A Comparison of Tornado Warning Lead Times with and without NEXRAD Doppler Radar

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ABSTRACT

The installation of the network of NEXRAD (Next Generation Weather Radar) WSR-88D (Weather Surveillance Radar—1988 Doppler) radars has been an ongoing process for more than three years. An assessment is made on how these radars and related changes at National Weather Service Offices have impacted the warning of tornadoes. Tornado warning statistics were employed to evaluate the improvements in warning lead times and detection after the installation of the WSR-88D. In an effort to remove a bias from the warning dataset, the statistics based on the first tornado event of each day were also considered. This early evaluation of the warning capability of these radars indicates an improvement at selected sites over the previous five years.

1. Introduction

With the installation of the national network of WSR-88D (Weather Surveillance Radar–1988 Doppler) radars, the National Weather Service (NWS) is now receiving some of the new technology it has long sought. These new radars have many improved capabilities that assist forecasters in warning the public of severe weather. Among the improved capabilities, arguably the most significant to the detection of tornadoes, is the Doppler capability of the WSR-88D. Certain patterns displayed in the WSR-88D velocity returns, related to mesocyclones, can be precursors of tornadic development. In addition to the Doppler capabilities, the WSR-88D can collect data at a higher resolution than older NWS radars. This presents the NWS forecasters with a more detailed picture in severe storms with and without mesocyclones. Both the Doppler capabilities and ability of the WSR-88D to collect data at a higher resolution are attributes that previous NWS radars did not possess. Computer algorithms and display software have been developed for this radar. These algorithms and software also improve the ability of the WSR-88D to detect tornadic thunderstorms and assist forecasters in the warning process. The capability of these new radars exceeds, in practically every respect, the radars that they replace. In addition to improved hardware, NWS forecasters receive additional radar and severe weather training that is associated with the arrival of the WSR-88D radar. These factors probably all contribute to the improvement of warning lead times and accuracy.

This study investigates the improvement of tornado warnings by several Weather Service Offices (WSOs) currently using the WSR-88D radars operationally. The statistics from WSOs where the earliest of these radars were deployed are used to show this improvement. Results are presented both by the number of events and by the percentage of tornadoes warned versus lead time. Lead time is defined as the relative time between when a tornado warning was issued and the beginning time of the event (warning time–event time). Lead times were calculated only for tornado events in which a warning was issued. For comparison, an event dataset from before the installation of the WSR-88D was used. This baseline dataset will now be referred to as the ''before WSR-88D'' dataset, and the dataset containing the information from after the installation of the WSR-88D will now be referred to as the ''after WSR-88D'' dataset. Since the after WSR-88D dataset begins at the installation date, it includes warning information from the WSOs prior to the commissioning of the WSR-88D radar. It should be noted that this study does not discriminate between the use of the WSR-88D system and the WSR-57 in the after WSR-88D dataset. During times that information from both radars were available, most likely the Doppler radar would have been used. This suggests that in the future, when a more extensive dataset using only commissioned radars is available, the statistics will likely improve even further. These improvements in warning statistics will probably be a reflection of the increased forecaster experience, completed training, and all of the other factors that are in place after the WSR-88D is commissioned.

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It is also important to recognize that the radar is only a single element in the warning process. Other technologies, such as improved satellite imagery, wind profilers, and faster computer systems, contribute a great deal to the success of the warning process. Spotters and civil defense officials also have key roles, and ultimately, the dissemination of warnings to the public is crucial to the success of the warning system. This study views the WSR-88D as a radar system, which includes hardware, software, personnel, and the training of these personnel. The successes of the system are a direct result of the successes of contributing individual components. Unfortunately, it is not possible to isolate the contributions of all of the other components in the warning process.

