STUDY

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

2019

Preamble

On April 18, 2017, the Weather Research and Forecast Innovation Act (Public Law 115-25) became law. The Act directs the Secretary of Commerce to conduct a study to assess the impact of limited radar coverage for warning for hazardous weather events, identify other sources of observations for high impact events, and the feasibility of integrating radar data other than Next Generation Radar (NEXRAD) data into operations.

This Study is in response to Section 414 of the Act that states:

(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.

This study is also in response to similar House Report language accompanying the NOAA FY 2017 Appropriation:

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.

There was much discussion within NOAA on what constitutes "hazardous weather," other than tornadoes as stated in the 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, coastal flooding, etc. While radar will help in overall situational awareness during these types of events, the radar data would likely not increase accuracy or lead time for those longer fuse phenomena, particularly when compared with the short-fused events.

The Act 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 language in the Act, and similar language in the FY 2017 Appropriations Report, implies that reduced radar coverage, or a "gap," is the ***sole*** factor for missing warnings for short fused events. This is not the case. There are numerous factors that play a role in any missed warning, and radar coverage is just one of many in an extremely complex decision process. No one argues the importance of radars, but spotter reports, satellites (especially the detail coming from the new geostationary satellites), the Multi Radar-Multi Sensor (MRMS) products, Probsevere, the High Resolution Rapid Refresh (HRRR) forecast model, etc., are also important. Indeed, low-level radar coverage is likely the most important source in the warning decision process, but the radar does not issue tornado or flash flood warnings, humans do. Humans understand that when a storm is farther from the radar, signatures will not be as clear cut or present at all, and they rely on other sources of information to make the decision. The NOAA study found that there are minor differences between the number of "misses" within the 6,000-foot radar coverage range as "outside" coverage. (The 6,000 ft above ground coverage demarcation comes from the FY 2017 House Appropriations Report Language.) In some cases, being far from the radar with the uncertainty and ambiguity involved leads to a lower threshold to issue a tornado warning (the finding of a higher false alarm ratio overall beyond 150 km in range by Brotzge et al [2011] supports this interpretation). This is one reason, we believe, that may explain why there was very little disparity in performance, in a bulk sense, inside and outside 6000 ft AGL radar coverage. A critical point to understand is that given the complexity of the integrated warning process, it is not possible to identify a single or primary root cause of missed warnings without investigating in depth every single missed event in detail, something far beyond the scope of this study.

The study defines limited NEXRAD coverage as that occurring beyond the range given by the bottom-of-the-beam at 6000 ft above ground level (AGL). This range can vary from one radar to the other and even within the azimuths of a given radar antenna beam pattern depending on obstructions and clutter. This level was selected based on congressional direction to address concerns that tornadoes far from the radar and below radar beam are less warned. For the purpose of the study, degraded forecast and insufficient warnings are both defined equally in terms of unwarned events. Hazardous weather consists of tornado and flash flood events. Substantial injuries and significant property damage are defined as those above the national average per event for each. The study is divided into tornado and flash flood performance and other appendices addressing technical issues, including the feasibility of adding new radars, the role of weather radar data in weather models, and others. For each category, further differentiation is made by separately tallying all events (warned or not) inside and outside the 6000 ft AGL envelope of radar coverage (as defined above, including obstructions to the beam). It should be noted that NEXRAD is not merely a radar, but a system that also generates real-time guidance to forecasters through identifications of certain features that may lead to a severe event, such as a tornado or downburst. These guidance algorithms are continually improved as more research is applied to them over time.

The study is broken into Appendices, each addressing a particular component identified by Congress in Section 414 of the Act.

Summary:

Tornado events from the National Weather Service (NWS) verification database are examined for the period 2006-2017 against radar coverage, the latter binned in terms of events inside and outside the range implied by the 6000 ft above ground level (AGL) bottom-of-the-beam at each of the NEXRAD radars. In addition, radar coverage is separately quantified by the percent surface areal coverage of the said 6 kft AGL range at each NWS Weather Forecast Office, a new metric that quantifies the relative density of coverage. Damage due to tornado events is quantified in terms of intensity. Fatalities and injuries are quantified along with NWS performance metrics in terms of radar coverage and geographical characteristics. There is relative parity between the percentage of tornado events warned or unwarned inside and outside of the selected range. Unwarned fatality, injury and significant damage events have weak to no statistical dependence on radar coverage in a linear model.

Linear regression have known limitations that include but are not limited to outlier sensitivity, and other factors [e.g., https://www.stat.berkeley.edu/~s133/Lr-a.html; http://www2.stat.duke.edu/courses/Fall00/sta103/lecture_notes/multregr.pdf; https://www.youtube.com/watch?v=EeDJ8tNFl-w]. However, its use in this study is not necessarily assuming that the response-driver relationship is intrinsically linear. Instead, the linear model is the means to explore first-order connections that may reveal strong associations or not. Not only are linear regressions generally useful to help characterize statistical relationships as a first step in exploratory data analysis [e.g., https://www.stat.berkeley.edu/~aldous/157/Papers/shmueli.pdf; https://link.springer.com/article/10.3758/s13428-010-0046-8; http://web.nchu.edu.tw/~numerical/course992/ra/Applied_Regression_Analysis_A_Research_Tool.pdf], but they have been used in other warning performance studies (see Appendix A) NWS flash flood warning performance is evaluated in terms of NEXRAD radar coverage by dividing coverage inside and outside of the range implied by the 6000 ft AGL bottom-of-the-beam. Over 33000 NWS-wide flash flood events are evaluated after the introduction of polygon warnings, which replaced county-wide warnings. Metrics such as events warned, unwarned, lethal and injury causing events as well as those inflicting property damage are analyzed. In addition, the role of radar coverage is considered by computing the percentage area for each NWS Weather Forecast Office below the 6000 ft beam range as affected by clutter and terrain obstruction.

In addition, a new metric is applied to a separate analysis accounting for relative surface area coverage variation per WFO county warning area as it exists in the NEXRAD. The area coverage metric quantifies the surface area covered by the NEXRAD beam under 6 kft AGL at each WFO (and state). At the WFO area scale, events and coverage are not completely independent. This study acknowledges and points to future work to obtain an understanding of the causes accounting for the observed warning performance and the relative importance of variations in radar coverage.

Study

Appendix A – Previous Studies on the Adequacy of NEXRAD Weather Radar Coverage and NWS Warning Performance

[**WRITERS:** STI/Daniel Meléndez, AFS/Kate Abshire (Flash Flood)]

The results of this technical study do not conflict with the findings of relevant peer reviewed articles the study authors we are aware of. Key studies are highlighted here, and where necessary, contrasting and comparisons are made with this study. Since no one study is necessarily the final word on any given subject, future studies are encouraged and necessary.

Increases in critical success index (CSI) are seen with the deployment of NEXRAD compared to the FAA Air Route Surveillance Radar (ARSR) skill values in DOT/FAA report by Dunbar and Mittelman (1993).

Maddox et al. (2002) [link] analyzed the spatial coverage afforded by the recently deployed NEXRAD network, updating earlier work by Westrick et al. (1999). They mapped spatial coverage at beam elevations of one, two and three km above ground level (AGL). In the mountainous western US, forecasters must rely more strongly on radar data from the higher elevation angles to infer weather threats. There are also dispersed gap areas in the central US at 3 km (~10,000 feet) AGL. They did not analyze performance, likely because of the relative newness of the NEXRAD network.

The NSF-funded Collaborative Adaptive Sensing of the Atmosphere (CASA) project, with NWS collaboration and under directed congressional appropriation to “determine the applicability to northeastern Wyoming and other regions the feasibility of integrating a number of small-scale Doppler radar technologies into future National Weather Service observing systems,” reported on the feasibility of small Doppler radar technology to complement NEXRAD coverage (CASA Radar Feasibility Study, 2009; report url). The study was partly propelled by two F2 tornado events in northeast Wyoming and a three-day coastal storm in Washington. That study concluded that severe storm warning lead times are “below-average” for those regions, which have limited radar coverage. They based their conclusions on performance data, interviews with forecasters and emergency managers, and socioeconomic vulnerabilities that consider population density and newness to the area, relative isolation, terrain, roads, and industry types.

For Wyoming, the report notes 161 tornado events between 1993 and 30 June 2008, with two fatalities, 17 injuries, and $6.1M in cumulative damage. This amounts to about 11 tornado events per year on average. Likewise, the report notes 176 flood events in the same period, with two fatalities, no injuries, and $5M in damages. This amounts to about 12 flood events per year on average. The report notes that Wyoming ranks 49th in the US in terms of flood damage per year, and these events have low intrinsic lead-time “warnability” due to the “flashiness” of stream and river basins in the region.

For western Washington, the report notes 22 tornado events between 1993 and 30 June 2008, with no fatalities or injuries and $1M in damages while listing 58 flood events with six fatalities, and $129.6M in damages (a separate “heavy precipitation” lists 36 injuries, no fatalities, and $184.4M in damages). In contrast to Wyoming, the bulk of the weather threat in western WA is much less related to tornadoes and more so regarding floods (and its economic impact) in spite of Wyoming having more flood events as such. Consequently, an important regional distinction is readily apparent in terms of the actual socioeconomic impact of floods, as determined by social and other non-meteorological factors.

Tornadic thunderstorms have characteristic tops reaching 9 km AGL on average, and the variation in echo height aloft is often used to assess tornadic potential [https://weather.msfc.nasa.gov/sport/journal/pdfs/2004_MWR_McCaul_etal.pdf; https://www.weather.gov/media/lmk/soo/Supercell_Structure.pdf; https://ams.confex.com/ams/91Annual/webprogram/Manuscript/Paper180516/AMSPaperRevised2.pdf]]. Most precipitation storms (excluding lake-effect snow) have even higher tops over 12 km on average. Thus, NEXRAD can still detect these weather features even when the lowest beam elevation is 3 km or higher. These studies are cited to point precursor signatures available to NWS forecasters and not confined to the lower levels in the atmosphere or exclusive to radar data.

Simmons and Sutter (2009) do not explicitly consider radar coverage. No finding of this study is in conflict with their work. The ranges of FAR and POD state values in their Table 3 are in general agreement with those in Figs. C.5 and C.7.

Brotzge and Erickson (2010). The results of this technical study do not conflict with the findings of peer reviewed articles that were reviewed. If anything, there is agreement between their comparable findings (e.g., Fig.9 of Brotzge and Erickson, 2010, and Fig. B.3 of this study). That study gives a mean percentage unwarned tornado events of 26%, which is 3% lower than the unwarned inside ratio of 29%. Likewise, that study's mean unwarned event ratio between 150-200 km range is about 32%, compared to 31% in the outside binning in Fig.B.3. Therefore, there is compatibility between the two studies regarding unwarned tornado ratios with distance, even though the dataset in this study is more recent and larger. This gives confidence in the binning method in this study introduced as one capturing the cumulative warning behavior inside the threshold range roughly similar to the range method, as well as suggesting no major changes to cumulative performance between the datasets in both studies. The binning in this study can be regarded as coarser than any scheme based on actual range, since all events are counted within a given range, as opposed to a partitioning by increasing range. Also, the cutoff range resulting from the 6 kft AGL bottom-of-the-beam height is about 165 km, so events beyond that are not counted in the linear fits in terms of relative area coverage (Appendix C).

