the first attempt to quantify the safety benefits of Doppler radar.

a. Econometric model and expected effects of control variables

We estimate the following model of tornado fatalities, where the variables are as defined in section 2:

$$\text{Fatalities} = f(\text{DOPPLER, F-SCALE, DENSITY, INCOME, MOBILE, LENGTH, LENGTH} * \text{DENSITY, SEASON, DAY, EVENING, YEAR}).$$

We also estimate the same model for injuries. We estimate the casualty models with yearly dummy variables, YEAR, so YEAR96 is a dummy variable that equals 1 for tornadoes occurring in 1996 and 0 otherwise. The year variables control for factors that vary from year to year across the entire nation and are not captured by our other variables.[6] We do not report the estimates of the year variables to conserve space. Note that F0 is the omitted category for F-SCALE, so the coefficients reported for the F-scale variables indicate the impact of a tornado of that classification relative to an F0 tornado.

We briefly describe our expectations concerning the signs of the variables before presenting the results. DOPPLER is of course the variable of prime interest here, and a negative sign indicates a reduction in casualties. Stronger tornadoes are more deadly, so we expect positive signs for each F-scale dummy, with the coefficients increasing with categories. That is, since the coefficients of the F2 and F3 variables, for example, measure the impact of tornadoes with these ratings compared to an F0 tornado, we expect the coefficient of the F3 variable to be larger than the coefficient of an F2. We expect a positive sign for DENSITY because tornadoes striking more populated areas should produce more casualties. Research by economists on risk preferences has established that, in general, safety is a normal good, meaning that as income goes up, people tend to spend more on safety.[7] With regard to tornadoes, this could include higher-quality housing, the installation of better tornado sirens, better emergency medical and search and rescue capabilities, and perhaps wider penetration of NOAA Weather Radio. A negative sign for INCOME in the casualty functions would indicate that tornado safety is a normal good. Mobile homes offer residents less protection from tornadoes than permanent homes so we expect a positive sign for MOBILE in the casualty functions.[8] Longer-track storms have the potential to kill and injure more persons, even controlling for storm strength, so we expect a positive sign for LENGTH. We have no strong expectation for SEASON, although residents might be more alert to and prepared for tornadoes during spring months

[6] Conceivably tornado fatalities in a year might depend on the number of tornadoes in the previous year. A year with few tornadoes could lull residents concerning the threat posed by tornadoes in the next year and vice versa.

[7] See Viscusi et al. (2000, chapter 19) and references cited therein for the conventional wisdom on the relationship between wealth and safety expenditures.

[8] Brooks and Doswell (2002) estimate that the fatality rate is 15 times higher for residents of mobile homes than residents of permanent homes, while Merrell et al. (2005) estimate that tornado shelters are about 10 times more cost effective in mobile homes than permanent homes.

TABLE 3. Summary statistics for tornado dataset.

Variable	Mean	Std dev	Min	Max
FATALITIES	0.0485	0.754	0	36
INJURIES	1.01	10.2	0	583
DOPPLER	0.473	0.499	0	1
DENSITY	160	447	0.105	11 800
INCOME	38 800	9410	12 600	89 400
MOBILE	0.137	0.0809	0.00219	0.640
LENGTH	25.6	58.2	0	1600
SEASON	0.601	0.490	0	1
DAY	0.603	0.489	0	1
EVENING	0.347	0.476	0	1
NIGHT	0.0496	0.217	0	1

when most tornadoes occur, and if so this would result in a negative sign for this variable. NIGHT tornadoes are the omitted category in our regressions, so the coefficients on DAY and EVENING indicate the effect of storms at these times compared to a storm at NIGHT. Residents are more likely to be asleep at night and less likely to receive a warning in time to take cover. Consequently, we expect negative signs for DAY and EVENING. We also interact DENSITY and LENGTH in the regression, since a long path storm in a highly populated county may have a greater effect in combination than separate increases in either variable. We expect a positive coefficient for the interaction term. Table 3 presents summary statistics for the variables in our dataset for regression analysis.