2. The dataset

The datasets used in this study are the tornado event files and the severe thunderstorm and tornado warning files from the National Severe Storm Forecast Center (NSSFC). These datasets are a compilation of the records collected by the WSOs for the purposes of statistical evaluation. For this study, data from the sites listed in Table 1 were used. These datasets contain information from sites encompassing various geographical locations. The climatological diversity of the sites incorporates a wide mix of storm types and conditions resulting in tornadoes. This reduces a possible bias of the radar system in detecting tornadoes in a particular storm type found predominantly in one region. The after WSR-88D dataset is made up of data from the radar delivery date through June of 1994. Even though the radars were not commissioned throughout the entire interval used, the WSR-88D most likely played a role in the warning process when WSR-88D data were available. The before WSR-88D dataset is composed of data from five years or less prior to the delivery of the WSR-88D. This short time interval was chosen in order to focus the change in statistics on the introduction of the WSR-88D and other radar-related components of the upgraded WSO. In each of the before WSR-88D and after WSR-88D datasets there were approximately 250–300 tornado events.

The tornado event dataset is known to contain errors. Storm damage misinterpreted as damage due to a tornado, versus tornadoes that were not reported at all, or misinterpreted damage versus tornadoes not detected due to the radars difficulty in detecting very weak tornadoes at long ranges, are examples of existing offsetting errors in the dataset. One bias error evident in the dataset is the observed increased tornado occurrence near large cities. It is reasonable to assume that at locations far from a large city, the actual rate of tornado occurrence is similar to that near a large city. However, the reported number of tornadoes decreases as one moves away from urban areas due to a combination of factors including time of occurrence, insignificant damage, lack of deaths, and simply too few spotters. The number of tornadoes that occur each year is likely to be significantly underreported, and the geographic distribution of occurrence contains a significant positive population bias. In addition to this apparent population bias, there is also a human factor that affects both the tornado event dataset and the tornado warning dataset. In each of these datasets this influence depends upon the personnel and management at the various WSOs. For example, the amount of effort placed into a WSO's verification program has a significant effect on determining the events that go into its tornado event files. There is a similar human influence on the tornado warning dataset. This dataset is ultimately defined by human decisions based on information from the WSR-88D and other sources. Unfortunately, it is not possible to separate all of these influences from the datasets. It is therefore important to keep in mind the human factors that can affect the results of a study of this type.

TABLE 1. Radar sites used in this study.

Station number	Identifier	Location
1	OKC	Norman/Oklahoma City, Oklahoma
2	HOU	Houston, Texas
3	MLB	Melbourne, Florida
4	STL	St. Louis, Missouri
5	DDC	Dodge City, Kansas
6	WBC	Sterling, Virginia

3. Methodology

The approach used in this study first considered cases when a tornado warning was in effect at the time the tornado touched down. If the tornadic event did not begin within the valid times of a tornado warning, then a check was made to see if any tornado warnings were issued within 30 min after the occurrence of a tornado. For cases where no tornado warnings were issued, a separate analysis was then performed using severe thunderstorm warnings instead of tornado warnings. As was the case with tornado warnings, severe thunderstorm warnings having a tornado event that fell within its valid times were counted first. If this criterion was not met, severe thunderstorm warnings issued after the event began were then counted. Using this methodology, the earliest tornado warning available for a particular event was considered first. Only in the instances where a tornado warning did not fit the criteria were severe thunderstorm warnings considered. By including this additional analysis that uses severe thunderstorm warnings, the scope of the study is expanded from considering only tornado warnings to a statistical analysis that is similar to that used by the NWS.

Once the warnings were matched with the tornado events, a calculation of the lead time was made based on the start time of the event and the time the warning was issued. These lead times were then categorized into 5-min intervals with a zero lead time being placed in the 0–5-min lead time interval. By sorting the warnings in this manner, the results then were an assessment of the temporal efficacy of tornado warnings.

Polger et al. (1994) investigated the NWS warning performance for severe thunderstorms, tornadoes, and flash floods following the availability of the WSR-88D. They showed that the WSR-88D was a key component in the improvement of warnings for these types of severe weather. In this study, Polger et al. (1994) approached this problem by looking at the warnings issued and then by determining what type of event verified the warning. No distinction was made between warnings issued before and after the event began. A warning could be verified by a tornado that began before the warning was issued but was still on the ground at the time the warning was issued. Very laconic treatments were given to the tornado warning lead times, and specifics on how the calculation was performed were not mentioned.

