REPORT TO CONGRESS

GAPS IN NEXRAD RADAR COVERAGE

Developed pursuant to: Section 414 of the Weather Research and Forecasting Act of 2017, Public Law 115-25, and the Consolidated Appropriations Act, 2017, Public Law 115-31, and the accompanying House Report 114-605

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PUBLIC LAW 115-25, THE WEATHER RESEARCH AND FORECASTING ACT OF 2017, SECTION 414, INCLUDED THE FOLLOWING LANGUAGE

(a) STUDY ON GAPS IN NEXRAD COVERAGE.—

(1) IN GENERAL.—Not later than 180 days after the date of the enactment of this Act, the Secretary of Commerce shall complete a study on gaps in the coverage of the Next Generation Weather Radar of the National Weather Service (''NEXRAD'').

(2) ELEMENTS.—In conducting the study required under paragraph (1), the Secretary shall— (

A) identify areas in the United States where limited or no NEXRAD coverage has resulted in—

(i) instances in which no or insufficient warnings were given for hazardous weather events, including tornadoes; or

(ii) degraded forecasts for hazardous weather events that resulted in fatalities, significant injuries, or substantial property damage; and

(B) for the areas identified under subparagraph (A)—

(i) identify the key weather effects for which prediction would improve with improved radar detection;

(ii) identify additional sources of observations for high impact weather that were available and operational for such areas on the day before the date of the enactment of this Act, including dense networks of x-band radars, Terminal Doppler Weather Radar (commonly known as ''TDWR''), air surveillance radars of the Federal Aviation Administration, and cooperative network observers;

(iii) assess the feasibility and advisability of efforts to integrate and upgrade Federal radar capabilities that are not owned or controlled by the National Oceanic and Atmospheric Administration, including radar capabilities of the Federal Aviation Administration and the Department of Defense;

(iv) assess the feasibility and advisability of incorporating State-operated and other non-Federal radars into the operations of the National Weather Service;

(v) identify options to improve hazardous weather detection and forecasting coverage; and

(vi) provide the estimated cost of, and timeline for, each of the options identified under clause (v).

(3) REPORT.—Upon the completion of the study required under paragraph (1), the Secretary shall submit to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science, Space, and Technology of the House of Representatives a report that includes the findings of the Secretary with respect to the study.

PUBLIC LAW 115-31, CONSOLIDATED APPROPRIATIONS ACT, 2017, HOUSE REPORT 114-605, INCLUDED THE FOLLOWING LANGUAGE

NEXRAD Coverage Report.—NOAA shall complete a study on gaps in NEXRAD coverage. Within this study, NOAA shall identify areas in the United States with limited or no NEXRAD coverage below 6,000 feet above ground level of the surrounding terrain. NOAA should identify the effects on prediction of improved radar detection, and identify additional sources of observations for high impact weather that are currently available and operational for such areas. NOAA shall assess the feasibility and advisability of efforts to integrate and upgrade Federal radar capabilities and incorporate other non-NOAA radars into NWS operations in such areas, and the cost and timeline for carrying out such radar improvements. NOAA shall submit the study findings to the Committee within 180 days of enactment of this Act. Not later than 30 days after the completion of the study, NOAA shall develop a plan to improve radar coverage in the identified areas.

THIS REPORT RESPONDS TO REQUESTS FROM THE COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION OF THE SENATE; THE COMMITTEE OF SCIENCE, SPACE, AND TECHNOLOGY OF THE HOUSE OF REPRESENTATIVES REQUEST; AND THE SENATE AND HOUSE APPROPRIATIONS COMMITTEES.

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I. Executive Summary

The Weather Research and Forecast Innovation Act of 2017 (Public Law 115-25) (aka the Weather Act) directs the Secretary of Commerce to conduct a study to assess the impact of limited radar coverage as it pertains to warning performance for hazardous weather events, identify other sources of observations for high impact events, and determine the feasibility of integrating radar data other than Next Generation Weather Radar (NEXRAD) data into operations. The agency submits this report on the findings of that study to the Committee on Commerce, Science, and Transportation of the Senate and the Committee on Science, Space, and Technology of the House of Representatives. This report is also in response to similar House Report 114-605 language accompanying P.L. 115-31, the Consolidated Appropriations Act, 2017, directing a NEXRAD Coverage Report, which directs the National Oceanic and Atmospheric Administration (NOAA) to examine warning performance associated with radar coverage at a range where the beam is 6,000 feet (ft.) above ground level (AGL) and higher, and other items similar to the language in the Weather Act.

What the Study and Report Considered

The study examined the impact of radar coverage on warnings for tornadoes and flash floods, although it should be noted that radar also provides necessary observations to support other weather warnings (e.g., hail/severe thunderstorms, winter weather, hurricanes, etc.,) that are not addressed by the study and this report. Tornadoes and flash floods are rare events in general, and only a small fraction of those events cause fatalities. For instance, tornadoes causing deaths comprise only about two percent of all tornadoes. To warn the Nation of these rare events, trained forecasters use a variety of tools and datasets. Data that come from the NEXRAD network are critical for tornado and flash flood warnings, and forecasters also use information from satellites, surface observations, storm-spotters, and high resolution forecast models (among other sources) to aid in the forecast and warning process.

What the Study Found

The study upon which this report is based indicates there is not a significant negative impact to warning performance tied directly to radar coverage where the beam is higher than 6,000 ft. AGL (i.e., where there is little coverage below 6,000 ft.). That evidence does not mean radar is unimportant, rather it suggests that there is significant, usable radar data above 6,000 ft. AGL and other information employed by forecasters to issue warnings. This report provides explanations as to why the tornado and flash flood performance statistics behave as they do. Forecasters, public or private sector, will say that arbitrarily increasing NEXRAD coverage would improve their ability to warn. This appears to be contrary to what the study's key findings say, and the reason is that humans issue the warnings, not the radar. For tornadoes that result in deaths, damage, and injuries, trained forecasters are able to overcome aspects of reduced radar coverage, resulting in warning performance that shows no statistically significant difference between inside or outside the 6,000 ft. AGL range. The NOAA study found that there are minor differences between the numbers of "misses" (i.e., unwarned events) within the range covered by radar beam at 6,000 ft. AGL compared to "outside" (i.e., beyond) the range across the contiguous United States (CONUS).

The study also examined the difference between the most and least intense tornadic events. For unwarned tornadic events causing fatality, injury, and/or significant damage, the study found weak to no statistical dependence on radar coverage in a linear model. This lack of correlation is especially true with the strongest tornadoes, Enhanced Fujita (EF) scale[3] EF3–EF5 events. The bottom line is that radar coverage, even outside of the coverage by radar beam at 6,000 ft. AGL, allows forecasters to rarely, if ever, miss warnings for EF3–EF5 tornadoes because of their ability to use all available data, including data far from the operational NEXRAD radar. NOAA's National Weather Service (NWS) warns for about 98% of these events. Conversely, weak, short-lived tornadoes are unwarned in many locations. Our ability to detect and warn for these tornadoes is consistent for areas covered by radar within 6,000 feet and those areas with lesser coverage. Short-lived tornadoes rarely cause fatalities or significant damage. Of the tornadoes in the study that went unwarned, only 2% of those caused injuries. The study also determined that tornado false alarm rate – issuing a warning for a storm that does not eventually reach warning criteria - is insensitive to radar coverage. Thus, radar coverage itself bears no discernible impact on false alarm rate.

Overall, the study showed that flash flood warning performance is more sensitive to radar coverage than tornado warning performance. However, the overall number of events seems to be a more important determinant of warning skill than radar coverage, and there are more tornado and flash floods events where there is more relative radar coverage. This is not because the number of recorded tornado and flash floods events is larger, unsurprisingly, where radars are present to observe them. Indeed, the radars were sited based in part upon historical occurrences of severe weather events. Since no statistical method is necessarily perfect or without limitations, the study acknowledges that additional geospatial analyses related to radar coverage may provide other information about NOAA's NWS performance, in particular about impact-based events. Moreover, the study is in general agreement with similar research published in peer-reviewed articles.

Future Considerations

While the study did not reveal significant areas of warning service deficiency due to reduced radar coverage, the report – per direction – does examine the availability and use of other observational data sources and analyzes options to improve hazardous weather detection. In summary, NOAA recommends an "all of the above" approach, using ongoing research and development to improve the prediction and detection of hazardous weather. These efforts include improved numerical model development, analysis of new weather satellite data, developing advanced radar technology, employing novel observation systems such as Unmanned Aircraft Systems (UAS), and others. NOAA will continue to strive to improve weather prediction at all scales.

[3] The Enhanced Fujita scale (EF-Scale) is a scale for rating tornado intensity based on damage surveys: EF0 (65-85 mph), EF1 (86–110 mph), EF2 (111-135 mph), EF3 (136-165 mph), EF4 (166-200 mph), F5 (>200 mph).