The findings in Brotzge et al (2011) also complement this study: their Fig.8b has a strikingly similar relationship to that in C.7 with FAR (1-FAR in their figure to be exact) showing nearly no variation with range until beyond 150 km (very close to the 165 km cutoff implied by the 6 kft beam height). The slope in C.7 here, while not statistically significant, is higher for lower coverage. Of course, the consistency up to about 150-165 km with the subsequently different warning profile in Brotzge et al indicates sensitivity to radar coverage beyond such range. Future work should look at the sensitivity of this and other threshold-based metrics and the causative role of radar coverage. Low NEXRAD coverage (be area or range or volume) in both studies does not uniformly seem to carry low performance, as there is large scatter in the data as seen in Figs. C.5, C.7--C.9 and others.

Brotzge and Donner, BAMS (2013) provide a comprehensive review that helps contextualize this study regarding the integrated warning process, and the meteorology of tornado detection, warning decision, dissemination and response. The study findings of low warning rates for weak EF0-EF1 tornadoes in Fig. B.6 is consistent with Brotzge and Erickson (2009) as noted in the subject work. They point out an increase of missed warnings with increasing range, consistent with the linear decrease with relative area coverage in Fig. C.6. They point that increases in lead time are a direct result of more tornadoes being warned, consistent with Fig. C.6. They also indicate that when zero-lead time events are excluded from the lead time calculation, a steady lead time of about 18.5 min is obtained (p1720, op. cit.). This is consistent with a fit to the non-zero lead times obtained using the relative area coverage metric for 2006-2017 (not shown, see Fig.C.5). Brotzge and Donner (2013) refer to a root cause analysis by Quoetone et al. (2009), listing radar and non-radar coverage issues as the top six reasons for warning misses. Wilson et al. (2017) and Bowden and Heinselman (2016) found positive impacts with higher temporal resolution (1-min) phased array radar data in the warning process. The latter study considered severe hail and wind events by 12 forecasters over a 6-week period. Their study does not conflict with this one as the former is concerned with faster sampling.

Anderson-Frey et al., (2016) study a 13-yr tornado event and warning climatology with respect to meteorological environments. The paper geospatially analyzes events and performance based on WFO and other spatial filtering. The range of FAR values (Fig.3) is consistent with those for the WFO values in Fig.C.7. This figure also shows generally fewer tornado events in the western US, consistent with the study Figs. C.3--C.4 showing more events in areas with lower coverage. There are no obvious discrepancies with this study and, perhaps more importantly, they do not explicitly consider radar coverage.

Martinaitis (2017) evaluates tornado warnings associated with tropical cyclones over Florida. This study points out the temporal contraction of low-level mesocyclones diameters down to 1.85 km, as well as these being rarely observed above 1.5^{o} elevation angle with inbound and outbound velocities separated by at least 5.5 km. The tornadoes in that study are EF1 or less, which comprise the majority of events but inflict relatively less damage than more intense ones. As range increases, the percent of both tornadic and non-tornadic events exhibiting supercell reflectivity signatures decreases with increasing range from the radar. No result in this study conflicts with these findings. Brooks and Correia, WAF (Dec. 2018), while this paper does not explicitly consider any radar distance or coverage variation, it finds that mean lead time for non-zero tornado lead time events is relatively constant from 1986 to 2011, which overlaps the period in this study (2006-2016). Also, they find a slow decrease in the false alarm ratio (FAR) after 2012, along with lead time and POD. Changes in the variation of the analyzed POD and FAR with radar coverage (Figs.C.5-C.7) match those in their corresponding annual variations (Figs. 1-2, and 6). This is interpreted to say that the sampling obtained in the 2006-2016 dataset of the study was large enough to match the variations in the paper. In qualitative terms, there seems to be consistency between the insensitivity of FAR vs coverage in Fig.C.7 and that in Brooks and Correia regarding the variation of FAR with POD (p1508). The removal of zero-lead times events in the Brooks and Correia statistical analysis is different from the NWS practice of including all warnings in the warned category, which is done in this study to maintain consistency with NWS verification policy. For comparison, a fit to the mean lead times as a function of %WFO-area coverage excluding zero lead time values gives a statistically insignificant slope (p=0.14), consistent with the nearly flat annual fluctuation in lead time of Brooks and Correia (2018). The annual variations of performance metrics in Brooks and Correia (op. cit.) are for all events per year, whereas those in this study are for events per WFO per relative WFO-area under linear-fits; the two studies refer to different domains. There is no theoretical reason to expect the two domains should covary. The fact that the annual variations and ranges in these metrics are identical does not necessarily imply that the two must behave similarly (or not) with regard to radar coverage. One variation is in the time domain while the other in the spatial domain. Also, Brooks and Correia do not analyze radar coverage as it relates to performance metrics, so it is unclear how the results reveal any coverage sensitivity. Also, the POD vs. EF-scale in Fig.11 for 2012-2016 and Fig.B.6 here appear to be in excellent agreement.

Appendix B – NWS Tornado Warning Performance Inside and Outside Areas of Limited Weather Radar Coverage

[Author: NWS/STIO/Daniel Meléndez]

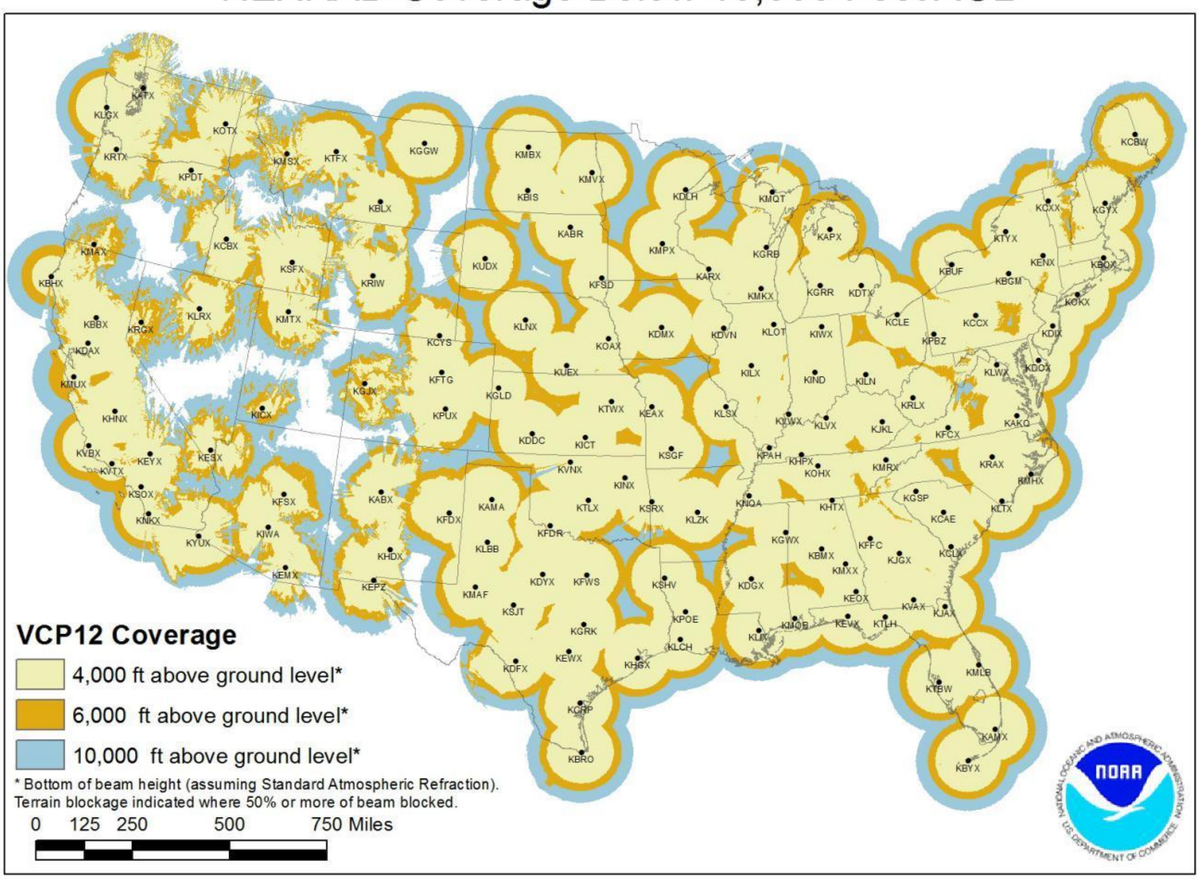
Public Law 115-25, Section 414 (Radar Coverage), contains the following questions regarding hazardous weather covered by radar: **Element A.(i). Identify areas in the US where limited or no NEXRAD coverage has resulted in: (i) instances in which no or insufficient warnings were given for hazardous weather events, including tornadoes; Element A.(ii). Identify areas in the US where limited or no NEXRAD coverage has resulted in: (ii) degraded forecasts for hazardous weather events that resulted in fatalities, significant injuries, or substantial property damage;** *and,* **Element B.(ii). For the areas in Element A: (ii) identify additional sources of observations for high impact weather that were available and operational for such areas on the day before date of enactment of Act, including dense networks of X-band radars, TDWRs, ASRs of FAA, and cooperative network observers**.

This appendix addresses these elements by evaluating warning performance of tornado events as a function of NWS-wide NEXRAD coverage by segregating events that fall inside the limited radar coverage and those outside. The analysis aggregates all such 12710 events between 2006 and 2016. The 2006-2016 is used since polygon warnings (as opposed to entire counties being warned) were started in 2007 along with the new Enhanced Fujita (EF) scale. By 2008 the old Fujita scale was not used. Polygon warnings are more precise by virtue of being geographically specific, but are also more challenging to count as falling inside or outside a given radar range given their irregular shape.

An event is counted as being "inside" the radar envelope (e.g., 6 kft AGL, bottom-of-the-beam) if any part of its initial location falls within that radar radius envelope. Summing all of the events nationally falling inside that envelope is the totality of events "inside." Likewise for events "outside." Since obstructions (natural or not) can block the radar beams partially or completely, the radar radii (and thus the counting) includes such effects, known commonly as "clutter." Figure B.1 shows the horizontal coverage for NEXRAD and for NEXRAD with TDWR combined at 6 kft. TDWR coverage largely overlaps that of NEXRAD. TDWR radars are located at or close to large metropolitan airports. Figure B.2 shows that as range from the radar increases, any feature is sampled more coarsely and the radar misses more of the lower elevations.

GIS analysis was completed by comparing the location of the NWS tornado database by constructing a line between the start and end point of the tornado. These lines were then analyzed against the radar coverage to create 2 categories, within or outside radar coverage. The first step was to select the event lines which fell within the radar coverage polygons. A new file was exported which only included these event lines completely within the radar coverage polygons. A switch selection was then performed to select the event lines that were outside radar coverage, this file was exported to create an outside coverage file. When investigating this file, it was discovered the outside coverage also included the events which crossed the radar boundary. In order to see how many events this affected and additional analysis was performed to indicate how many of the "outside" events actually crossed the radar coverage boundary. The event files were then subdivided by their warned (yes or no) attribute to create the six final files and counts - warned within radar, warned outside of radar, warned crossed radar, unwarned, within radar, unwarned outside of radar and unwarned crossed radar. The attributes of each of these files were also analyzed to include counts of injuries, deaths, and significant property damage.