The present study approaches the problem by taking tornado events and determining if and when a warning was issued for that event. The majority of this study examines tornado events warned for by tornado warnings only. The high discrimination employed here focuses on the specialized warning for a particular type of severe storm. This is of interest because the public perceives tornado and severe thunderstorm warnings differently.

To enhance the evaluation of the radar system's effectiveness in detecting tornadic thunderstorms, this study also looks at the first tornado events of each day. Often, it is more difficult to warn for the first tornadic event of the day than for subsequent tornadic events. This is because once one tornado occurs, forecasters know that the storms are capable of producing additional tornadoes over the storms' lifetimes. This makes subsequent warnings somewhat easier and possibly less dependent upon the WSR-88D radar system. Thus, it is believed that the first event of each day is more representative of the effect that the Doppler radar has in aiding in the warning process. The study begins by simply separating the first tornado of the day for each station into a new tornado event dataset. This subset of the total event dataset is then sorted in the same manner as was previously done to the entire tornado event dataset. For comparison, this same procedure was also used on the before WSR-88D dataset.

4. Results

The results of this study have been separated into two different categories. One category is the statistics for the first tornado of the day. The second category is for all reported tornado events. In both categories, the before WSR-88D dataset is compared to the after WSR-88D dataset. In general, improved probability of detection statistics and better lead times are shown in the after WSR-88D dataset throughout the results of this study. The probability of detection (POD) is defined as the ratio of correctly forecasted tornadoes to the number of known tornado events (Doswell et al. 1990). There are significant improvements in both the lead times and POD when comparing the before WSR-88D dataset to the after WSR-88D dataset for both categories. This seems to indicate that the WSR-88D has a continued positive effect on not only warnings for the first tornado of each day but for the rest of the tornadoes as well. However, as one might expect, when all reported tornadoes are considered, POD and the lead times both increase over their respective values for the first tornado of each day.

The distributions of the lead times for the first tornadoes of each day are shown in Fig. 1. In Fig. 1a, the number of tornado warnings and their corresponding lead times are plotted for both the period before and after the installation of the WSR-88D. For both the be-

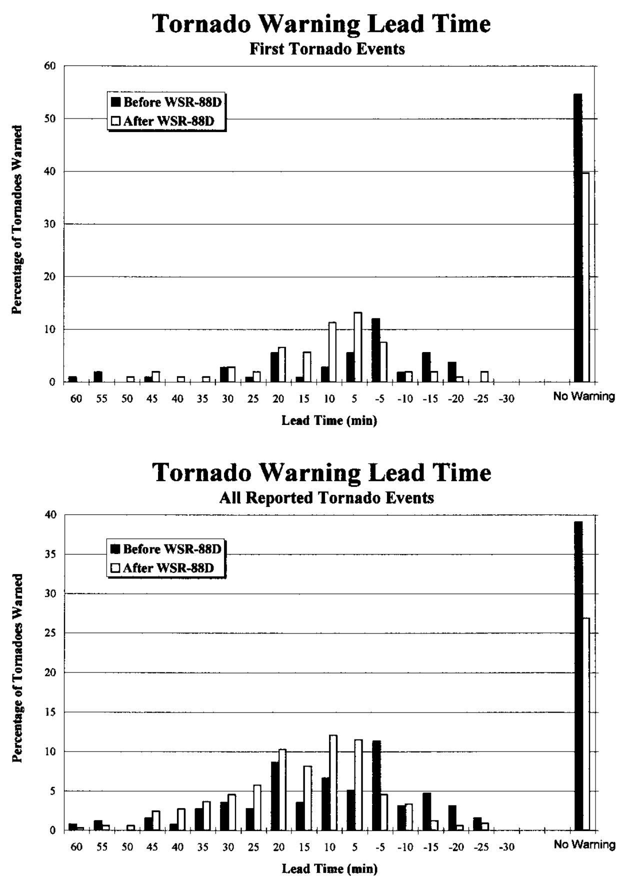

FIG. 1. (a) Histogram of tornado warning lead times before and after the installation of the WSR-88D for the first tornado of each day. (b) Histogram of the percent distribution of tornado warning lead times before and after the installation of the WSR-88D for the first tornado of each day.