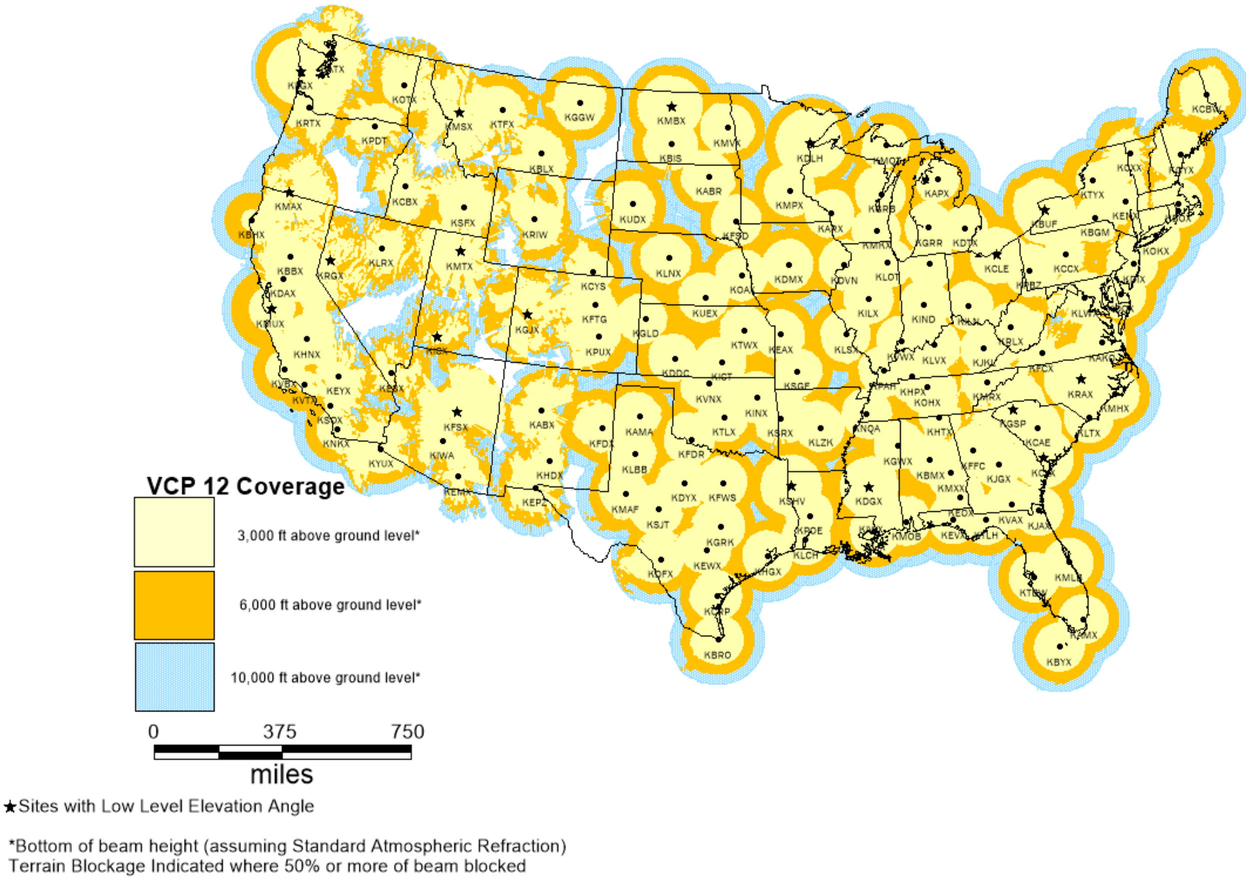


Figure 1. NEXRAD coverage at the bottom of the radar beam of 4,000, 6,000, and 10,000 ft. AGL.

II. Background

Tornadoes and flash floods are two of nature's most violent events, sometimes leaving incredible damage and casualties in their wake. In the 1980s, the Department of Commerce, the Department of Defense (DoD), and the Federal Aviation Administration (FAA) strategically designed the NEXRAD network with geographical locations of radars to provide extensive radar coverage, with overlapping radars where possible east of the Rockies, to detect the precursors to tornadoes, increase tornado warning lead time, and help improve rainfall estimates which contribute to flash flooding. Radar coverage over the western and intermountain areas (defined as western Montana, Wyoming, western Colorado, western New Mexico, and all states to the west) was increased dramatically through the NEXRAD program, although areas of poor coverage remain, especially in the complex terrain of the western United States. Within, CONUS the NEXRAD network consists of 142 radars that provide coverage of about 73 percent of the land mass and 94 percent of the population at the 6,000 ft. AGL range. An additional 17 NEXRAD sites are deployed in Alaska, Hawaii, U.S. territories, and military bases. The deployment of the NEXRAD network achieved its goal: tornado warning lead times increased from four minutes in the 1980s before NEXRAD to about an 11 minute average over the past 10 years; and flash flood warning lead time increased from 18 minutes in the 1980s to over 70 minutes today.

This study and report examine warning performance in the context of current Government Performance and Results Act goals, not future performance as described in Section 103 of the Weather Act. With the ongoing Service Life Extension Program, the NEXRAD network should be operational for approximately the next 20 years. Efforts are underway now in NOAA to define and refine the future requirements for hazardous weather detection post-NEXRAD. A key component during the requirements process for a potential follow-on to NEXRAD is to ensure that NWS continues to lead the way in hazardous weather warnings. There is a real opportunity to improve observation and prediction capabilities, as stated in the Weather Act, far beyond current network capabilities, and as highlighted in this report and its attendant study. As is shown in this report and via data in the study, improving NEXRAD coverage alone is not likely to significantly improve warning performance for tornadoes and flash flooding. That is not to say that NEXRAD is not important to warning performance, because quite the opposite is true. Numerous studies (including this one) have clearly demonstrated the value of NEXRAD for saving lives and property, and it cannot be understated that NEXRAD is the single most important source of data used by public and private sector forecasters in the tornado and flash flood warning decision processes. It is expected that the next significant leap forward in lead time for tornadoes and flash flooding will be the result of the Warn-on-Forecast paradigm that has been discussed in the weather community, potentially leading to 60 minute lead time for tornadoes, and described in Section 103 of the Weather Act: Tornado Warning Improvement and Extension Program, "…to reduce the loss of life and economic losses from tornadoes through the development and extension of accurate, effective, and timely tornado forecasts, predictions, and warnings, including the prediction of tornadoes beyond 1 hour in advance." A follow-on to NEXRAD would necessarily provide the foundational observational needs of Warn-on-Forecast.

This report summarizes a comprehensive, nationwide study performed by NOAA to examine warning performance for instances in which no, or insufficient warnings, were given for hazardous weather events, including tornadoes. It also looks at whether limited or no NEXRAD coverage in areas in the United States has resulted in degraded forecasts for hazardous weather events that resulted in fatalities, significant injuries, or substantial property damage.

An important definition used in the study is where to draw the line between "optimal" and "poor" radar coverage. NOAA used the definition from the House Report for the Consolidated Appropriations Act, 2017, of the radar beam at 6,000 ft. AGL as the demarcation between "optimal" and "poor" radar coverage. This level was selected to address concerns that some forms of severe weather, such as tornadoes, can occur far from the radar, escape detection (because the beam shoots over the top of the phenomena) and, therefore, are more likely to be unwarned. The horizontal distance this corresponds to is about 71 miles from the radar, though useful radar data are available to about 144 miles in range.

Another key distinction in this report is how to characterize "hazardous weather", other than tornadoes as stated in the Weather Act. The impetus for the study was congressional concern over "missed" tornados and "missed" flash floods and the impact on loss of life, injuries and property damage. Warnings for these short fuse events can benefit most from radar coverage, because forecasters use the radar to detect features in real-time, such as precursors to tornado formation and heavy rainfall. There are many other weather conditions that can be considered hazardous, such as winter storms, high winds, hurricanes, coastal flooding, etc. While radar will help in overall situational awareness during these types of events, in general the most critical data source for issuing watches and warnings for these longer time-scale events come via numerical weather prediction. Therefore, this report will focus on tornados and flash floods as the relevant "hazardous weather" under review. Also for this study, "degraded forecasts" or "insufficient warnings" are considered the same and defined as "unwarned events." In order for a tornado or flash flood event to be considered significant, there must be one or more injuries caused by the event. Significant tornado property damage is about $1.6 million per event, while for flash floods significant property damage is defined at and above about $416,000 per event.

A detailed explanation is warranted regarding language in the Weather Act where it states "*identify areas in the United States where limited or no NEXRAD coverage resulted in—(i) instances in which no or insufficient warnings were given for hazardous weather events, including tornadoes; or (ii) degraded forecasts for hazardous weather events that resulted in fatalities, significant injuries, or substantial property damage.*" This and similar language in the House Report for the Consolidated Appropriations Act, 2017, implies that limited radar coverage, or a "gap", is a primary factor for missing warnings for short fused events. This is typically not the case. There are numerous factors that play a role in any missed warning, and radar coverage is one of many in an extremely complex decision process. No one argues the importance of radars and that optimal coverage is beneficial to hazardous weather detection, but humans are responsible for issuing hazardous weather warnings, not the radar. Humans routinely integrate numerous sources of information, often times conflicting information, from storm spotters/chasers, webcams, satellites (especially the high resolution data coming from the new geostationary satellites), the Multi Radar-Multi Sensor (MRMS) products, surface observations like those available through the Mesonet Program, Probsevere, the High Resolution Rapid Refresh forecast model, and other high-resolution modeling systems, prior to issuing warnings. The operational version of MRMS includes NEXRAD and Canadian radar networks, numerical weather models, precipitation gauges, background climatologies, and lightning mapping arrays to generate severe weather and quantitative precipitation estimates products for the forecasters.