Tornado fatalities and injuries take on integer values with a high proportion of zero observations, what econometricians call "count data." Of the nearly 15 000 tornado records in our sample, only 250 tornadoes (fortunately) produced one or more fatalities (with a maximum of 36) and 1523 produced one or more injuries (with a maximum of 583). Application of 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 typically 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 $\mathbf{x}_i$ (Greene 2000, 880–886). The Poisson model assumes equality of the conditional mean and variance of the dependent variable; 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 exhibits overdispersion. Several tests (deviance, Pearson chi-square, and likelihood ratio) indicate that tornado injuries, not fatalities, exhibit overdispersion. The negative binomial model adds an individual, unobserved disturbance ε_i to the log of the conditional mean so that y_i conditioned on $\mathbf{x}_i$ and ε_i has a Poisson distribution with equality of the conditional mean and variance and is recommended if data exhibit overdispersion (Greene 2000, 886–888). We estimated both Poisson and negative binomial regression models for both fatalities and injuries. Based on the overdispersion tests our preferred specifications are the Poisson for fatalities and negative binomial for injuries, but we present both models for fatalities and injuries for completeness.

b. *Determinants of fatalities*

Table 4 presents the estimates of the determinants of fatalities. The dependent variable is the natural logarithm of expected fatalities. DOPPLER has a negative point estimate in each specification, but the coefficient is statistically different from zero only in the Poisson model, although this is our preferred model for fatalities. DOPPLER is significant at the 1% level in the Poisson specification. The effect of DOPPLER in the Poisson model is a 45% reduction in expected fatalities. The limits of the 95% confidence interval for the coefficient on DOPPLER in the Poisson model are -0.221 and -0.983, which yields a confidence interval for the effect of WSR-88D of a 20%–63% reduction in expected fatalities. In the negative binomial model the point estimate yields a smaller though still sizable 29% reduction in expected fatalities. Thus, although the raw fatality totals did not indicate a reduction in fatalities due to Doppler radar, once storm and path characteristics are controlled through regression analysis, a reduction is observed.

For the other variables, the only differences in significance across the two specifications are for LENGTH and SEASON. LENGTH is positive and

TABLE 4. Analysis of the determinants of tornado fatalities. Dependent variable is the natural logarithm of expected fatalities. Standard errors are in parentheses.

Independent variable	Poisson	Negative binomial
DOPPLER	−0.602*	−0.349
	(0.194)	(0.368)
DENSITY	−0.0842	0.218
	(0.0959)	(0.196)
INCOME	0.0382*	0.0226**
	(0.0059)	(0.0111)
MOBILE	5.97*	5.48*
	(0.600)	(1.06)
LENGTH	0.0003	0.0023*
	(0.0002)	(0.0009)
LENGTH × DENSITY	0.0070*	0.0108*
	(0.0010)	(0.0033)
SEASON	−0.132	−0.410**
	(0.0942)	(0.164)
DAY	−1.08*	−1.55*
	(0.131)	(0.234)
EVENING	−0.600*	−1.04*
	(0.135)	(0.240)
F1	2.75*	2.64*
	(0.432)	(0.438)
F2	4.63*	4.43*
	(0.419)	(0.433)
F3	6.25*	5.76*
	(0.417)	(0.451)
F4	7.82*	7.44*
	(0.419)	(0.494)
F5	9.91*	9.52*
	(0.431)	(0.877)
Intercept	−9.04*	−7.62*
	(0.562)	(0.738)
Deviance/DF	0.163	0.0647
Pearson chi square/DF	1.50	0.911
Log likelihood	−662.6	−282.7

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

TABLE 5. Same as Table 4 but for determinants of tornado injuries.