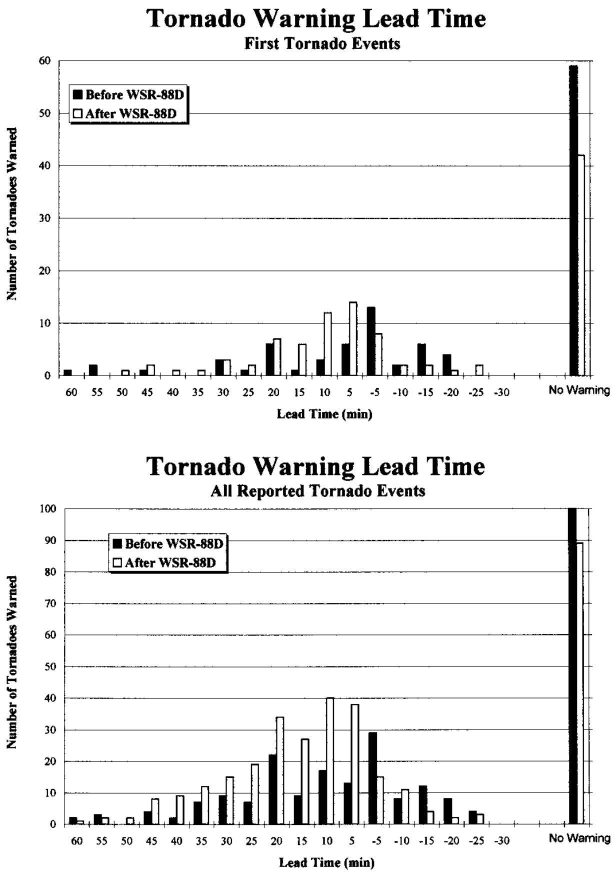

FIG. 2. (a) Histogram of tornado warning lead times before and after the installation of the WSR-88D for all reported tornadoes. (b) Histogram of the percent distribution of tornado warning lead times before and after the installation of the WSR-88D for all reported tornadoes.

fore and after cases, there is a clustering around the time of tornado occurrence. In this sample, over 40 tornadoes were apparently not detected at all by the WSR-88D, since they were not warned for even 30 min after the occurrence. This is less than the nearly 60 tornadoes for which warnings were not issued even 30 min after the event in the before WSR-88D dataset. Figure 1b shows the percentage of first tornadoes of the day that were warned for at times both before and after the occurrence. The percentage of first tornadoes of the day not receiving a warning decreased approximately 15% after the installation of the WSR-88D. In both Figs. 1a and 1b more tornadoes had positive lead times after the installation of the WSR-88D than before. Overall, there is an improvement in the warning statistics for the first tornado of the day following the arrival of the WSR-88D radars. Since both the before WSR-88D and after WSR-88D first tornado of the day datasets each contained approximately 100 events, Figs. 1a and 1b look very similar.

When all reported tornadoes are considered, as in Fig. 2, there is an obvious tendency for warnings to precede the occurrence of the tornado. This tendency is apparent after the installation of the WSR-88D. Before the deployment of the WSR-88D, shown in both Figs. 2a and 2b, the tendency for warnings to precede a tornado event is less pronounced. A large number of the reported tornadoes never receive a tornado warning within 30 min after the beginning of the event. It is possible that some of these tornadoes may have occurred during a severe thunderstorm warning, but that is not quite the same since the general public perceives these warnings differently than tornado warnings. Figure 2b gives the distribution in terms of percent of the total reported number of tornadoes. In this figure, the number of tornadoes for which there was no tornado warning decreases from 39% in the before WSR-88D dataset to 27% in the after WSR-88D dataset. Table 2 shows the related statistic, POD, which has increased from about 61% to 73% following the installation of the WSR-88D radar. This is an improvement that is significant with a confidence of greater than 99%.