NEXRAD Coverage Below 10,000 Feet AGL



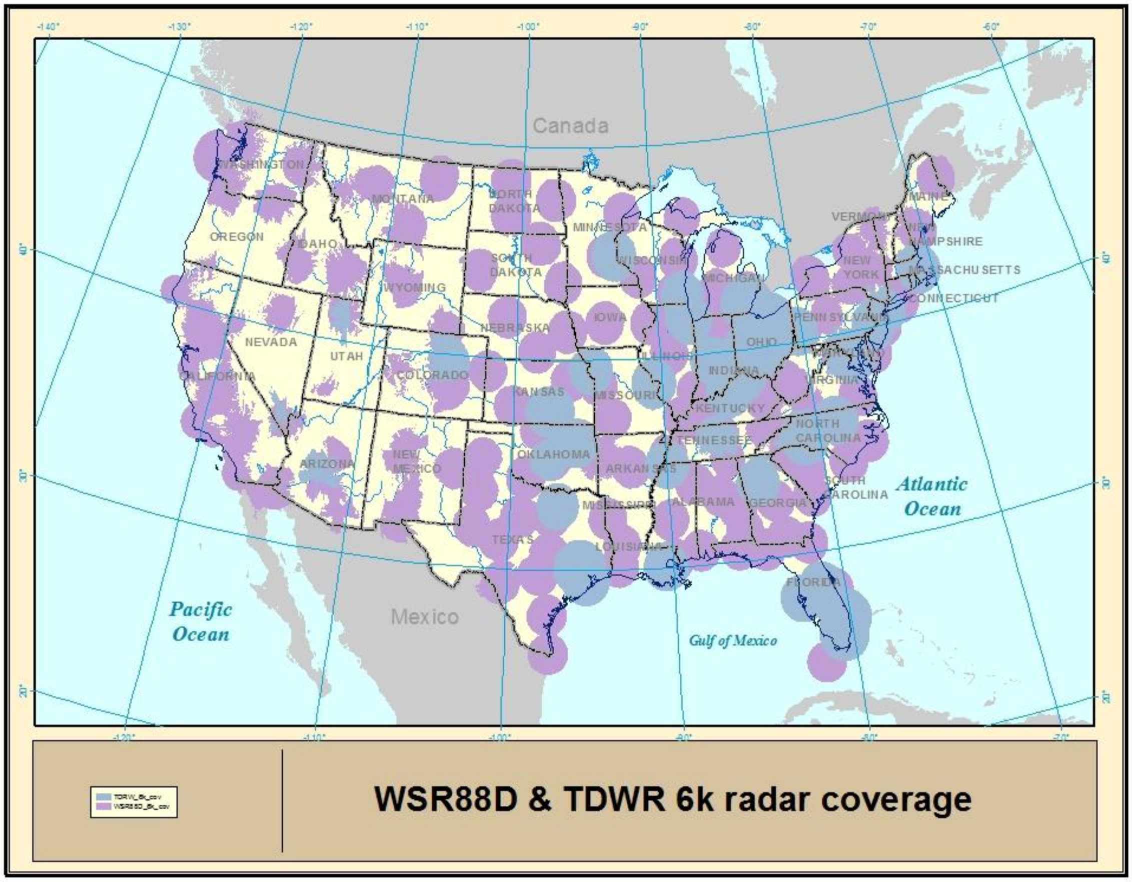


Figure B.1 - **(top panel)** NEXRAD WSR-88D coverage below 10 kft AGL for beams extending to 4 kft (yellow), 6 kft (brown), and 10 kft (blue) AGL at the bottom of the nearly one-degree beam at each NEXRAD site in CONUS. The jaggedness of the coverage is largely the result of obstructions such as mountains and buildings. Most of the radar coverage gaps are in the intermountain western US. NEXRAD coverage maps are based on the bottom-of-the-beam height. **(bottom panel)** Composite NEXRAD and FAA Terminal Doppler Weather Radar (TDWR) coverage at 6 kft bottom-of-the-beam. Light blue is TDWR, purple is NEXRAD.

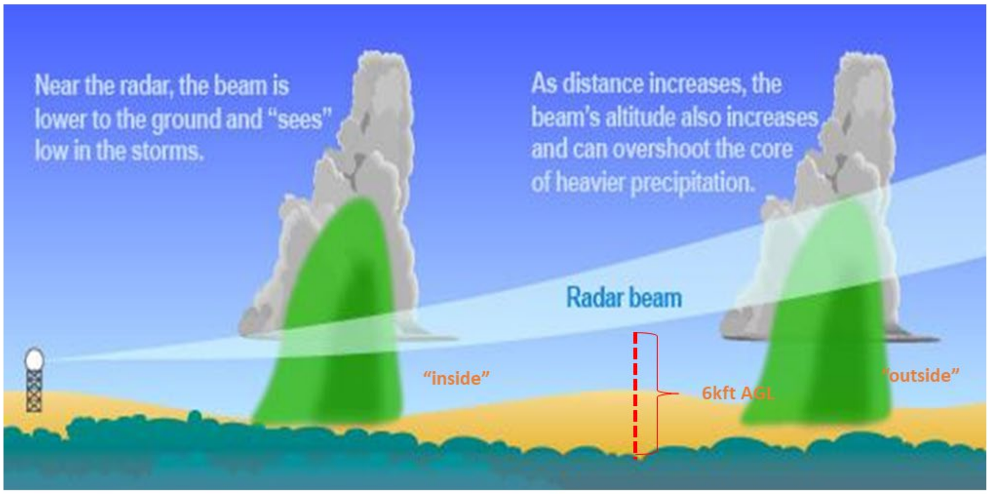


Figure B.2 - Geometry of the event "binning" method and of the increasing radar beam size with greater distance. The farther out a given feature is located relative to the radar antenna, the more coarsely it is sampled by the radar beam - if at all - and the higher the minimum altitude observable. The binning categorizes all events under the bottom-of-the-beam altitude of 6000 ft AGL as "inside", and all events beyond that range (ca. 165 km or 89 nm) as "outside".

For the purposes of this analysis, "limited coverage" is prescribed as the range obtained for a bottom-of-the-beam elevation of 6 kft AGL at each particular NEXRAD site. Since the lowest radar elevation in the NEXRAD network is (with the exception of one radar in Washington state authorized to scan below the lowest network-wide elevation angle of 0.5°). For the lowest elevation angle of 0.5°, the range is about 89 nm. A convenient calculator can be found online at http://training.weather.gov/wdtd/tools/misc/beamwidth/beamwidth.html.

When all such events are tallied against the closest 6 kft radar envelope over all radar sites, a comparison of events warned and unwarned as a function of being "inside" or "outside", shows remarkable relative parity between the two in Figure B.3. With 12710 tornado events (warned and not), about the same percentage was warned inside or outside the above specified range and, consequently, about the same percentage was unwarned (crossed events are generally a few percent of the totals inside). Without obstructions, the range implied by the bottom-of-the-beam height of 6 kft is about 165 km or about 72% of the peak range of NEXRAD (230 km) while about 79% of all events occur within the 6 kft beam height (which implies at most the 165 km range since beam obstructions can reduce this range at particular sites). Thus, in a bulk radar network sense, there is no noteworthy difference between the two regions of coverage (i.e., inside/outside). There is hardly any difference in the ratios obtained with and without adding TDWR coverage in the analysis so for all practical purposes they are the same (±1%).

In terms of events considered "partially-warned," these account for about 10% of all events in the extant period. Partially-warned means some portion of the event (tornado track in this case) was not warned within the polygon assigned to the event in real-time operations. In this analysis, the partially-warned were included as warned, as is NWS practice. This can be seen to bias the partitioning toward the warned category by at most 10%. Subsequent analysis shows little or no sensitivity in the number and the fraction of partially-warned tornado events as a function of percent area covered per WFO based on the coefficients of determination (R^2) of 0.002 and 0.007, respectively. Since there is no statistically significant dependence on radar area covered under the 6 kft range (not shown), there is likely to be equality in the ratios partially-warned "inside vs. outside" this range.

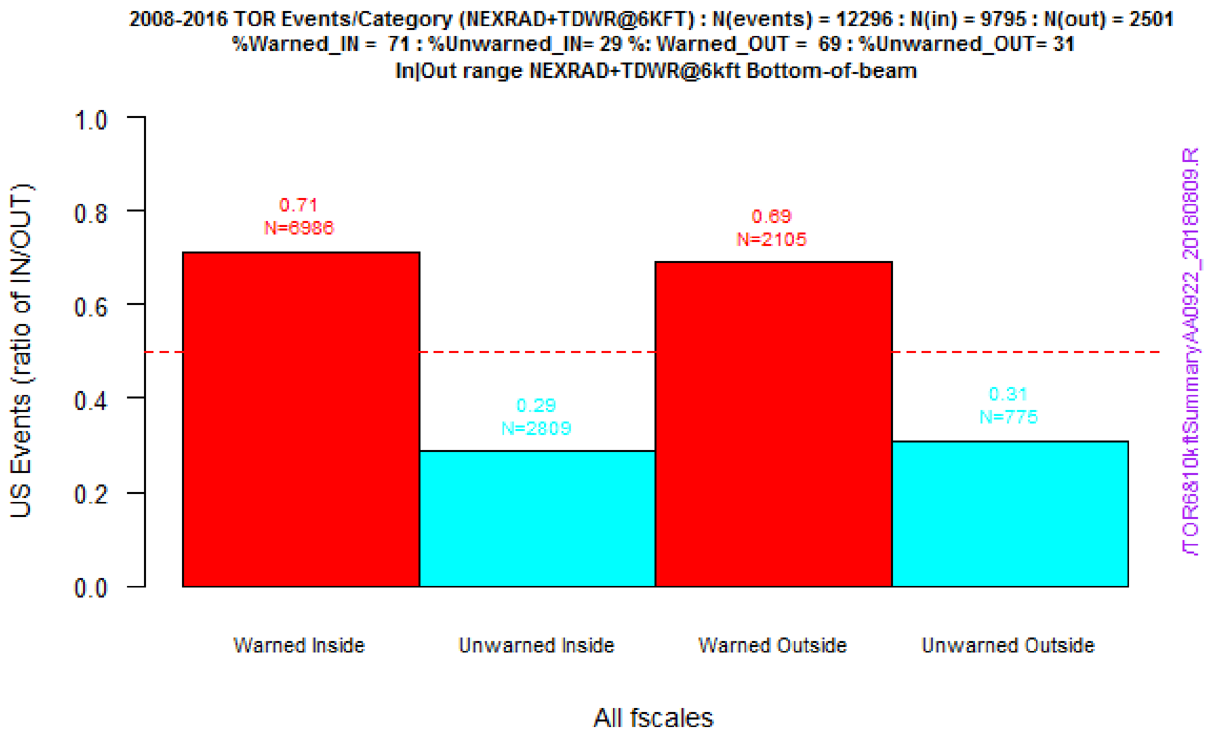


Figure B.3 - Ratios of tornado (TOR) events warned (red bars) and unwarned (cyan) inside (left) the 6 kft AGL radar envelope for the entire NEXRAD and TDWR network coverage and outside that range between 2008 and 2016, in a re-analysis excluding events categorized by the earlier Fujita scale. The numbers above the color bars are the ratios for each bar and the corresponding events.