Independent variable	Poisson	Negative binomial
DOPPLER	−0.692*	−0.513*
	(0.0406)	(0.170)
DENSITY	0.0751*	0.636*
	(0.0140)	(0.105)
INCOME	0.0252*	0.0176*
	(0.0012)	(0.0051)
MOBILE	3.16*	4.99*
	(0.130)	(0.505)
LENGTH	0.0007*	0.0028*
	(0.0000)	(0.0007)
LENGTH × DENSITY	0.0054*	0.0126*
	(0.0002)	(0.0030)
SEASON	−0.348*	−0.325*
	(0.0188)	(0.0742)
DAY	−0.577*	−0.644*
	(0.0288)	(.140)
EVENING	−0.510*	−0.564**
	(0.0306)	(0.144)
F1	2.47*	2.41*
	(0.0626)	(0.0891)
F2	4.15*	4.01*
	(0.0608)	(0.114)
F3	5.39*	5.08*
	(0.0610)	(0.173)
F4	6.65*	6.47*
	(0.0619)	(0.296)
F5	8.17*	7.10*
	(0.0668)	(0.924)
Intercept	−04.28*	−4.19*
	(0.0943)	(0.291)
Deviance/DF	2.72	0.277
Pearson chi square/DF	8.25	1.89
Log likelihood	18 824	33 871

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

significant at the 1% level in the negative binomial model but insignificant in the Poisson model, while SEASON is negative and significant at the 10% level in the negative binomial model and insignificant in the Poisson model. DENSITY is insignificant in both specifications, but a more populated tornado track does increase expected fatalities in both models through the interaction with LENGTH. INCOME has an unexpected positive and significant impact on fatalities; we expected a negative sign since safety is generally considered to be a normal good. Since we include the percentage of mobile homes as a control variable, the expected effect of income on safety through housing quality may be captured by that variable. Tornado safety may not be a normal good. MOBILE has a positive and highly significant effect on fatalities in each specification, which is not surprising. The impact of this variable is quantitatively large; if mobiles homes compose an additional 1% of the housing stock, expected fatalities increase by about 6% in each model. DAY and EVENING are negative and highly significant in both specifications. The negative coefficients on these variables indicate that tornadoes occurring at night are more lethal; by implication, residents must be able to take more effective precautions during the day or evening than at night. The time-of-day effect is large in magnitude, with the point estimate of the Poisson (negative binomial) model indicating that expected fatalities are 66% (79%) lower for a DAY tornado compared to a similar tornado at NIGHT. The point estimates from the Poisson (negative binomial) model indicate that expected fatalities for an EVENING tornado are 45% (65%) lower than a comparable tornado at NIGHT. The time-of-day variables provide evidence of the effectiveness of tornado warnings and precautions, assuming that residents are more likely to receive a warning during the day or evening compared to during the night. The F-scale dummy variables are all positive and highly significant in both models, as expected, and the coefficient for each higher F-scale category is significantly larger than the previous category.

c. Determinants of injuries

Table 5 presents the results for estimation of the injury models. The dependent variable is the natural logarithm of expected injuries. DOPPLER is negative and significant at better than the 1% level for both the Poisson and negative binomial models. Since injuries exhibit considerable evidence of overdispersion, the negative binomial model is our preferred model for injuries. The point estimates indicate a sizable impact of DOPPLER on injuries as well; expected injuries are 40% (50%) lower with WSR-88D radar in the negative binomial (Poisson) model. The limits of the 95% confidence interval for the coefficient on DOPPLER in the negative binomial injury model are −0.179 and −0.846, so the confidence interval for the effect of WSR-88D radar is a 16%–57% reduction in expected injuries. All the other control variables are significant in both the negative binomial and Poisson models at better than the 1% level. DENSITY is positive and significant for injuries, so a more populated tornado path increases injuries but not fatalities (at least directly). Again we have the surprising result of a positive and significant coefficient for INCOME, meaning that injuries are higher when income is higher. Conceivably for injuries this might be a result of wealthier residents being more likely to seek medical attention for relatively minor injuries or more efficient emergency managers who report a larger percentage of injuries. But combined with the positive sign for INCOME in the fatalities analysis, this seems to be an anomaly deserving of further investigation. MOBILE again has a quantitatively large impact on injuries; if mobile homes compose an additional 1% of the housing stock, expected injuries increase by 5.1% (3.2%) in the negative binomial (Poisson) model. The DAY and EVENING effects are again both large in magnitude and statistically significant. Expected injuries for a DAY tornado are 47% (47%) lower expected injuries based on the point estimate of the negative binomial (Poisson) model than a tornado at NIGHT, while expected injuries for an EVENING tornado are 43% (40%) lower than at NIGHT. Again this is evidence that tornado warnings and precautions are effective, assuming that residents are less likely to be alerted at night than during the day. The F-scale coefficients are again all significant and the coefficients increase in the expected fashion, with each stronger tornado producing more expected injuries, and the differences are all significant at the 1% level.