Forecasters also use the FAA Terminal Doppler Weather Radars (TDWR), installed near many major airports, to aid the warning decision process. In some cases, these data have been instrumental to pinpointing the threat of a tornado, especially in areas where the TDWR offers better radar coverage than the NEXRAD. Trained forecasters understand that when a storm is farther from the radar, signatures will not be as clear cut or perhaps not present at all, and they rely on other sources of information to make the warning decision. As the study shows, they are skilled at making these difficult decisions with sometimes sub-optimal radar data. Additionally, an informal examination of unwarned events, including tornadoes, was gathered as part of a training exercise covering 15 years. Forecasters were asked to list the various factors they felt played a role in an event being unwarned. There were tens of individual factors identified during the root cause analyses, each of which, in isolation, did not cause an unwarned event. However, when several factors cascade together, unwarned events can occur. Poor radar coverage was a contributing factor for some unwarned events, but the majority of the root causes were related to human factors. Poor radar coverage is never the single contributing factor to an unwarned event. To identify unwarned events where poor radar coverage played a role, each individual event would need to be closely scrutinized, including interviews with all the forecasters on shift, and it would need to be done within days or weeks of the event given the need to capture minute details of the decision process. This kind of post-event work is well beyond the scope of the study and this report. Instead, the report will examine the bulk statistics associated with radar coverage and warning performance conducted in the study.

Much of the previous discussion is related to the tornado warning process, but NEXRAD is also an important piece of the flash flood warning decision process. This is because the radars are able to estimate the amount and rate of rainfall, which, combined with the knowledge of the local hydrological response to heavy rain, allows forecasters the ability to issue warnings with significant lead times. The precipitation estimates from the radar have vastly improved NWS flash flood warning prediction, and the lead time has increased from about seven minutes in the late 1980s, to near 50 minutes or more after NEXRAD became operational nationwide in the late 1990s. As with tornadoes, NWS forecasters use other tools in the flash flood warning process such as satellites, rain gauges, storm spotters, and high-resolution forecast models both in good and sub-optimal radar coverage.

Finally, no single observational source, such as the NEXRAD, will mitigate warning challenges and eliminate the potential for loss of life, given that every observational system has inherent limitations. Even if perfectly detected, predicted and warned, these events can still cause damage, injuries, and fatalities. Ask any forecaster and he or she will tell you NEXRAD is the preferred source for issuing warnings for hazardous weather, but no single data source is used exclusively, whether near or far from a NEXRAD radar. The availability and usage of multiple sources of data in the warning decision process is the backdrop for the study and will help explain some of the study's findings in this report.

III. Study Methodology

The study examines National Weather Service (NWS) warning performance for both tornado and flash flood events over a 10-year period.[4] Each type of hazardous weather event is tallied by all events (warned or not) using the definition of radar coverage with the beam below 6000 ft. AGL. NOAA examined over 12,000 tornado events and over 30,000 flash flood events from 2008-2016. The source of performance data is the NWS Local Storm Reports.[5]

As discussed previously, NWS forecasters use several sources of data, including additional Federal Government radar assets like the TDWRs, when available, to make warning decisions. Data from the 45 TDWRs provide radar coverage in many locations, including Charlotte, North Carolina, Columbus, Ohio, Las Vegas, Nevada, and Puerto Rico. In general, TDWR coverage is

[4] A 10-year period was used to determine damage, injuries and deaths for tornadoes. An 8-year period (2008-2016) was used for GIS analysis of tornadoes of polygon tornado warnings, which began in 2008.
[5] Available at https://www.spc.noaa.gov/exper/reports/?&all&date=20200311.

supplemental to the NEXRAD network and overlaps existing NEXRAD coverage for many major U.S. cities. It would not be possible to isolate the impact of TWDR data usage on tornado warning performance without examining every warning decision in detail, thus, NOAA assumes any positive impacts from the usage of TDWR would not change the overall statistical results in the study.

The study also examined integrating data from other FAA radars and from non-Federal radars. Other FAA radars, such as the Air Surveillance Radars, are not useful to NWS operations to improve detection and prediction of hazardous weather events like tornadoes and flash floods due to optimizations that are made to track aircraft. Non-Federal radars have considerable cost and technical challenges to deliver the data to NWS offices, and are not generally viable, especially in light of the fact that most of these "additional" radars are primarily in regions that are covered by the existing NEXRAD and/or TDWR networks. Non-Federal radars may not have the same rigorous maintenance and calibration standards, and may not be scanning at all times during the day and night.

While there are gaps evident on maps depicting coverage by radar beams at 6000 ft. or 10,000 ft. AGL, the radar data above those levels still provide important information for the forecasters to use as they develop their forecasts and issue warnings for hazardous weather events. The possible exception is the intermountain west, where radar data coverage is reduced and the hazardous events are limited, and in the case of strong tornadoes, are very rare. However, even in the intermountain region, the benefits would be limited to potentially improving flash flood warnings, with some impacts (reduced deaths and property damage) limited here as well. The tornadoes that occur in the intermountain region are typically of the weaker variety, EF0 or EF1, and the statistical correlation to damage, fatalities, and injuries is very low.

IV. Tornado Warning Performance

Tornado events (both warned and unwarned) which occurred within radar coverage (e.g., areas of coverage at 6000 ft. AGL or lower) were compared with events that occurred outside of optimal radar coverage (no coverage at beam centerpoint 6000 ft. AGL). Further analysis compared radar coverage at beam centerpoint 6000 ft. as a percent of state (i.e., Colorado) covered compared against the national average of warning skill. A similar measure of percent coverage below 6000 ft. for each NWS Weather Forecast Office's (WFO) area of warning responsibility was conducted to see if there was any correlation between good and sub-optimal radar coverage related to warning performance. Nationwide, the mean coverage of NEXRAD at 6000 ft. AGL is about 60 percent of each state. Western states, except California, have coverage at or below average. Preliminary national analyses of tornado warnings between 2008 and 2016 show similar performance among events inside, outside, or those that cross the boundaries of radar coverage, with a consistent majority of events having been warned, regardless of radar coverage (Figure 2).

The analysis in Figure 2 shows high parity in the fractions of events warned and unwarned nationally inside or outside of radar coverage, regardless of whether supplemental TDWR information is added. In some cases, being far from the radar, with the uncertainty and ambiguity involved because of the poorer radar coverage, leads a forecaster to lower his or her internal threshold to issue a tornado warning (The finding of a higher false alarm ratio overall beyond 150 km (93.7 miles) in range by Brotzge et al., 2011, supports this interpretation.). A lower warning threshold may explain why there was little difference in performance, in a bulk sense, inside and outside the range covered by a radar beam at 6000 ft. AGL.

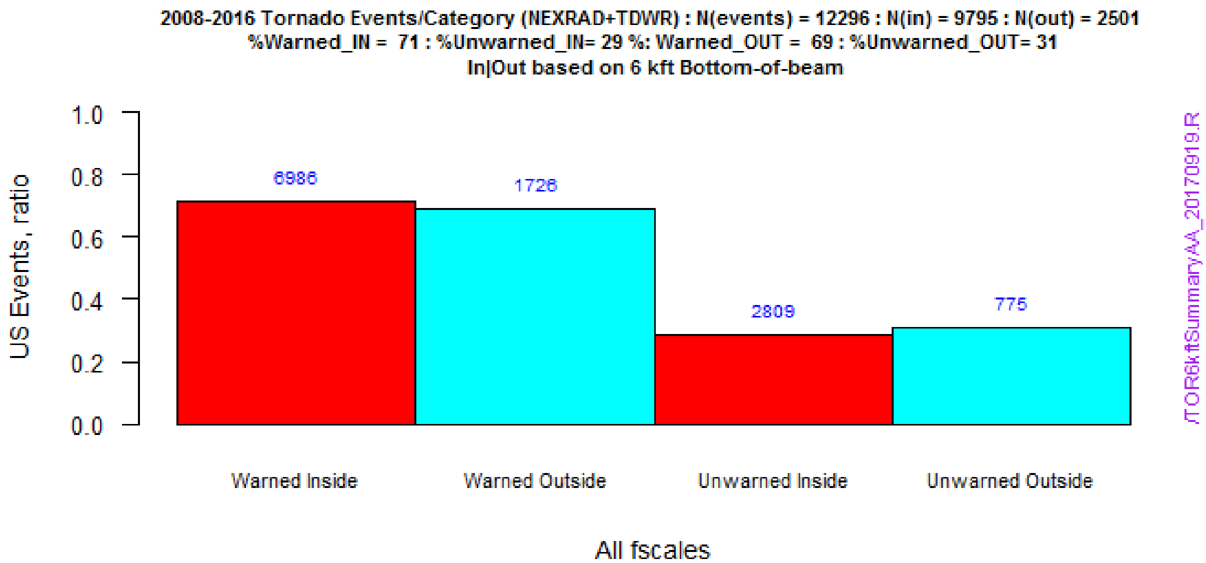


Figure 2. Tornado event fraction (from all events) as a function of tornado events for 2008-2016. The red color bars denote events inside NEXRAD and TDWR radar coverage threshold at 6000 ft. AGL that are warned (left red bar) and unwarned (right red bar). The cyan bars are the corresponding warned events outside (left bar) and unwarned outside (right bar). The numbers atop the color bars denote the event counts out of a total of 12,296. The bars are ratios. Note the **ratio** of warned and unwarned events inside coverage and outside coverage is virtually the same.