Of the total of 12710 in 2006-2016 events, 94% occur inside the NEXRAD 6 kft radii. Only 665 events occur outside the coverage range here defined. This is a consequence of the fact that most of the coverage gaps in the NEXRAD network happen to have low numbers of tornadic events as such, as shown in Figure B.4. Comparing Figures B.1 and B.4 shows that <u>most of the events occur away from regions of large coverage gaps except for relatively small gaps in Texas and Nebraska.</u> Of course, it can be argued that most of the events are away from the gap areas because of their reduced detectability therein. However, there are low event counts inside high radar coverage areas so this is an unlikely situation in addition to reflecting accurately the known tornado climatology in addition to the fact that radar is not the only means to identify tornado occurrences. There is a potential bias in the event fractions due to the way events that cross the radar boundary are counted in the georeferencing of the tornado events. In this analysis, tornado tracks crossing the radar coverage threshold are counted as "inside." This adds only 279 warned and 67 unwarned events to corresponding inside event counts of 6671 and 2652, respectively (4% and 2.5%). In terms of events outside, such accounting represents 12% of events warned outside and 6% of events unwarned outside. Subsequent discussion will be developed without further assumptions about this issue.

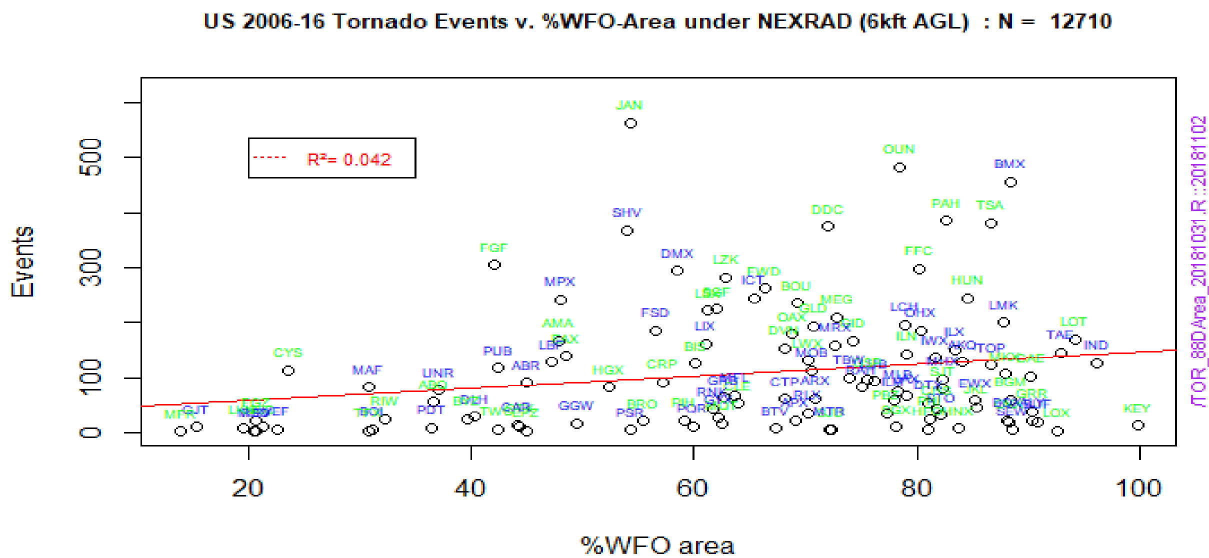
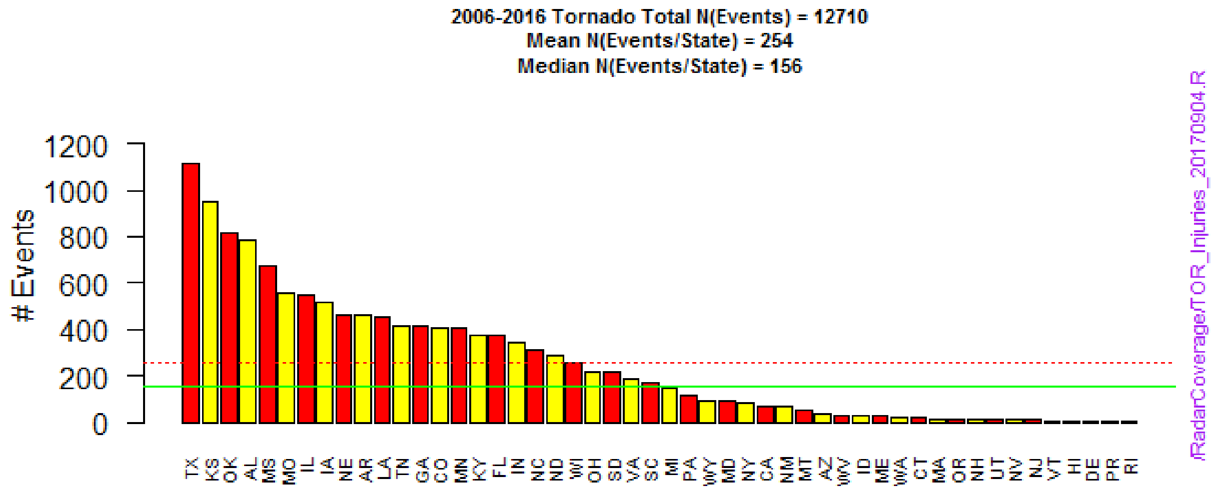


Figure B.4 - (top) Distribution of tornado events per US jurisdiction. The ten year sample has 12710 events in 2006-2016. Abbreviations follow the postal convention (e.g., PR = Puerto Rico, etc.). Most events occur in the central and southeastern portions of the US. The red dotted line is the mean number of events per state (254); the green solid line is the median (156) for the entire ten year period. In the ten year period, Colorado (CO) and North Dakota (ND) have event counts above the mean-per-state, each having around 400 and 300 events in total, respectively. **(bottom)** Tornado events as a function of radar coverage. The slope of the linear fit (blue line) is statistically significant at better than the 95% level. The mean area coverage is 65% and the median 69%. <u>Most areas with the greatest area radar coverage gaps (low coverage) are also areas of relatively low tornado event rates.</u>



As shown in Fig. B.11, warning skill increases with the total number of events.

In terms of intensity, the majority of tornadic events in the dataset are EF0s to EF2s, known as weak tornadoes in terms of its effects as defined by the Fujita or F-scale (and as revised by the Enhanced Fujita or EF-scale: http://www.spc.noaa.gov/efscale/), seen in Figure B.5. Weak tornadoes are known to be smaller in diameter and have shorter path lengths on average [https://www.researchgate.net/publication/275057155_New_Methods_in_Tornado_Climatology?enrichId=rgreq-88a1b0b3ca6ac6a94ee60a1e80f86b3e-XXX&enrichSource=Y292ZXJQYWdlOzI3NTA1NzE1NTtBUzoyNDA5MjYyMzY4Njg2MDhAMTQzNDQ1MjY5OTM4MA%3D%3D&el=1_x_2&_esc=publicationCov]. Consequently, weak tornadoes should be less detectable by radar. The latter inference is borne out in the percentage of warned tornado events as a function of intensity (EF scale), shown in Figure B.6, where intense tornado events are warned at higher rates. Since most tornadoes are weak, the mean fraction of warned events is effectively determined by the fraction of EF0s and EF1s. This reflects the tornado radar detection challenge arising from the spatial (beam width and elevation) and temporal NEXRAD coverage and scanning characteristics that has been studied previously at NOAA and elsewhere.

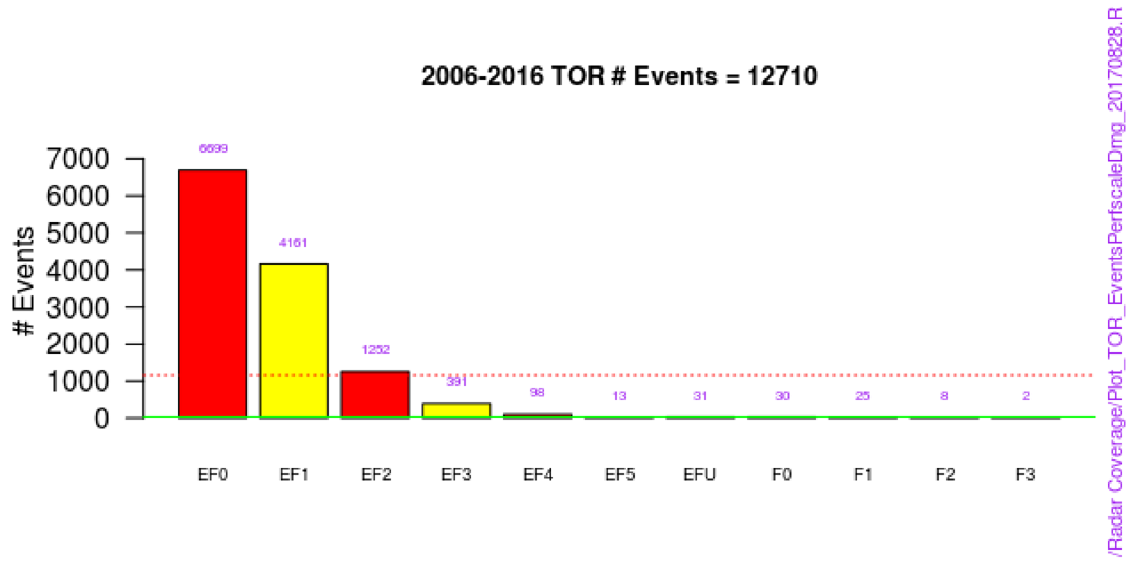


Figure B.5 - Distribution of tornadic events in the 2006-2016 period as a function of intensity. The vast majority of tornado events are in the relatively weak (EF0-EF2, and F0-F2 in the other scale).

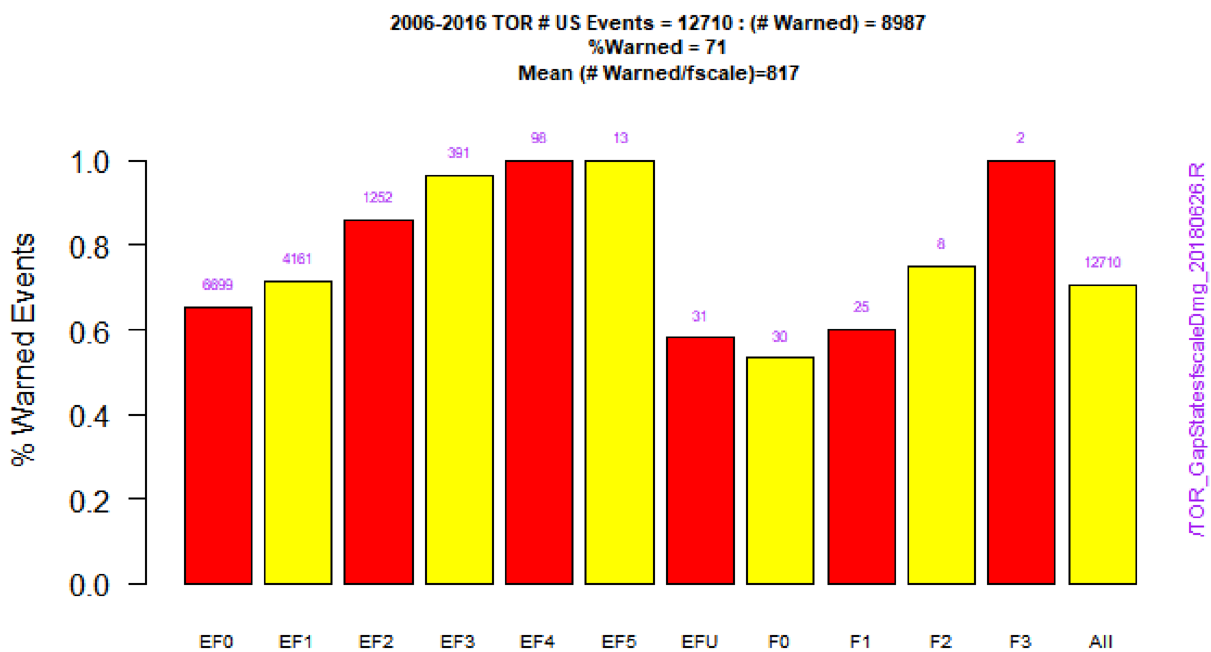


Figure B.6 - Distribution of 12710 warned tornado events for 2006-2016 as a function of intensity (EF/F-scales). A greater fraction of intense EF3+ tornadoes are warned compared to the weaker ones. (EF0-EF2, and F0-F2 in the older Fujita scale). EFU means events undefined intensity-wise. The mean warned fraction is 78% (shown in the rightmost bar "All"); the median is 73%.