A total of 291 fatalities and 4735 injuries occurred due to tornadoes over the period 1997–99 when the NEXRAD system was almost complete (only two WFOs did not have Doppler radar installed by the start of 1997). Our preferred models indicate that expected fatalities were 45% lower and expected injuries 40% lower with Doppler radar installed. Thus, we can infer that fatalities would have averaged 176 per year in these years without NEXRAD compared to the observed total of 97 per year, or an estimated 79 lives saved per year. Similarly we can infer that 2630 injuries per year over this period would have occurred without NEXRAD compared to the observed total of 1578 per year, so 1052 injuries were prevented per year. The 95% confidence interval for RADAR yields a range of 24 to 165 lives saved per year and 309 to 2100 injuries avoided per year. 1999 and 1998 produce the highest tornado fatality totals over the past 20 yr, which indicates the importance of controlling for storm and path characteristics in evaluating the impact of NEXRAD on fatalities. But the high casualty totals also inflate the number of lives that radar will save in a more normal tornado year. Nationally tornado deaths averaged 68.1 per year over the period 1997–2003, so assuming that this total was 45% lower due to NEXRAD, we can infer that Doppler radar avoided 56 tornado fatalities per year.

5. Conclusions

We have investigated whether the installation of WSR-88D radar has yielded benefits to society with regard to tornado safety. Based on a regression analysis of almost 15 000 tornadoes, expected fatalities after Doppler radar installation were 45% lower and expected injuries 40% lower, a substantial benefit. Based on the number of fatalities and injuries observed nationally between 1997 and 1999, this implies that 79 fatalities and over 1050 injuries from tornadoes were avoided per year during this period. The impact of Doppler radar is statistically significant, and the lower bounds of the 95% confidence interval for our Doppler variable are a 20% reduction in fatalities and a 16% reduction in injuries.

Radar composes only one portion of the tornado warning system, and better warnings require timely and effective dissemination of warnings and the appropriate public response to reduce casualties (Doswell et al. 1999). Our method in this study has not attempted to specify the precise channel through which Doppler radar has made tornadoes less deadly (e.g., longer lead times or warnings that are more credible with the public). Rather we have conducted a simple before-and-after test of Doppler radar installation, on the assumption that via some channel, tornadoes should be less deadly after installation of the WSR-88D radars. Thus, the question arises of whether we can attribute the impact of our Doppler radar variable to the new radars, or if other explanations are valid. To address this, we performed the same before-and-after analysis of three components of the quality of tornado warnings. We found that the percentage of storms warned for increased by 70%, the mean warning lead time increased by 80%, and the false alarm ratio fell slightly after installation of WSR-88D. The improvement in tornado warning quality indicates a plausible channel through which Doppler radar has made tornadoes less deadly.

Two further aspects of our study help rule out alternative explanations as well. As documented by Brooks and Doswell (2002), there has been a downward trend in the national tornado fatality rate since 1925. By limiting our study to a relatively short, recent dataset, we avoid letting this long-run trend influence our results. And inclusion of yearly dummy variables in our regression model should capture any NWS or societal change (improved communications and broadcast media for warning) that occurred across the country in say a given year. Our DOPPLER variable takes advantage of the different dates of WSR-88D installation, so any factor besides radar that our variable might happen to capture would have to exhibit a similar variation over time across WFOs.