The evidence that only minor improvement occurs regarding tornado warning performance within 6,000 feet AGL radar coverage should not be misconstrued or misunderstood as a reason to downplay the importance of the NEXRAD network. On the contrary, the radar network is the most important tool for short fuse, high impact warnings and without it the loss of life from severe weather would be extraordinarily higher (The Economic and Societal Impacts of Tornadoes by Simmons and Sutter, 2011). The fact is that human forecasters know to rely on other data sources in poor radar coverage areas to make warning decisions. Overall confidence in those decisions are enhanced when the event is near the radar, a fact that cannot be overlooked because as discussed earlier, human factors constitute a majority of the reasons behind unwarned events. Parity is also seen in terms of tornado intensity. Violent tornadoes (EF3–EF5) are properly warned for at higher rates than weaker tornadoes (EF0–EF2), and the weaker tornadoes are much more numerous than the stronger ones. Some tornado metrics have a moderate sensitivity to the degree of radar coverage, an exception is that there is a strong correlation between the number of tornado events and the number of warned events per WFO area of responsibility. As the number of tornado events increases to close to 200 per 8 years, the percent of warned events increases rapidly, leveling off at about 80 percent. This implies that the offices that have the most tornadoes typically perform the best in terms of warning performance. The reason this is the case is primarily because of forecaster experience. NWS offices that issue more tornadoes warnings have better experience and more training for events that are relatively more frequent, particularly across the plains and southeastern states. The study also found that on average, there are very few tornado events in most western states (Figure 3). This means that the region with the poorest radar coverage also experiences the fewest tornadoes. This is not surprising because radar coverage was designed to be maximized in the regions with the most severe convective weather and where beam blockage due to terrain is not as severe, both of which are true east of the Rocky Mountains.

Tornadoes that cause deaths are rare and comprise about two percent of all tornadoes. There were about 1,000 fatalities that occurred in 270 tornado events, out of over 12,000 tornado events over the 8 years. Trained forecasters do an excellent job in detecting violent tornadoes, in part because NEXRAD radars likewise can better detect tornadic signatures associated with violent tornadoes, and this is true whether there is radar coverage below 6,000 ft. or not. The data show there is virtually no sensitivity relative to radar coverage for the killer tornadoes. About half of the fatalities occurred in the southeastern United States and Oklahoma, which generally have very good radar coverage.

Injuries are also generally related to strong or violent tornadoes. Fewer than 10 percent of events had any injuries, and fewer than two percent of all injuries occurred during unwarned events. The same relationship applies for the tornado fatality statistics; NEXRAD radars and human forecasters generally detect and warn for the vast majority of stronger tornadoes which result in injuries. In most cases, strong and violent tornadoes are well warned everywhere, and injuries have virtually no sensitivity to relative radar coverage. Both fatalities and injuries are highly variable and concentrated in spikes due to large-scale severe weather outbreaks (April and May of 2011 account for about half of the fatalities and injuries in the study). About 85 percent of fatalities are due to violent tornadoes (EF3, EF4, and EF5). A similar pattern is seen in the few unwarned fatal events, also mostly due to strong to violent tornadoes. In summary, the study's results show that radar coverage is statistically not a significant factor in tornado warning performance regarding unwarned events that resulted in fatalities or injuries.

A similar pattern is seen in terms of warned and unwarned tornadoes that result in significant damage, defined as at or above the mean damage of about $1.6 million per event. Four percent of all the tornado events in the study generated at or above $1.6 million in damages. Most of the damaging tornadoes were concentrated in 2008, accounting for 20 percent of all such events in the study.

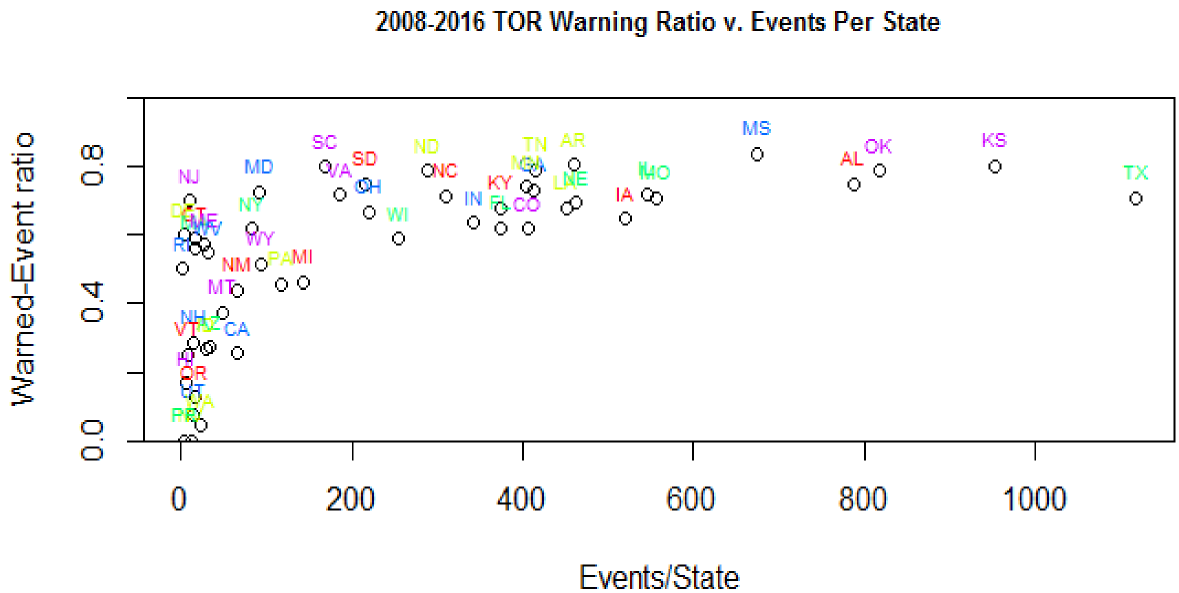


Figure 3. Warned tornado event fraction (from all events) as a function of tornado events per state for 2008-2016. There are very few tornado events in western states. The percent of events warned increases rapidly as the event rate grows and stays uniformly high past 200 events/state.

Significant property damage has some correlation with radar coverage, but with large variance. Seventy-two percent of the most damaging tornadoes (based on a threshold of $1.6 million in damages) are accurately warned inside the coverage of a radar beam at 6,000 ft. AGL, while 68 percent are accurately warned outside the same threshold. The unwarned numbers for the most damaging tornadoes are 28 percent inside the threshold compared to 32 percent outside, a minor difference in performance but not statistically significant due to the low occurrence of such tornadoes.

One of the tools used to measure the effectiveness of the NWS tornado warning program is to use metrics called “probability of detection” and “false alarm ratio” (FAR). A FAR is determined by the number of tornado warnings that were issued against the number of warnings that were associated with no tornado occurrence. Analysis from this study found no correlation with regard to radar coverage regarding FAR or fatalities, and nearly no correlation with unwarned injury event ratios regardless of range of the warned event from the radar (Figure 4).