Another view of this can be seen in the events warned and unwarned inside vs. outside the radar coverage range threshold defined earlier at each EF/F-scale intensity level, shown in Figures B.7--B.9. With the exception of the undefined (EFUs) and the earlier Fujita F0-F3 levels, there is relative parity in warned and unwarned ratios in the shown intensity levels. In other words, when looking at a national aggregate, <u>events in each level of the tornado EF-scale are as nearly as well warned as those same intensities outside of the radar coverage</u> (6 kft AGL range). There is only a few percent difference as in the case of EF1 events. Notice that the number of tornado events falls off very rapidly with increasing intensity (Fig B.5). So, when analyzing performance regarding intense tornadoes (EF3 and higher), the sample size is rather meager compared to the weaker ones. One disparity in the data is for the undefined-intensity events (EFU in Fig B.8 bottom left) or events with unassigned intensity. Though this is a very small number of events (31), these events were warned even more skillfully outside of the coverage of the radar at 6 kft AGL. However, this in and of itself is inconsequential as EFUs can accept a mix a wide variety of intensities. The few events in the old Fujita scale F0 through F2 are better warned inside the radar coverage (Figs. B.8-9), however, as with EFUs, the sample sizes are rather small. The previous F-scale is less meteorologically precise than the current one.

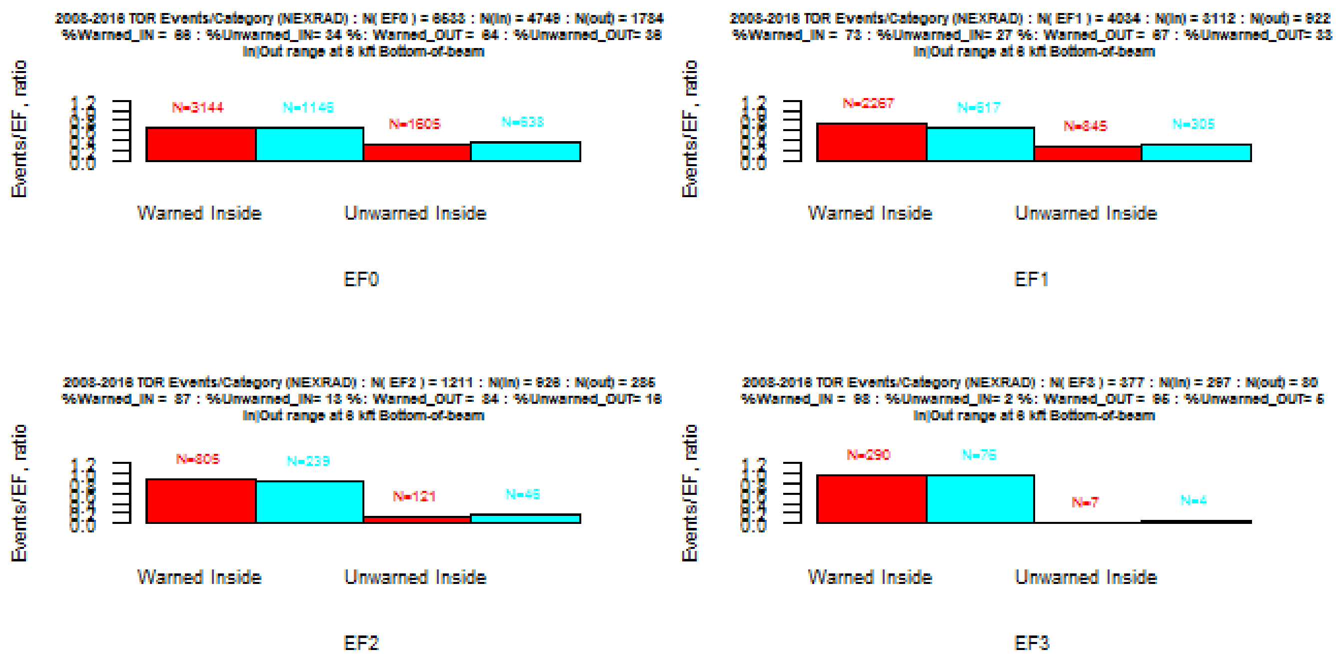


Figure B.7 - Fractions of warned events (first two bars of each plot) and unwarned (second pair of bars in each) inside (red) and outside (cyan) the radar coverage range threshold at 6 kft AGL (see text) for EF0 (top left), EF1 (top right), EF2 (bottom left) and EF3 (bottom right). The labels for the color bars are: Warned Inside (red), Warned Outside (cyan to the right), Unwarned Inside (next red), and Unwarned Outside (last cyan bar on the right). Numbers atop bars indicate events per category for each EF plot.

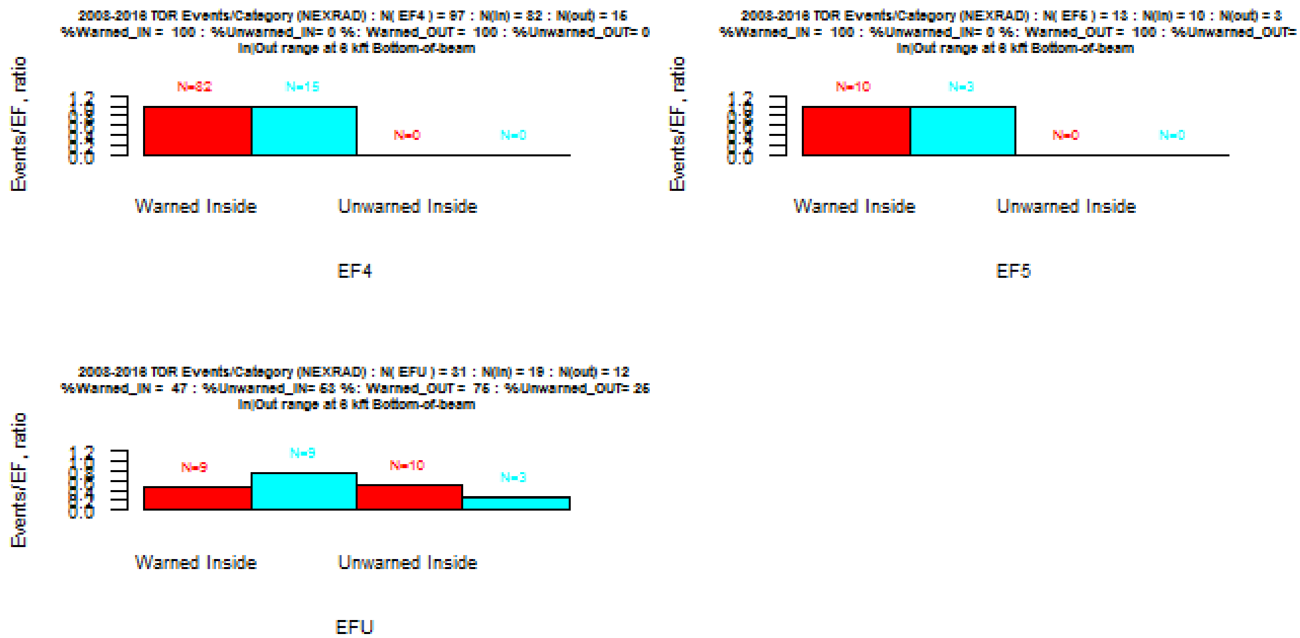


Figure B.8 - As Fig. B.7 but for EF4 (top left), EF5 (top right) and undefined events (EFU). Numbers atop color bars denote event counts in 2008-2016.

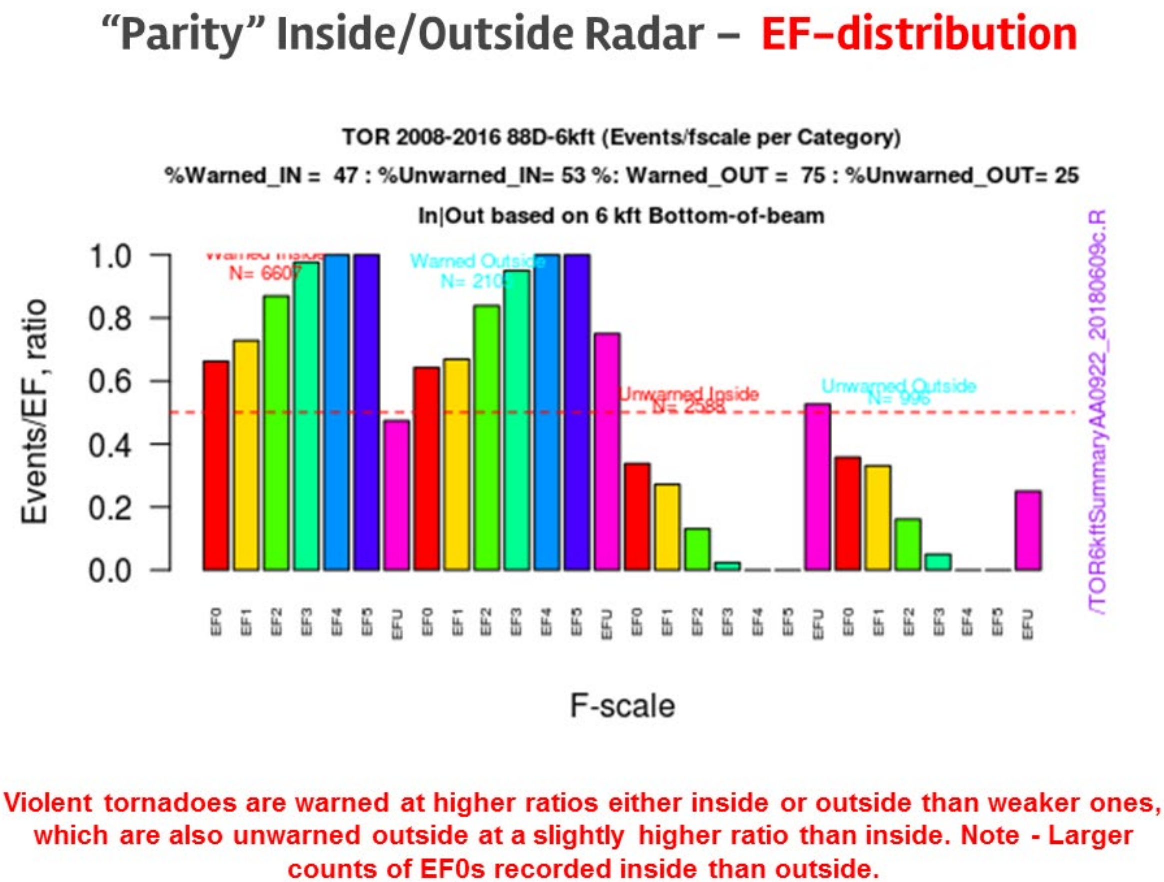


Figure B.9 - Event fractions separated by EF scale, including undefined (EFU), clustered by warning and unwarned inside and outside in 2008-16. The first cluster of seven color bars are ratios of EF events warned inside (N=6607) the 6 kft AGL radii of NEXRAD. The second cluster of seven color bars correspond to ratios of events warned outside (N=2105). The third set is the event ratio unwarned outside (N=2588), and the fourth set to unwarned outside (N=996). The normalization is with respect to total number of events in each EF category. More events are warned inside than outside while more are unwarned outside than inside in relative terms. However, violent tornadoes (EF3 and higher) and warned about equally inside and outside and very few are missed (unwarned).