In Fig. 3 the enhanced performance of the warning system after the installation of the WSR-88D is illustrated. Figure 3a shows the cumulative percentage of first tornadoes for which there were warnings. Figure 3b is a similar figure for all reported tornadoes. In both figures, the cumulative percentage of tornadoes warned for starts an hour before touchdown and continues until 30 min after touchdown. Before the deployment of the WSR-88D radars, about 22% of the first tornadoes of

TABLE 2. Statistics using only tornado warnings.

Events used	Number of events	Mean lead time (min)	Median lead time (min)	Probability of detection
All tornado events (before WSR-88D)	256	8.0	5.0	60.9%
All tornado events (after WSR-88D)	331	13.0	11.0	73.4%
First tornado events (before WSR-88D)	108	5.2	−0.5	45.4%
First tornado events (after WSR-88D)	106	7.6	6.0	60.3%

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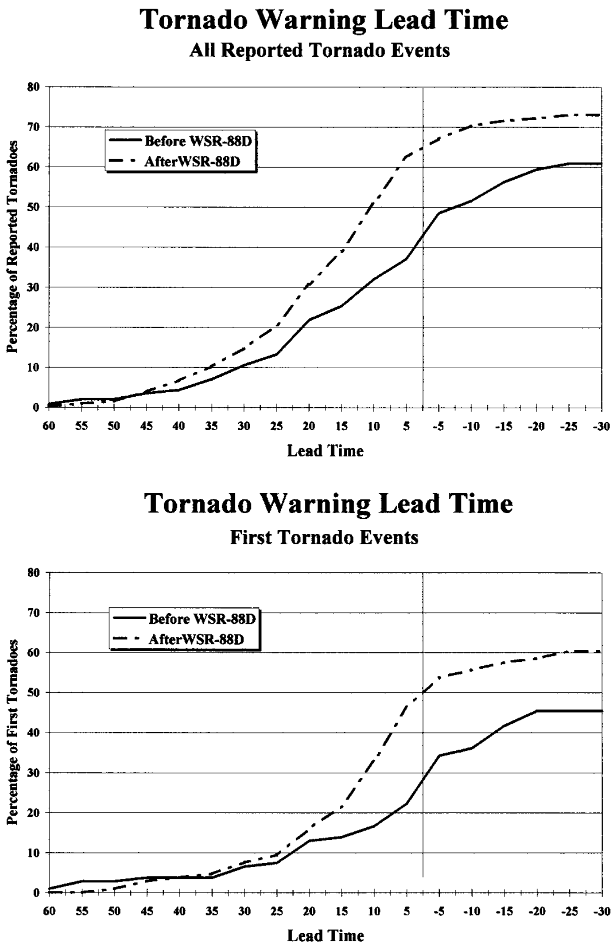

FIG. 3. (a) Cumulative probability of tornado warning lead times before and after the installation of the WSR-88D for the first tornado of each day. (b) Cumulative probability of tornado warning lead times before and after the installation of the WSR-88D for all reported tornadoes.

the day had been warned for before touchdown. Following the deployment of the WSR-88D radars, this percentage increased to 45% of the first tornado events of the day that had tornado warnings issued for them before the tornado touched down. Within 30 min after touchdown, approximately 45% of the first tornadoes before the WSR-88D installation, and 60% of the first tornadoes after the WSR-88 installation had tornado warnings. In Fig. 3b, the cumulative percentage of tornado warnings with lead times improved from approximately 37% before WSR-88D to 62% after WSR-88D for warnings issued before the tornado touchdown. There is an interesting finding in both of these figures. After the installation of the WSR-88D, tornado events had an equal or higher chance of getting a warning issued with a lead time than tornado events before the WSR-88D had of being warned for even 30 min after touchdown.