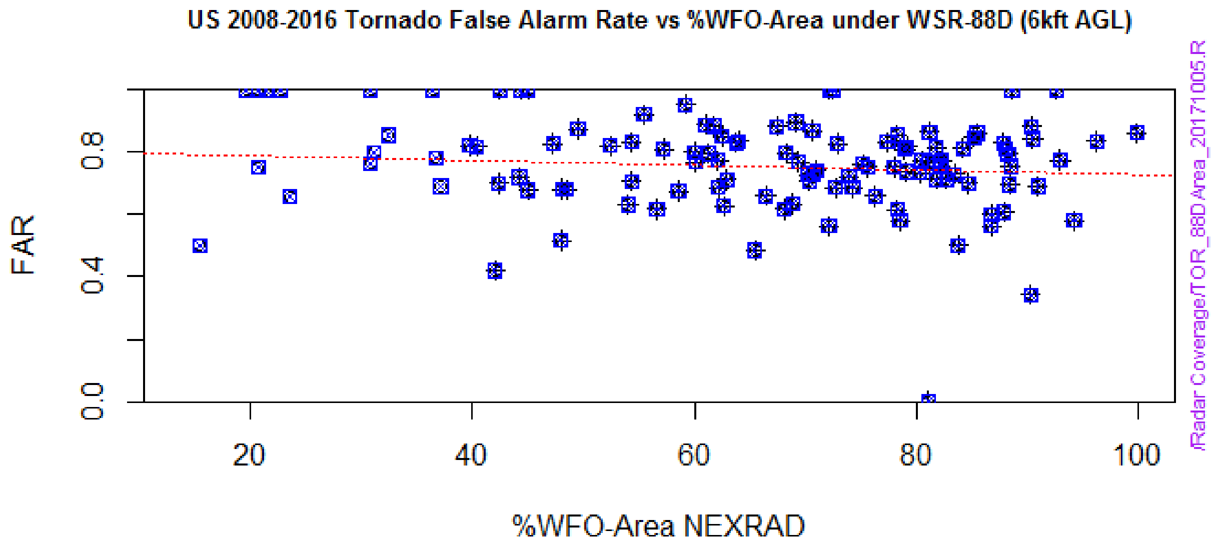


Figure 4. Tornado false alarm ratio (FAR) for 2008-2016, and percentage of WFO-area covered by NEXRAD. Fitted line is essentially insensitive to radar coverage.

This analysis reinforces the results from the coarser inside/outside 6,000 ft. AGL spatial binning that show no significant systematic warning degradation for tornadoes due to variations in radar coverage. There is a slight degradation in FAR beyond the range of a radar beam at 6,000 ft. AGL, but it is extremely small and not statistically significant.

It is thus not surprising that radar coverage in and of itself is a weak predictor of tornado warning performance overall, because as discussed at length earlier in this report, warning skill draws from multiple sources, some of which cannot be easily measured. Very high-resolution (time and space) numerical weather models (called storm-scale models) are expected to replace today's warn-on-detection practice with warnings based on model predictions, such as those being developed under the NOAA Warn-on-Forecast project. This report details the significance of Warn-on-Forecast advances in Section VII.

V. Flash Flood Warning Performance

NWS WFOs assess and monitor the threat of flash flooding 24 hours a day, 7 days a week, to provide timely and accurate life-saving flash flood forecasts, watches, and warnings. The issuance of flash flood warnings helps the NWS meet its mission by providing advance notification of dangerous, short-fused flood events. This allows users to take immediate mitigation actions, such as evacuating to higher ground, helping to protect life and property. Toward this end, WFOs integrate a wide range of numerical model guidance, radar-based precipitation estimates, satellite-based precipitation estimates, and real-time telemetered precipitation and stream gauge observations to provide critical decision support services, including issuing flash flood warnings when precipitation capable of causing flash flooding or debris flows is indicated by radar, rain gauges, and/or satellite.

Precipitation estimates from radar have vastly improved NWS flash flood warning prediction and the lead time has increased from about seven minutes in the late 1980s to around 50 minutes or more after NEXRAD became operational nationwide in the 1990s. Accurate radar-rainfall estimates are of critical importance and are shown to be improved when the range from storm to radar is less than 60 miles, and when there are at least two overlapping radars within 142 miles. In general, storm-total radar-rainfall measurement accuracy decreases farther from the radar because at that height, frozen precipitation is typical, and it is much harder to estimate the liquid content once the precipitation reaches the ground (Rogalus and Ogden, 2013).

As with tornadoes, forecasters use multiple sources of information during the flash flood warning decision process, which minimizes the impact and/or reliance on a single source of information. Radars are the most important source of information for detecting heavy rainfall, but in poor radar coverage areas forecasters are for the most part able to incorporate other sources of information to help make warning decisions. Seasonal changes and climatological patterns play a more significant role in flash flood warning skill compared to tornadoes. During the course of a year, if the majority of flash flood events result from widespread, highly predictable rainfall events, such as large scale, well-forecasted land falling tropical or winter storms, the overall effect of improved national average performance metrics for flash flood warnings is observed. Conversely, lower lead times and accuracy would be expected when there is a general lack of these widespread, highly predictable rainfall events. Additional forecasting and verification challenges arise in areas of steep terrain or where wildfires can leave burn scars across the land surface, conditions notably observed in the western United States. In these situations and regions, warning lead time and accuracy is often diminished, as hydrologic response is very rapid, and oftentimes not that much rainfall is needed to produce life-threatening impacts.

Preliminary national analyses of flash flood warnings between 2008 and 2016 show similar performance among events inside, outside, or those that cross the boundaries of radar coverage, with a consistent majority of events having been warned, regardless of radar coverage (Figure 5). There is a more significant increase in the ratio of unwarned flash flood events outside the coverage of radar beams at the 6,000 ft. AGL level compared to tornadoes, but the differences are still quite small (12 percent inside 6,000 ft. AGL v. 18 percent outside). National analysis shows a slight increase in probability of detection, critical success index, and lead time and a decrease in false alarm rate with increasing WFO area under the coverage radar beams at 6,000 ft. AGL.

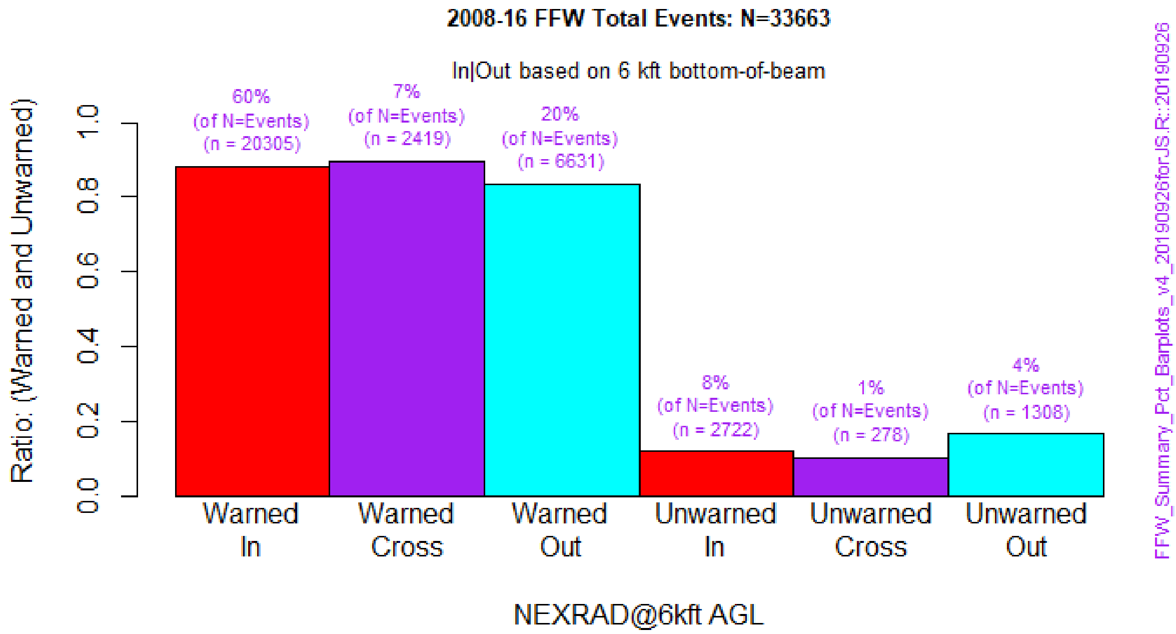
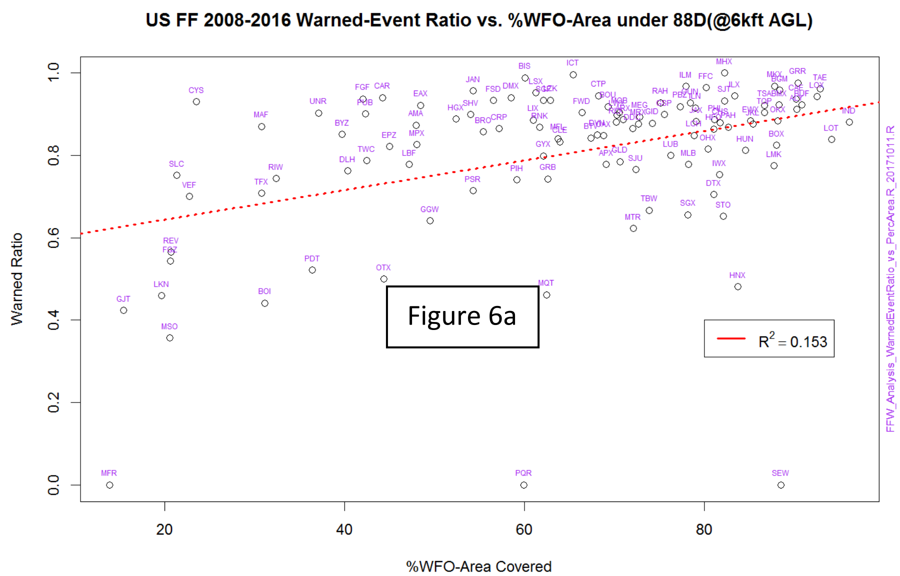