When a handful of arbitrarily selected states is analyzed, an interesting suggestion arises, as seen in Figure B.10, where the percentage of warned events is highest for states with relatively high event totals whereas the percentage is smallest for states with the lowest event rates. This suggests that the number of events is strongly connected to the warning performance or skill. Further exploration shows a very strong relationship between the overall number of events and the percent of events warned, seen in Figure B.11. Most remarkably, the skill increases very rapidly as the total number of tornadic events (warned and unwarned) increases. This suggests that warning skill is strongly tied to the frequency of events in a given area and that a relatively uniform skill is achieved beyond a particular event rate. In other words, skill is strongly related to experience as quantified through event numbers. In this case, a skill level of more than 50%, for instance, is seen for event rates larger than 200. This relationship appears also with number of events per WFO (Fig. C.6) where about 150 events/WFO marks the transition to a steady skill level in warned ratio, and accounting for near half of the scatter in the data. Since the skill at warning intense tornadoes is rather high (Fig. B.6), the relatively lower skill is happening with the least intense tornadoes, which are more difficult to detect and issue warnings. Areas in the US with low event frequencies have consequently lower relative skill on average. An apparent exception is Colorado, which has above average events and not as high skill level as other states in the same region while enjoying average NEXRAD coverage (about 60%). Nonetheless, the skill level there is within the average. There are various likely reasons for the skill increase with more events that include forecaster experience, supplementary alert systems and spotters, and higher frequency of large-scale weather systems that impact broad regions such as in outbreaks and "super-outbreaks" [for recent discussion on the latter see https://www.nature.com/articles/ncomms10668].

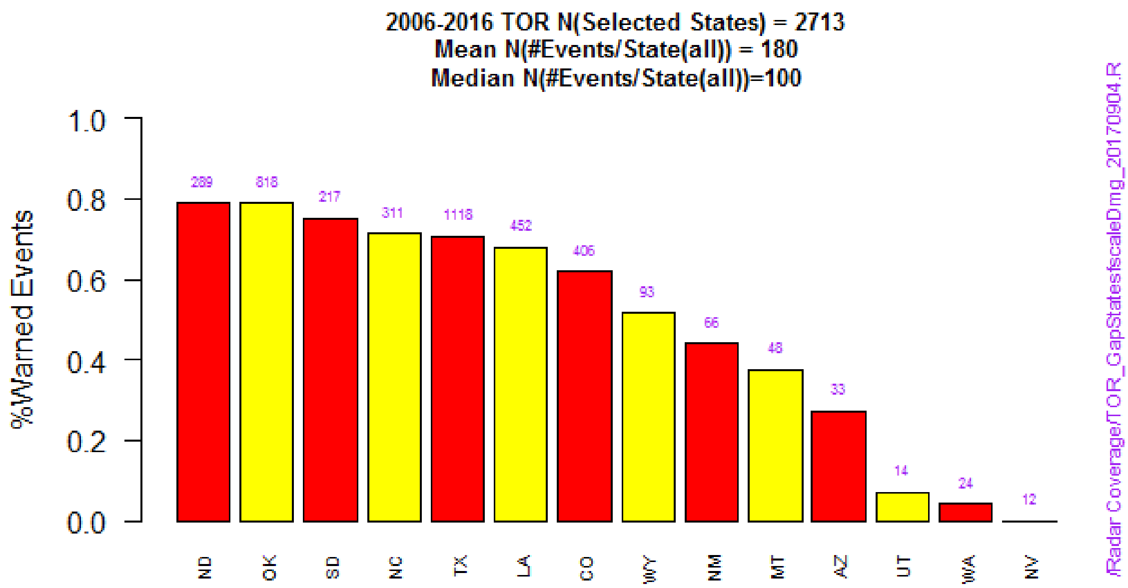


Figure B.10 - Percent tornado warned events for an arbitrary sample of a handful of states between 2006 and 2016, representing a selection of 2713 events (out of a total of 12710). The mean number of events per state for all US is 180, the median 100. The number of cases for each of the states shown is at the top of the bars (in purple).

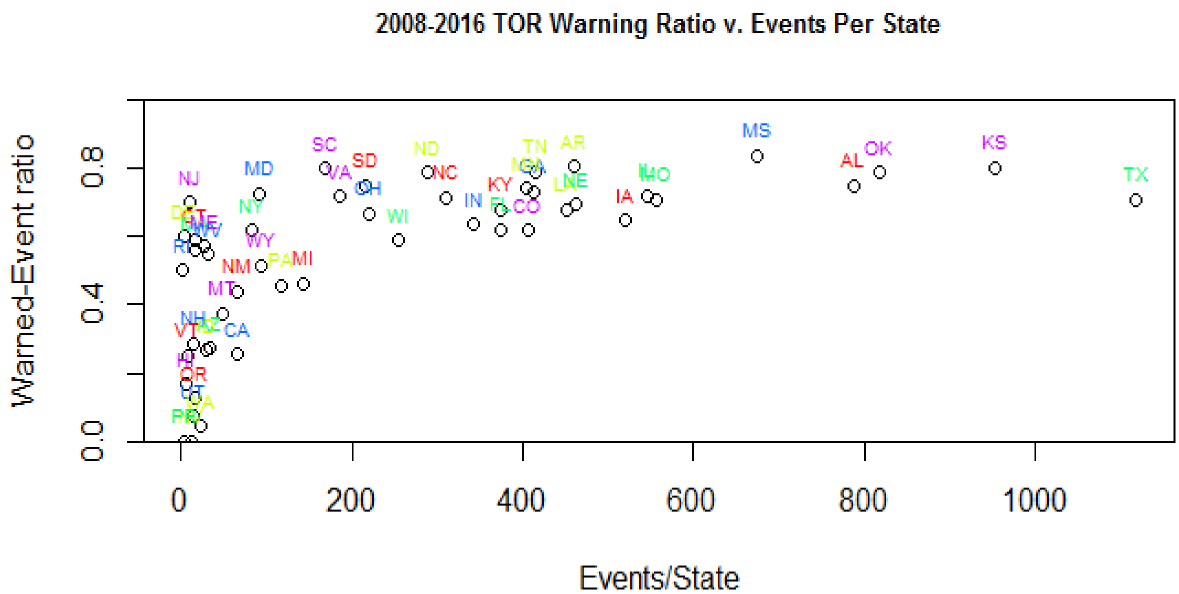


Figure B.11 - Percent tornado events warned (probability of detection) as a function of event rate (events per state) for 2008 to 2016. The percent of events warned increases rapidly as the event rate grows and stays uniformly high past 200 events/state.

Fatalities

The distribution of fatalities per tornado event in the US has considerable variability, as seen in Figure B.12. Only a few jurisdictions (states and territories) show fatality rates above the US-mean fatality rate (about 8 per 100 tornado events), mostly located in the central and eastern parts of the US. The vast majority of jurisdictions had zero fatalities per event. Looking only at the distribution of events with fatalities (that is, excluding the non-fatal events), shows 271 lethal events, as seen in Figure B.13. Again, only a handful of jurisdictions have fatal events above the national lethal-event average of 21 in the ten year sample. Jurisdictions with highest lethal event rates are mostly in the eastern; only two are in the western US. Interestingly, most fatalities are clustered in 2011, as seen in Figure B.14, accounting for a little over half (567) of the total fatalities of 1032 for the ten year period. This can be regarded as anomalous relative to the ten year sample. However, lacking a long enough record of super-outbreaks, the return frequency of super-outbreaks is not known definitively. A recent study points to increased frequency of tornadoes per outbreaks (and tornadic outbreaks though this is definition-sensitive) since 1954 (https://www.nature.com/articles/ncomms10668.) Media discussion of the 2011 outbreak can be found in http://www.ustornadoes.com/2012/04/25/april-25-26-27-28-2011-super-outbreak/. The remainder of the ten-year record has much lower fatalities, the next year being 2008 with 132, and the remainder having fewer than 100. This suggests tornado fatalities are relatively rare in the US, mostly tied to outbreaks. The top three jurisdictions in the distribution of lethal events add up to over 500 fatalities in the entire ten-year sample, as seen in Figure B.15, all of them in the southeast and one in the central US.

Although the reported tornadoes during the 2008 and 2011 seasons were nearly identical (1,692 in 2008, 1,699 in 2011), the Spring of 2011 will be remembered for a number of catastrophic events that place it in the same historical context as the tornado outbreaks in 1965 ("Palm Sunday) and 1974 (the "Super Outbreak"). Two events that set this year apart from outbreaks in previous years. The first, referred to as the "2011 Super Outbreak", was a widespread outbreak of tornadoes, with 11 EF4s and 4 EF5s, most occurring over northern and central Alabama on April 27th. Over 300 tornado-related fatalities and an estimated 2,000 people were injured from this outbreak with the most infamous of these tornadoes, a large EF4 that tore through the middle of Tuscaloosa, AL a few blocks away from the University of Alabama campus. One month later, a massive and slow-moving EF5 tornado churned through the middle of the city of Joplin, MO, resulting in over 150 fatalities and nearly 1,200 reported injured. Both of these intense tornadoes that tore populated areas were well-warned in advance from Tornado Warnings issued by the local NWS offices, but the loss of life elicited questions about whether an in-advance warning was enough of a service to the public to prompt them to take sheltering actions in these cases. Three years earlier, the 2008 tornado season saw a number of events with dozens of reported tornadoes in various locations across the country. The "Super Tuesday Outbreak" of Feb 5th was one of the most notable, not only for the number of confirmed tornadoes (87) but the rarity of having such a widespread tornado outbreak that early in the year, which resulted in nearly 60 fatalities and over 400 injuries. This event was a key example in forecast messaging to the public before an out-of-season event and one that occurred when numerous states were holding primaries and caucuses for the upcoming presidential election (later that year).