As mentioned earlier, the NEXRAD system was only one part of NWS modernization. In addition, the quality of satellite observations (Crum et al. 1998) and meteorology's understanding of tornadogenesis improved over the period as well (Brooks 2004). And as Crum et al. (1998) explain, the NEXRAD program has undergone almost continual improvements since installation. Again our yearly dummy variables should capture components of modernization that occurred across all offices at the same time. Further research though would be required to determine the exact contribution of NEXRAD and other elements of NWS modernization to the reduction in casualties documented here.

Although our primary interest here has been quantifying the impact of the WSR-88D network, our tornado casualty models yield other insights. Perhaps the most noteworthy result in our casualty models is the significant time-of-day effects. Tornadoes occurring during the day produce 66% fewer expected fatalities and 47% fewer expected injuries than an equivalent storm occurring during the night. We find similarly significant and somewhat smaller results for tornadoes occurring in the evening versus at night as well. These findings provide strong though indirect evidence concerning the effectiveness of tornado warnings and tornado precautions. Residents are probably less likely to receive a warning issued for a tornado at 0300 LT in time to take precautions, and the differences in casualty rates bear this out. We must emphasize though that we have presented no direct evidence that residents are less likely to receive warnings at night than during the day or evening, and indeed, the difference in casualties might also be due to residents of mobile homes being in safer locations than their homes during the day. Nonetheless, the time-of-day effects identified here are worth of additional investigation. This result suggests the potential safety benefits to society if tornadoes at night could be made no less deadly than tornadoes during the day.

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REFERENCES

Bieringer, P., and P. S. Ray, 1996: A comparison of tornado warning lead times with and without NEXRAD Doppler radar. *Wea. Forecasting,* **11,** 47–52.

Brooks, H. E., 2004: Tornado-warning performance in the past and future: A perspective from signal detection theory. *Bull. Amer. Meteor. Soc.,* **85,** 837–843.

——, and C. A. Doswell III, 2002: Deaths in the 3 May 1999 Oklahoma City tornado from an historical perspective. *Wea. Forecasting,* **17,** 354–361.

Crum, T. D., and R. L. Alberty, 1993: The WSR-88D and the WSR-88D Operational Support Facility. *Bull. Amer. Meteor. Soc.,* **74,** 1669–1687.

——, R. E. Saffle, and J. W. Wilson, 1998: An update on the NEXRAD program and future WSR-88D support to operations. *Wea. Forecasting,* **13,** 253–262.

Doswell, C. A., III, and D. W. Burgess, 1988: On some issues of United States tornado climatology. *Mon. Wea. Rev.,* **116,** 495–501.

——, A. R. Moller, and H. E. Brooks, 1999: Storm spotting and public awareness since the first tornado forecasts of 1948. *Wea. Forecasting,* **14,** 544–557.

Friday, E. W., Jr., 1994: The modernization and associated restructuring of the National Weather Service: An overview. *Bull. Amer. Meteor. Soc.,* **75,** 43–52.

Golden, J. H., and C. R. Adams, 2000: The tornado problem: Forecast, warning, and response. *Nat. Hazards Rev.,* **1,** 107–118.

Greene, W. H., 2000: *Econometric Analysis*. 4th ed. Prentice Hall, 1004 pp.

Merrell, D., K. M. Simmons, and D. Sutter, 2005: The determinants of tornado casualties and the safety benefits of tornado shelters. *Land Econ.,* **81,** 87–99.

National Academy of Sciences, 2002: *Weather Radar Technology beyond NEXRAD*. National Academy Press, 72 pp.

Polger, P. D., B. S. Goldsmith, R. C. Pryzwarty, and J. R. Bocchieri, 1994: National Weather Service warning performance based on the WSR-88D. *Bull. Amer. Meteor. Soc.,* **75,** 203–214.

Serafin, R. J., and J. W. Wilson, 2000: Operational weather radar in the United States: Progress and opportunity. *Bull. Amer. Meteor. Soc.,* **81,** 501–518.

Viscusi, W. K., J. M. Vernon, and J. E. Harrington Jr., 2000: *Economics of Regulation and Antitrust*. 2d ed. MIT Press, 890 pp.