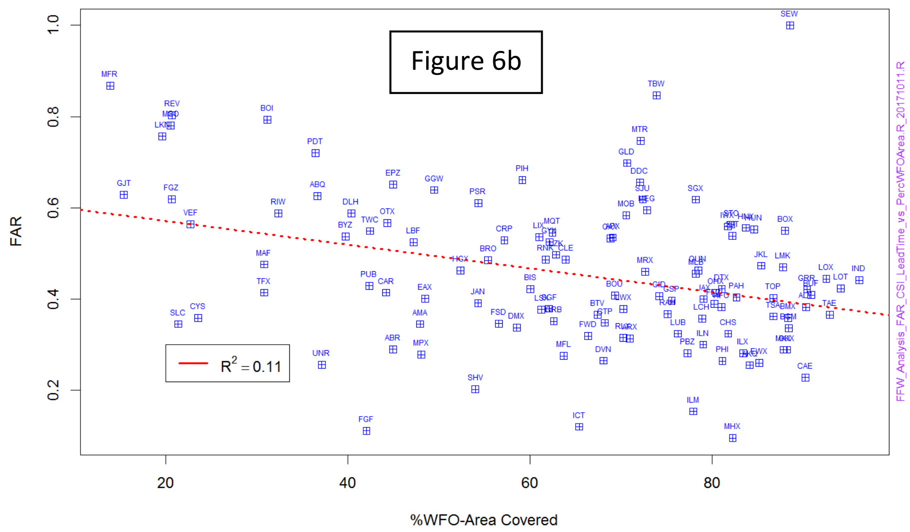
Figure 5. Ratio of warned inside coverage (red), warned cross (purple), and warned outside (cyan) to unwarned inside (red), unwarned cross (purple), and unwarned outside (cyan). These are for flash flood events from 2008-2016 normalized by the total number of events inside or outside coverage area of the 6 kft. beam bottom altitude according to the radar coverage type (within radar coverage, outside of radar coverage, or crossing limit of radar coverage). The two purple bars are "crossed" events that fell partially inside and outside the 6 kft. beam bottom altitude range. Flash floods events are generally warned at the same proportion regardless of radar coverage. Most flash floods events (68.4 percent) occur inside radar coverage.

The ratio of warned flash flood events to total number of events shows most states have a high warned ratio for all levels of events and little apparent difference between the warned event ratio for events inside radar coverage as compared to those outside. The exception is a set of western states, which show a smaller decrease in warned event ratio with increasing radar coverage as compared to states with similar numbers of events. Further analysis could better differentiate regional trends and relationships among radar coverage, event type, population, warning performance, and other variables.

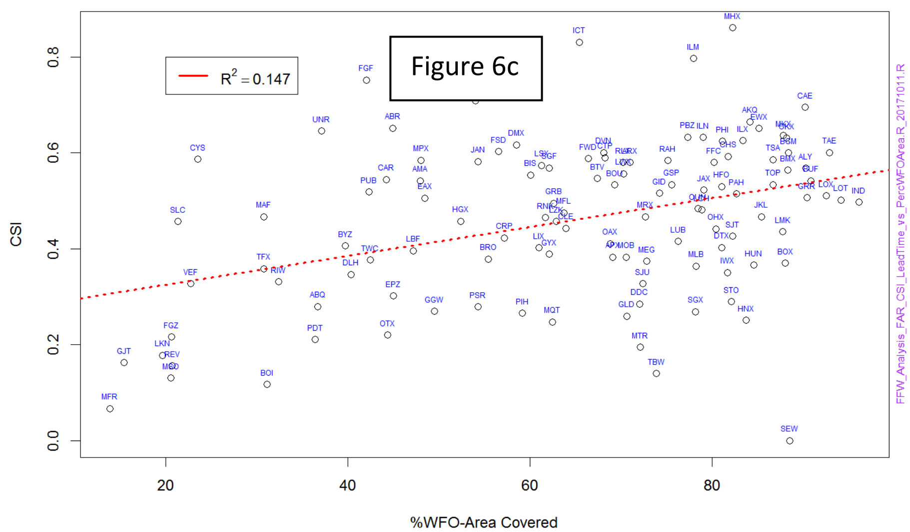
From 2008 to 2016, 17 fatalities and 13 injuries occurred for every 1,000 flash flood events. Injury statistics, already a small dataset, are dominated by a single event encompassing nearly a quarter of all injuries for the 8-year period. This strong bias makes trend analysis less meaningful for these data. Nevertheless, there is some positive correlation between the number of events per state as well as injuries per state and state population. There is very little relationship between flash flood events, fatalities, injuries, damages, or significant damages compared to radar coverage for the CONUS. Around 4,300 flash flood events went unwarned during that period (12 percent of all events), with a rate of 28 fatalities and 17 injuries per 1,000 unwarned events. Most fatalities in unwarned events occurred in events inside of or very close to the coverage threshold of a radar beam at 6,000 ft. AGL. Overall, radar coverage does have some relationship to NWS flash flood warning performance statistics at a national level (e.g., detection of a flash flood) (Figure 6).



US FF 2008-2016 False Alarm Rate vs. %WFO-Area under 88D(6kft AGL)



US FF 2008-2016 Critical Success Index vs. %WFO-Area under 88D(6kft AGL)



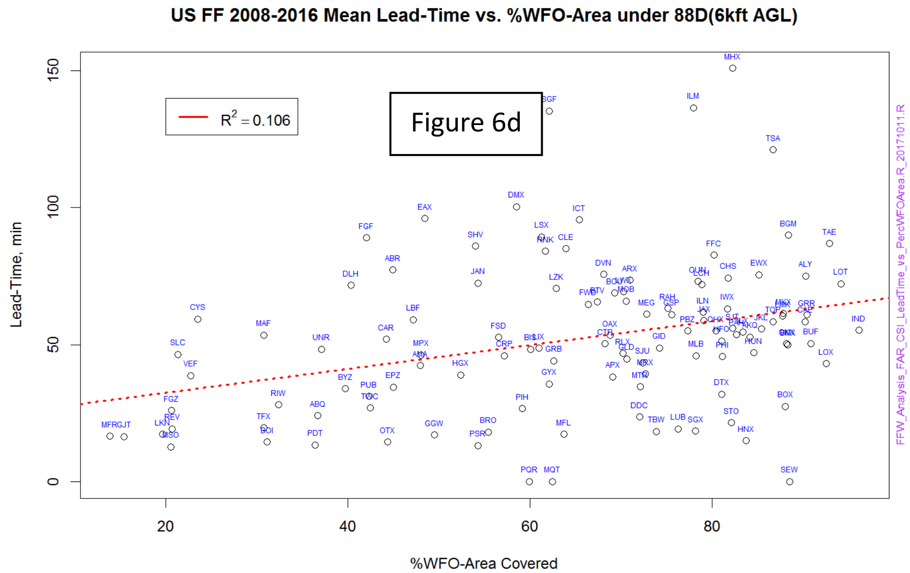


Figure 6. Flash flood (a) warned-event ratio (probability of detection), (b) false alarm ratio, (c) critical success index, (a performance measure including warned and unwarned events), and (d) mean lead time 2008-2016 and percentage of WFO-area covered by NEXRAD. Probability of detection, critical success index, and mean lead time are all positively correlated with increasing percentage of WFO area covered by radar with a coefficient of determination of around 0.1. False alarm rate is negatively correlated with increasing percent of WFO area covered by radar with a coefficient of determination (R^2) of around 0.1 also.

VI. Other Observational Sources Available

On the day before enactment of the Weather Act,[6] there were many observational systems operating across the Nation that are used for high-impact weather, some in areas of limited NEXRAD coverage below 6,000 ft. AGL. These included mesonets, rain gauges, river gauges, lightning data, FAA TDWR radars, research X-band radars (e.g., Collaborative Adaptive Sensing of the Atmosphere (CASA) in the Dallas-Fort Worth, TX, area), and the NOAA geostationary weather satellites. For this report, satellite data from polar-orbiting weather satellites are not considered because while extremely useful for longer range forecasting, the data are not frequent enough to aid in the warning decision process for tornadoes or flash flooding that require new data on the order of minutes. NWS uses other observational systems to obtain additional information on severe weather hazards, precipitation estimates, or even help adjust precipitation rates in sub-standard or non-existent radar coverage areas. The different platforms are described below.

<u>Other Observational Data</u>

[6] *See* Weather Act at 131 Stat. 114(a)(2)(ii) requiring the Secretary to "identify additional sources of observations for high impact weather that were available and operational for such areas on the day before the date of the enactment of this Act. . .".