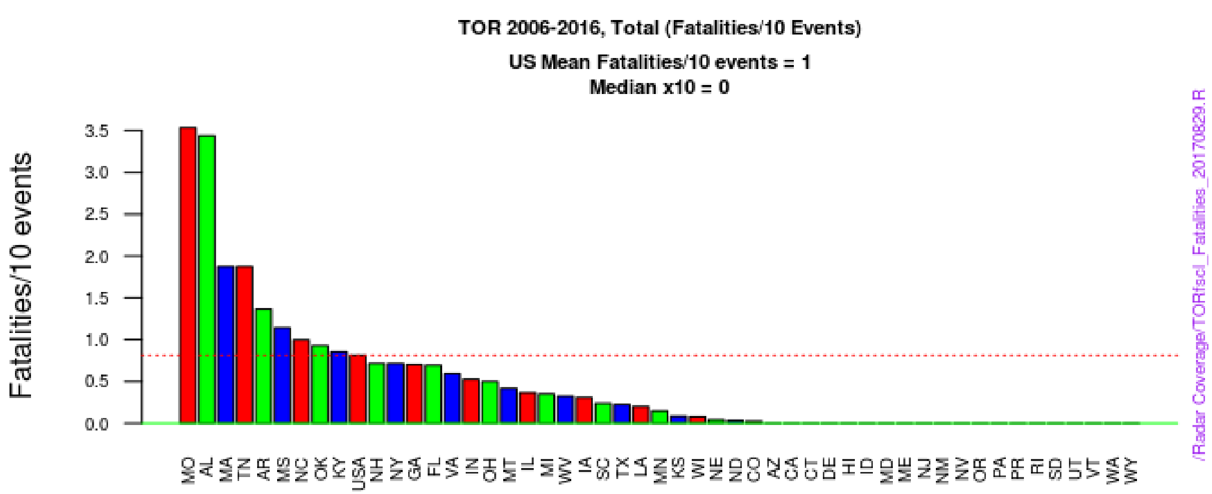


Figure B.12 - Number of fatalities per ten events for the US between 2006 and 2016 by state. The mean number of fatalities per 10 events is about one, the median is zero. Only a handful of jurisdictions have fatality rates above the national average.

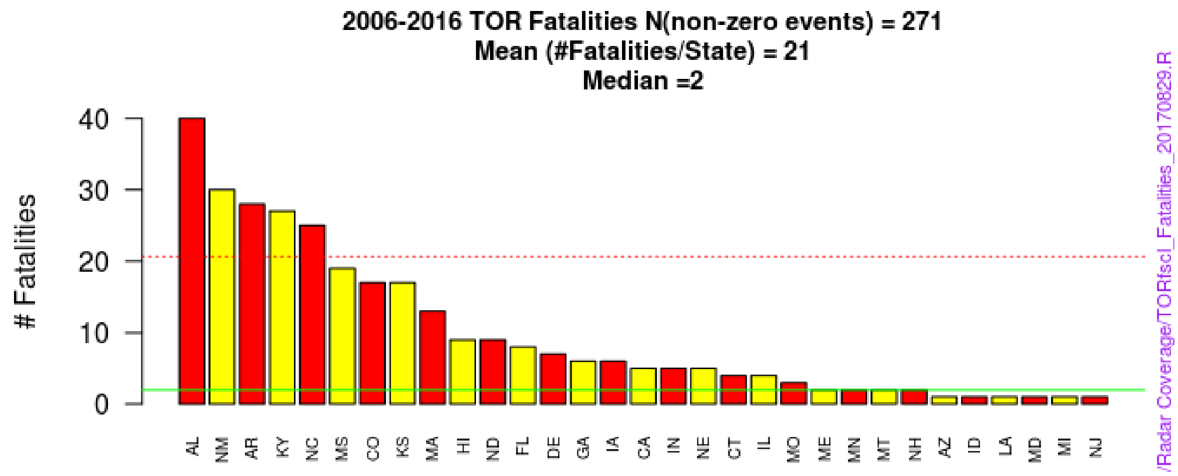


Figure B.13 - **(top)** Distribution of non-zero fatality events by state across the US. Nationally, there were 271 non-zero fatal events, resulting in 1032 deaths. The mean fatalities per state for the fatal events is 21, and the median is two. **(bottom)** Distribution of fatal events divided by the non-zero fatal events per state.

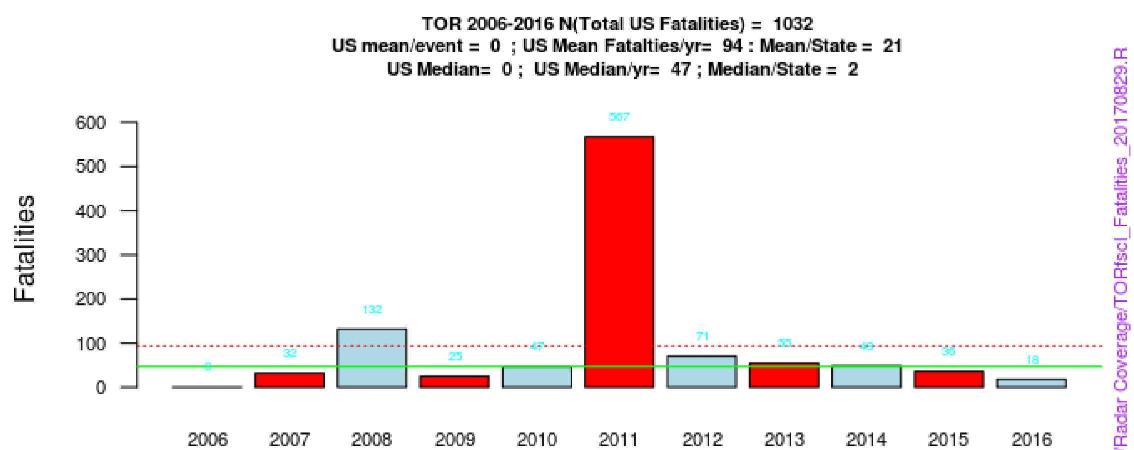


Figure B.14.a - Tornado fatalities as a function of year. Year 2011 had the most fatalities at 567 (shown above bars), the next was 2008 with 132 while the rest of the period had less than 100 fatalities per year.

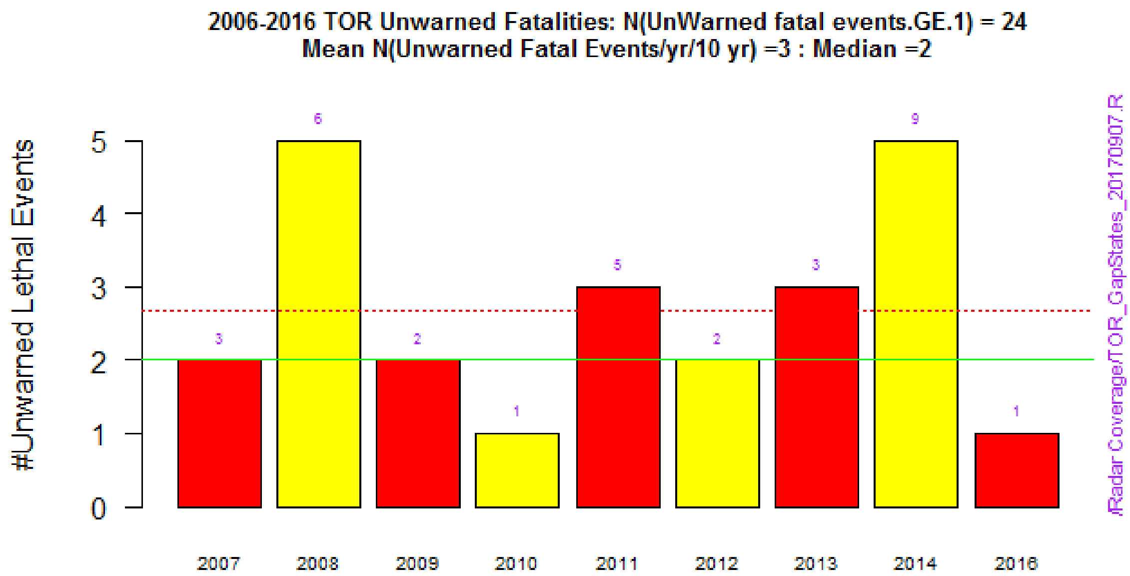


Figure B.14.b – Unwarned tornado lethal events as a function of year. Year 2014 had the most fatalities at nine (shown above bars); next was 2008 with six. These are also the years with most unwarned lethal events.

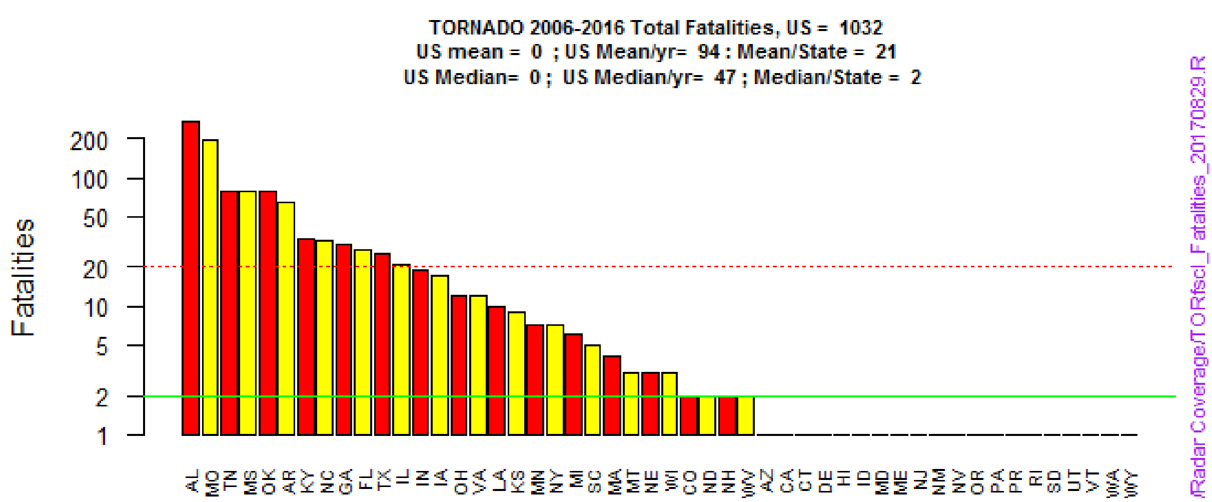


Figure B.15 - Total US tornado-related fatalities (direct and indirect) per state between 2006 and 2016. Note that the fatality scale has been compressed for clarity. The total number of fatalities in the US is 1032 in that ten year period. Red line is the US mean fatalities per state per 10 years, green is the median of two. States with zero-fatalities are to the right of WV (West Virginia), and shown for comparison.

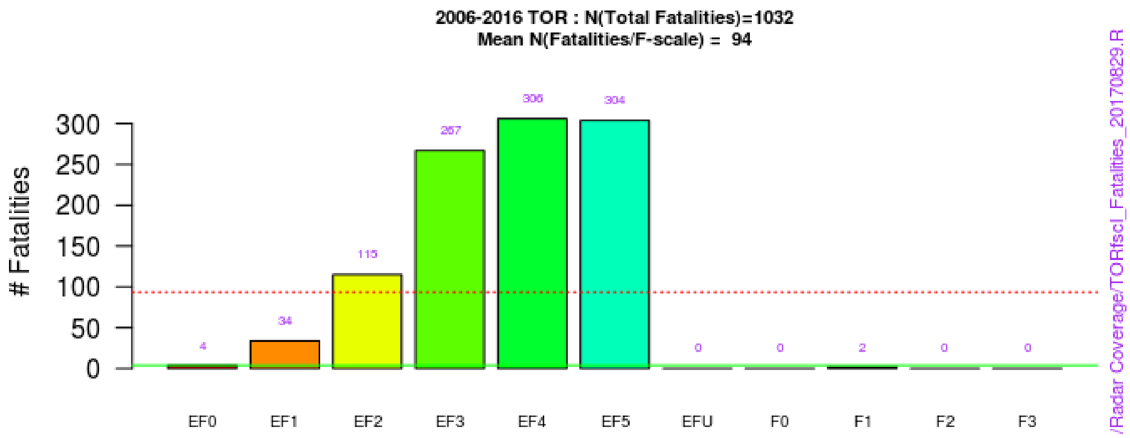


Figure B.16 - Total US tornado-related fatalities (direct and indirect) as a function of tornado intensity using the Enhanced Fujita (EF) and the Fujita (F) scale (discontinued in 2007) for all events between 2006 and 2016. The red line is the mean fatalities for all scales, the green is the median. The higher the scale number, the more intense the tornado. Most fatalities (out of 1032) are associated with more intense tornadoes in spite of their much lower frequencies (violent or intense tornadoes are EF3/F3 and higher). All categories to the right of EF5 recorded zero fatalities except for two F1-related deaths.