Table 3 displays some of the same information except that both tornado and severe thunderstorm warnings were used to generate these statistics. When severe thunderstorm warnings were considered, the statistics improved even further. The percentage of first tornadoes receiving either a tornado or severe thunderstorm warning before the deployment of the WSR-88D radars was 63%. After the deployment of the WSR-88D radars, this percentage increased to 68%. The percentage of all reported tornadoes having a warning on them within 30 min after touchdown increased from 75% before WSR-88D to 86% after WSR-88D installation. In addition to the POD statistics, both Tables 2 and 3 give the mean and median lead times. In general, improvements in the average lead times are quite favorable. When only tornado warnings were considered, mean lead times increased over 2 min for first tornado events of each day, and 5 min when all of the reported tornado events were used. Similar improvements are seen in the median lead times as well. When severe thunderstorm warnings were included, the statistics are also favorable with mean and median lead times increasing 2–3 min. One exception to this was in the first tornado event of each day; the mean lead time decreased by about 1 min in this case.

In addition to the statistics in Tables 2 and 3, the False Alarm Ratio (FAR) and Critical Success Index (CSI) were calculated for cases in which all tornado events were used and only tornado warnings were used to verify warnings. The FAR is defined as the ratio of the number of nonverifying tornado warnings to the

TABLE 3. Statistics using both tornado and severe thunderstorm warnings.

Events used	Number of events	Mean lead time (min)	Median lead time (min)	Probability of detection
All tornado events (before WSR-88D)	256	11.4	9.0	75.4%
All tornado events (after WSR-88D)	331	13.8	11.0	86.4%
First tornado events (before WSR-88D)	108	11.4	5.0	63.0%
First tornado events (after WSR-88D)	106	10.1	8.0	68.9%

TABLE 4. (FAR) and (CSI) statistics when only tornado warnings are used as verifying warnings.

Events used	Number of warnings	Number of verified warnings	False alarm ratio	Critical success index
All tornado events (before WSR-88D)	392	156	0.60	0.32
All tornado events (after WSR-88D)	480	243	0.49	0.43

total number of tornado warnings. The CSI is the ratio of the number of verified tornado warnings to the number of tornado events occurring or forecast to occur (Doswell et al. 1990). Table 4 shows the results of the calculations of these two indices. Results are positive with a decrease of 0.11 in the FAR and an increase of 0.11 in the CSI after the introduction of the WSR-88D radar system.

5. Conclusions

This study has used tornado warning verification to demonstrate that the WSR-88D Doppler weather radar is an invaluable tool in the tornado warning process. The efficacy of the warning process depends on many parts (e.g., radar, spotters, communications), and an improvement in one area is only part of the total process. Even though the forecasters may not have been depending exclusively on the WSR-88D for their radar data, there were marked improvements in the statistics after its installation. Lead times were improved as was the probability of detection. It should be further noted that the use of the WSR-88Ds in this study were, for the most part, the use of noncommissioned radars, meaning that at some of the sites used in this study, the conventional radars, the WSR-57 and WSR-74C, were still in use. This study assumes that, when available, the data from the WSR-88D would be used to assist in the forecasters warning decision. Since it is possible that the WSR-88D radars were not used all of the time, these favorable early results may be a precursor of even more favorable results in the future.

There are a number of factors that play a role in the datasets used in this study. It can be argued that individual judgment, training, experience, etc., affects the warning process and therefore the statistics used in this study. By combining the warning and event information from different sites, some of the variations due to these human factors were, it is hoped, minimized. Whether it was the human factors, the technological improvements, or both, in general there were significant improvements in the warning statistics. Overall, this study has shown POD calculations that increased 10%–15% following the arrival of the WSR-88D. These increases are significant with a confidence of greater than 99%. The only exception to this is the first tornado events in Table 3. These statistics showed increases that were significant with only a 90% confidence. In addition, this study also showed improvements in mean and median warning lead times. Even if the human factors cannot be separated from the technological improvements, the results still show that improvements have occurred following the arrival of the WSR-88D radar. With this type of improvement so soon after deployment, it appears that the WSR-88D radar system will be a valuable asset to the National Weather Service in warning for tornadoes.

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