Satellite Observations: The most important source of data for severe convective warnings other than radar comes from space. Instruments on geostationary orbiting satellites provide a way to assess environmental and storm characteristics that can improve severe weather and heavy rainfall detection. Precipitation estimation from orbiting satellites can provide rainfall information in areas of complex terrain that cannot be sampled by the NEXRAD network. The high-resolution data from Geostationary Operational Environmental Satellite – R (GOES-R) Series currently in orbit (GOES East and West), although just recently made operational, are identifying features that have never been seen before. NOAA believes the improved temporal and spatial resolution with the GOES-R Series will improve the short-fuse warning decision process. When combined with other sources of information, data from geostationary orbit increases forecaster confidence in the severity of a storm. There is promising, ongoing research related to the utility of GOES-R Series data for rainfall estimation, particularly important in the data-sparse regions of the western United States. Overall, NOAA anticipates that continued research using the GOES-R Series data should continue to have a significantly positive impact on NWS tornado and flash flood warnings.

Total Lightning Data: Lightning mapping arrays can detect intra-cloud and cloud-to-ground lightning within convective storms. There are lightning mapping arrays across the country, and a new Geostationary Lightning Mapper is employed on the GOES East and West satellites. Ground-based networks also provide NOAA with total lightning data, purchased from vendors. Studies have shown that increased lightning activity, more commonly known as "lightning jumps," can be a precursor to severe weather events (e.g., tornadoes) by up to tens of minutes. NOAA is encouraged about the potential impact this information may have on NWS severe weather warnings, including for tornadoes, but research still needs to be done to validate the role of lightning jumps as precursors to severe weather and tornadoes. From a precipitation perspective, studies have shown some correlation between lightning frequency and precipitation rates, which can be beneficial for adjusting precipitation rates of convective storms occurring in areas of inadequate radar coverage.

Multi-Radar Multi-Sensor System: Each of the observational platforms have strengths and challenges regarding severe weather and heavy rain/flash flood detection. The development effort to incorporate multiple platforms/systems together to improve the short-term prediction and detection of hazardous weather became operational in the NWS in the last few years. NOAA's National Severe Storms Laboratory (NSSL) developed a Multi-Radar Multi-Sensor system (MRMS) (Zhang et al., 2016). The current operational version of MRMS includes the following in its product generation for severe weather and quantitative precipitation estimates (QPEs): NEXRAD and Canadian radar networks; numerical weather models; precipitation gauges; background climatologies; and lightning mapping arrays. All data from MRMS are provided at a 1 km × 1 km spatial resolution with most radar-based products generated every 5 minutes. Longer duration QPEs and those that are gauge-derived or gauge-adjusted are available every hour. NOAA is exploring options to include non-federal radar assets into MRMS. This could allow NOAA to use data from other radar assets in the private and academic sectors to improve the overall product. Finally, MRMS data help drive an NSSL-developed system called "Flooded Location and Simulated Hydrographs" (FLASH), which shows promise for helping detect flash floods at the small hydrologic basin scale. FLASH is being tested and evaluated by NWS forecasters.

Precipitation Gauges: Various precipitation gauge networks provide accumulated liquid precipitation values on different temporal scales. Gauges are commonly referred to as "ground truth"; however, they do not have the adequate coverage densities to capture the spatial gradients and variabilities of precipitation. Precipitation observations from gauges are provided by such entities as the NWS, United States Geological Survey (USGS), local departments of transportation, city/county networks, etc. States, such as Oklahoma, Kentucky, and New York, even have their own statewide mesonet systems, which generally places at least one observing system in each county. National collections of gauge networks include the Hydrometeorological Automated Data System (HADS) and Meteorological Assimilation Data Ingest System (MADIS) allow for a compiled, more direct access to multiple data sources. These "ground truth" observations are also used to calibrate the precipitation estimates from the NEXRADs and for validation of research satellites such as the NASA-Global Precipitation Mission.

USGS Stream Gauges: For flash flood events, point observations from USGS stream gauges can provide information on local waterways in 15-minute increments. Significant jumps in discharge and stage height alerts forecasters to rising waters relating to flash flooding.

Unmanned Aerial Weather Systems: Remotely controlled aircraft can carry weather instrumentation, including radars and dropsondes, which can be flown over weather features to improve data collection and forecasting. More details on NOAA unmanned aircraft systems can be found at http://uas.noaa.gov/. Currently, this is entirely in the research phase and non-operational. Other organizations are also experimenting with weather drones.

Non-NOAA Radars

Terminal Doppler Weather Radars: TDWRs owned and operated by FAA, are strategically placed near airports and provide radar observations at a greater spatio-temporal resolution than the NEXRAD network. TDWR data are processed similarly to the NEXRAD radars and are viewable by NWS personnel in WFOs. The low-elevation angles of the TDWR's radar beam combined with a more frequent temporal resolution and higher spatial resolution provide supplemental data that are valuable to the detection of short-fused severe weather hazards, especially tornadic circulations. However, current limitations with TDWR data make it challenging to obtain accurate precipitation information operationally. Data from TDWRs is supplemental to NEXRAD radar coverage at or near airports, surveilling below the radar beam of the NEXRAD and providing wind and precipitation data to forecasters.

CASA Radars: The Collaborative Adaptive Sensing of the Atmosphere (CASA) project uses small-scale Doppler radars for observing the lower part of the atmosphere where weather occurs. The CASA project (http://www.casa.umass.edu/) started with the National Science Foundation (NSF), and was subsequently supported with limited NOAA funding, around 2004. NSF funding ended in 2013. After operating in Oklahoma, the current CASA experiment in the Dallas-Fort Worth Metro area began in 2012 with the installation of the first radar. A total of seven networked radars were installed by 2015 at a cost of approximately $3.5 million with annual operating costs of the network around $600,000. These radars have a shorter range (around 25 miles) and are much more susceptible to attenuation, or degradation of the beam, than the NEXRAD or the TDWR. The advantage of this system is that the beam is never very far off the ground; the disadvantage is that you need many radars in close proximity to cover an area. The CASA experiment has provided NWS forecasters in Fort Worth rapid updates of high-resolution data (both spatial and temporal) during severe weather events in the metropolitan area. This supplemental radar has been modestly beneficial to the WFO's warning decision making and their impact-based decision support services. The high-resolution CASA radar data has, however, expedited NWS post-event storm damage surveys by providing additional information regarding tornado location and track. Additional benefits of the radar network, such as the urban flash flood modeling and warning project, may still be realized, but are currently unknown due to infrequent hazardous weather events and a delayed integration of data into the NWS display system. CASA receives partial funding and support from NWS via the National Mesonet Program.

Other non-NOAA Radars: There are some non-NOAA radars deployed across the country that are accessible by NOAA offices. For instance, some universities have development radars that may be of use to NWS. One example is the University of Louisiana-Monroe that has a radar built to similar specifications as the NEXRAD radar fleet that is located between Shreveport, Louisiana, and Jackson, Mississippi, where the lowest available data from the NEXRAD network can exceed 6,500 ft. AGL. Another example is the University of Missouri radar between Kansas City, Missouri, and St. Louis, Missouri, that can provide additional coverage over northern Missouri. Environment Canada also has a radar network providing additional coverage across the northern border of the United States. Local forecast offices have access to these university and Canadian radars. There are a large number of TV weather radars having widely different operating characteristics; these detailed data are not directly available to NOAA at this time. DoD radars were not considered in this report because they do not provide weather detection capabilities that meet the mission of the NWS.

The study examined integrating data from non-Federal and non-academically supported radars. This scenario has considerable cost and technical challenges, and is not seen as a viable direction, given these radars are primarily in regions that are covered by the existing NEXRAD and/or TDWR networks. The discussion of feasibility of integrating and upgrading the NEXRAD network with non-NOAA weather radars should be separated into two categories: 1) integrating data from weather radars that are owned, operated, and maintained by third parties; and 2) integrating and upgrading the NEXRAD network with non-NOAA weather radars to be owned, operated, and maintained by NOAA.

In both categories, there are starting and recurring costs associated with every connection. For example, communication lines and bandwidth would need to be upgraded and maintained to support effective delivery and display of the data. Integrating radars that are operated and maintained by third parties would encompass NOAA receiving the data from state or university owned radars, local community radar networks (similar to the CASA experiment), or television radars. While the maintenance and sustainment of these radars would not be the responsibility of

NOAA, there would be non-trivial recurring and one-time costs associated with every connection to third party radars. Integrating the data into NOAA's Advanced Weather Interactive Processing System would require external weather radar data to be processed through a supplemental radar product generator, which would require maintenance and sustainment of that software and hardware infrastructure. Ingesting data from non-NEXRAD weather radars requires security updates and monitoring. Requirements for any third-party weather radars must be established prior to ingesting the data, including data availability, quality, and reliability standards consistent with the operational needs of the NWS. These requirements include accepting data from weather radars only in NEXRAD Level II format, data quality of sufficient level (as determined by NOAA), reflectivity and velocity data available and dual polarization as high priority. These are neither inexpensive nor technically simple solutions, especially in light of the fact that NEXRAD data are the gold standard across the world for operational weather radar data.

VII. Options to Improve Hazardous Weather Detection and Forecasting Coverage

Even ideal or perfect radar coverage does not, and will not, mitigate against all key weather events, as found in the results of this study and from basic scientific considerations, such as limitations in predictability and complex human responses in the high stress environment of warning decision making. There are still gaps in the understanding of meteorological phenomena as well as intrinsic and practical limits to numerical prediction. Improvements in warning and forecasting, especially for high-impact and hazardous weather conditions, remain a top priority for NOAA. This section will highlight the cutting-edge research that could one day transform the NWS warning decision process.

There are many projects underway within NOAA, including the Hurricane Forecast and Improvement Project (HFIP), tornado detection and prediction (undergoing development), Unmanned Aircraft Systems Program (UAS) and other specific event-focused projects. There are also efforts underway in NOAA to change the warning paradigm from "Warn-on-Detect," where binary warning decisions are made with 0-10s minutes of lead time, to "Warn-on-Forecast", where probabilistic information on hazardous weather informs decisions 1-2 hours ahead of the event. Research and development on higher resolution and improved numerical models is expected to improve NWS prediction and warning capabilities for these high-impact events. Social science is also a critical component of "Warn on Forecast," as it is essential that the information is communicated in a way for people to understand and take appropriate action. Additional and frequent observations, particularly in the lower few thousand feet of the atmosphere, may provide the data needed for the next increase in predictive capability. These are options that can be enhanced or accelerated to improve key weather event performance. Candidate observational systems can be tested for impact in various numerical models. A significant option under research is the potential use of phased array weather radar, technology developed initially for military applications, shown by NOAA to be capable of sampling weather more rapidly. This rapid scan capability is essential for storm-scale modeling efforts and increasing warning lead time for hazardous weather events. Below is a summary of some options to improve hazardous weather detection and coverage, but much more research and development is being done.

1. New Technology to Expand Coverage with the Existing NEXRAD Network: Following the completion of the study (and thus not addressed therein), the NWS has recently begun using innovative technologies to improve the radar coverage within the existing NEXRAD network. Over the last two years, the NWS tested and has now begun to implement lower angle operations to extend the range of the radar. Once it was determined that NEXRAD could physically and electronically operate at an angle lower than the standard base angle of 0.5 degrees (above horizontal), NWS lowered the angle at ten sites, with an additional eight sites planned in 2020. This low-cost enhancement has or will expand the effective low-level coverage at these 18 sites. [These sites and improved coverages are reflected with stars in Figure 1]
2. Advanced Radars: NOAA has recognized the potential benefit of new radar technology and has been conducting necessary research and development in Phased Array Radar (PAR) that includes high temporal data with a goal of not sacrificing the high-quality Doppler and dual-polarimetric data currently available with the NEXRAD network. High-resolution temporal data, such as those available from a PAR-type radar network, are needed to improve the high-resolution modeling necessary for attaining the prediction of tornadoes one hour in advance, as stated in the goal of Section 103 of the Weather Act. Initial results from these forecast models look promising. Increased high-resolution radar coverage, strategically located and as planned for the next generation of radars, could also improve the prediction of flash floods, as these data feed forecast models that may provide improved precipitation forecasts that can be provided to run-off and flooding models.
3. Advanced Models: NOAA, and the weather enterprise continue to work on high-resolution convective-allowing numerical model with 1km or higher horizontal resolution and associated continual improvements. This may be an under-appreciated option. This technology is rapidly evolving toward achieving a more complete representation of weather systems by ingesting high-resolution observations, especially in the lower atmosphere. These high-resolution modeling systems are also incorporating ensemble-based solutions, which provide a measure of forecast certainty, which is an important part of Impact-based Decision Support Services from NWS.
4. Advanced Paradigms: Incremental improvements, on the order of a few minutes, are possible using the present warn-on-detection concept the NWS has employed since weather radars became operational. NOAA is approaching that limit in lead time and accuracy because there are limits to warning based on detecting precursor signatures and favorable atmospheric conditions. The next dramatic increase in severe storm warning performance is likely to come from a change to Warn-On-Forecast paradigm. Combining the efforts of advanced radar and high-resolution models, the Warn-On-Forecast program could one day result in accurate, 1-2 hour lead time probabilistic tornado warnings. Numerical weather prediction has made giant leaps forward in terms of predicting winter storms and hurricanes over the past 15-20 years. The next frontier for numerical prediction is storm-scale modeling, which requires high-resolution observations (like PAR and mesonets) in both horizontal and vertical dimensions. Warn-On-Forecast aims to accurately predict the location and severity of severe storms hours in advance, and

despite this being a long-term goal, any improvements in the prediction and evolution of severe weather along the way will be beneficial to NWS forecasters.

5. Advanced Satellites: The new suite of NOAA polar and geostationary satellites is providing greater space-based multi-band (visible, infrared, microwave) imagery with 1-km horizontal resolution or better, including winds. The new GOES East and West satellites are providing unprecedented spectral coverage and spatial resolution. GOES East and West imagery is a main backup for radar estimation of precipitation, and certainly a valuable operational source for NWS warnings. We are just learning about the information that can be derived operationally from the new GOES-R Series data.
6. Complementary sensors: Greater coverage of precipitation sensors and hydrographs measuring water level in basins not currently covered. This amounts to greater coverage by surface-based sensor networks. No information is available at this time on the key weather event performance of these systems in areas of limited radar coverage.
7. Emerging Technologies: Adoption of both unmanned and manned aerial systems to sample particular areas and weather features in an operationally targeted fashion. This is an active area of research.

VIII. Cost and Timeline for Hazardous Weather Detection and Forecasting Coverage

There are significant costs associated with many of the above options that must be balanced with sustaining the existing operations infrastructure including NEXRAD. Some of the work described in this report is work already being done within NOAA. As the detailed analysis shows, increasing radar coverage in and of itself is not the best way to improve hazardous weather detection and forecasts. It takes an integrated effort for all components and sources of data that will improve overall services to the Nation. Much ongoing work at NOAA is intended to improve forecast and warnings for the Nation, and is being accomplished through NOAA's continued research and development (programs such as MRMS, HFIP (http://www.hfip.org/), Warn-On-Forecast, and tornado warning improvement project), improvements in atmospheric modeling, water modeling, observations (satellites and *in situ*), new radar design (or PAR), and computing capacity. The largest cost item would be a new and upgraded radar system. These ongoing programs will address improving detection, and more importantly prediction of the hazardous weather and water events.

IX. Summary

NOAA conducted a comprehensive national-scale study assessing the impact of limitations in radar coverage for warning for hazardous weather events (tornadoes and flash floods), identifying other sources of observations for high impact events, and addressing the feasibility of integrating radar data other than NEXRAD data into operations.

This analysis supports that the original rationale for the geographical distribution of the national NEXRAD network coverage remains valid, as warning performance holds fairly steady under the complete envelope of radar coverage shown in Figure 1. While there are gaps evident on any map depicting radar coverage of beams at 6,000 or 10,000 ft. AGL, the data above those levels still provide important information for forecasters to use as they issue their forecasts and warnings for hazardous weather events. Radars are required and very necessary to issue lifesaving warnings, however, variations in radar coverage do not lead to significant variations in warning services provided by the NWS, especially when considering events that kill or injure people. Even ideal or perfect radar coverage does not, and will not, mitigate against all key weather events, as found in the results of this study and from basic scientific considerations such as limitations in predictability, detection, resolution, verification methods, and in complex human responses.

The study finds no significant statistical difference between warned and unwarned tornadoes at the national scale inside the coverage area of radar beams at 6,000 ft. AGL and outside radar coverage. Preliminary national analyses of flash flood warnings also show similar performance among events inside or outside radar coverage. The number of tornado or flash flood events, in contrast, has a strong correlation with the ratio of warned events overall. The number of events across an NWS warning area of responsibility seems to be a more important determinant of warning skill than radar coverage. The exception is a set of western states, where data show a slight decrease in warned flash flood event ratio under radar coverage as compared to states with similar numbers of events. It is important to recognize that the sample size in these states is relatively small, so any conclusions must be done carefully. Tornado and flash flood warning and detection rely on many other sources of information, including satellites, mesonets, forecast model output, and spotter reports, which aid forecasters, especially where there is minimal radar coverage, which could explain the parity.

NOAA research and development is ongoing to improve the prediction and detection of hazardous weather. These efforts include numerical model development, analysis of the new GOES-R Series satellite data, advanced radar technology through the phased array, other observation systems such as UAS, and scientific research and development within NOAA, and with partners in the academic and private weather community. These advances and new data will help meet the direction of Section 103 of the Weather Act: Tornado Warning Improvement and Extension Program, "…to reduce the loss of life and economic losses from tornadoes through the development and extension of accurate, effective, and timely tornado forecasts, predictions, and warnings, including the prediction of tornadoes beyond 1 hour in advance."

NOAA will continue to strive to improve weather prediction at all scales. There are still significant gaps in the understanding and detection capability of meteorological phenomena, as well as intrinsic and practical limits to numerical prediction. These are active areas of research the value of which should be not overlooked in any rigorous effort to significantly raise weather warning performance.