Comparison of Figures B.5 and B.16 shows that violent tornadoes (EF3/F3 and higher) cause the majority of fatalities in spite of their much lower frequencies. Out of the 1032 fatalities (both direct and indirect), EF3 and higher tornadoes account for 85% of the fatalities (including the earlier F-scale events). Since intense tornadoes are almost all warned (Fig. B.6), it appears that there is considerable skill at warning lethal tornado events in the past ten years. In other words, the lesser warned tornadoes incur much fewer fatalities (less than 15% of the total). Few states suffered from unwarned fatal events and related fatalities in the 2006-2016 record, as seen in Figure B.17. There were only 55 such unwarned fatalities, for an average of two fatal events per state per 10 years (rounded up). There is little spread in this value since most of the jurisdictions with unwarned lethal events experienced the fatalities in only two events give or take one. In terms of geographical distribution, most fatal unwarned events happened in the eastern and south-central parts of the US, away from regions with the most limited radar coverage. In fact, Michigan had the highest number of unwarned lethal events (Fig.B.17) while being at the US median number of tornado events. In terms of fatalities, the states do not differ by more than one or two events or fatalities for that matter. This strongly suggest that unwarned fatal events are extremely rare given that only 24 out of 12710 events had fatalities (or out of 3723 unwarned events overall), and unrelated to spatial variations in NEXRAD coverage.

Furthermore, there is no indication that limited radar coverage as being a major fatality factor since the strongest tornado events on record (EF3-5), have the highest number of fatalities. The largest numbers of unwarned fatal events are for the stronger EF2s in the extant intensity distribution (Fig. B.18). As mentioned previously, intense tornadoes have high warning rates (Fig. B.6). Radar coverage cannot be discounted altogether: EF0 events were missed more often than the EF2. However, EF0s and EF2s were missed in nearly equal proportions inside and outside of radar coverage relative to the total number of events inside, or outside the radar coverage nationally (Fig B.7). Given the very low number of unwarned fatal events involved, any inference about the role of radar coverage is statistically weak. Again, 24 events out of a grand total of 12710 events (or even 3723 unwarned events) is a very low fraction. Consistent with the earlier findings (Fig. B.16), stronger tornadoes are significantly more deadly. <u>As far as fatalities are concerned, limitations in radar coverage appear to be not as significant as frequency of events and tornado severity</u>. Even if weaker tornadoes are missed at a greater fraction than intense ones, the fatality count would draw overwhelmingly from the intense tornado events. Population density is probably a variable but is not quantified.

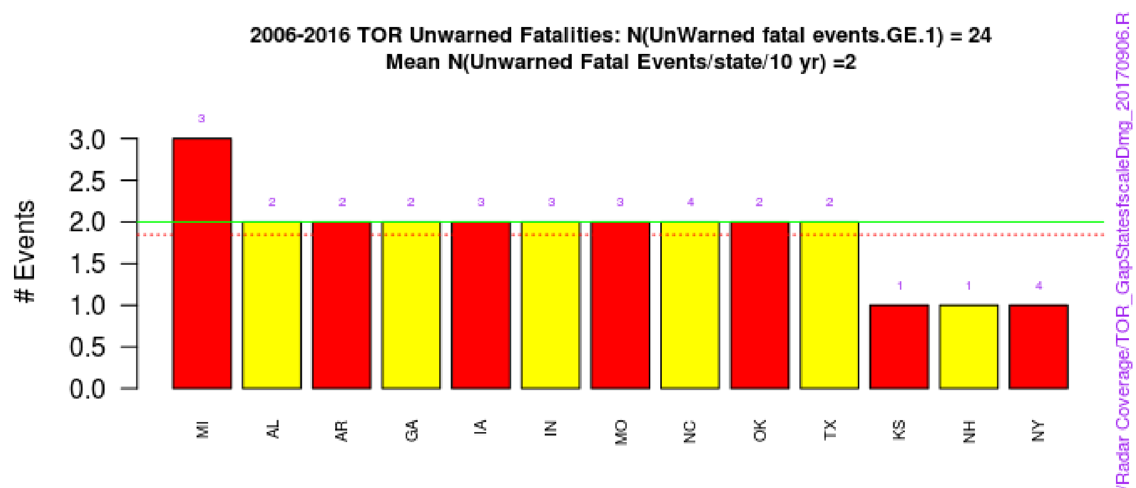


Figure B.17 - Unwarned fatal events between 2006-2016 in the jurisdictions with such events. The fatalities per state are in purple above the color bars. A total of 24 such events are recorded, resulting in two unwarned fatal events per state in ten years, with a median close below it. NC and NY have each four unwarned fatalities, which is the largest unwarned fatal count per state/territory.

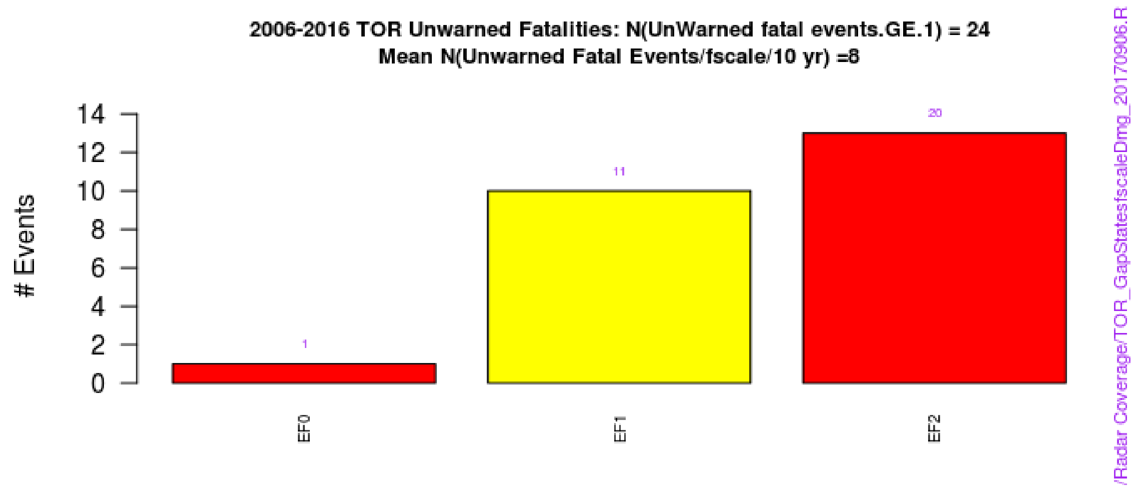


Figure B.18 - Unwarned fatal tornado events between 2006-2016 as a function of intensity (EF scale). Most unwarned tornado fatalities occurred with EF2s. The actual recorded fatalities are in purple above the color bars, totaling 32 fatalities in 24 unwarned-fatal events out of 3723 unwarned events in ten years). No unwarned fatalities were reported for EF3+ intensities.

Injuries

Just as most tornado fatalities are concentrated in 2011 so are injuries (direct and indirect) in Figure B.19, with 5646 out of 12226 injuries for the ten year period shown. Nearly half (46% to be exact) of all recorded injuries happened that year. There are nearly as many injuries as tornado events though the majority of events have no injuries reported - less than 1000 out of 12710 events do. The next highest injury-year has only 1731. The mean is 1111 injuries per year, median is 707 per year. Clearly, absent the type of intense outbreak-related events of 2011, the rates would be lower. While 2011 had a major injury producing tornado outbreak (Fig.B.19), it was an average year in terms of unwarned injuries (Fig.B.24).

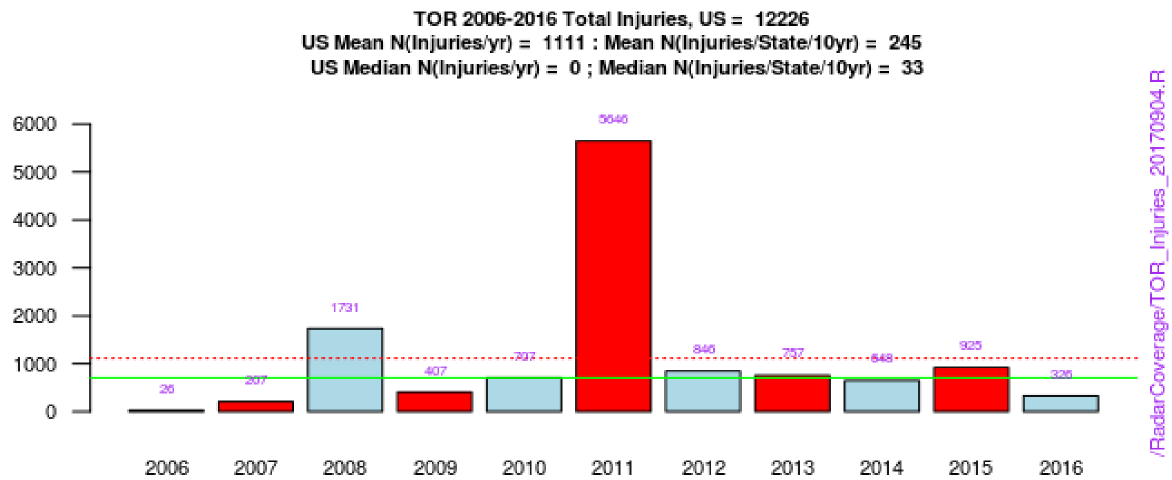


Figure B.19 - Total injuries per year for 2006-2016. The actual recorded injuries are in purple above the color bars.

In terms of tornado events with one or more injuries, only 982 out of 12710 events did, amounting to less than 8% in Figure B.20. The mean number of injury-events per state per 10 years is 23, and the mean of injuries per state per 10 years is 245. Only a handful of states had more injury-events than the national average, most of these in the southeastern US and one in the center. The high injury-event rates are correlated with the highest total injuries per jurisdiction, as seen in Figures B.20--B.21. While there is a fairly good correlation between injuries and injury-events per jurisdiction, that correlation does not carry completely to injuries per event, as seen in Figure B.22. Southeastern and central states (MS, AL, AR, OK, GA, TX, TN) dominate both the injury-events and injury counts in the ten year sample. These jurisdictions have no large gaps in NEXRAD area coverage (Fig. B.1), suggesting that injuries and coverage are largely uncorrelated. However, one state dominates in injuries per event (MA) in the ten year period (Fig. B.22), which also ranks high in fatalities per event due to the 2011 outbreak.

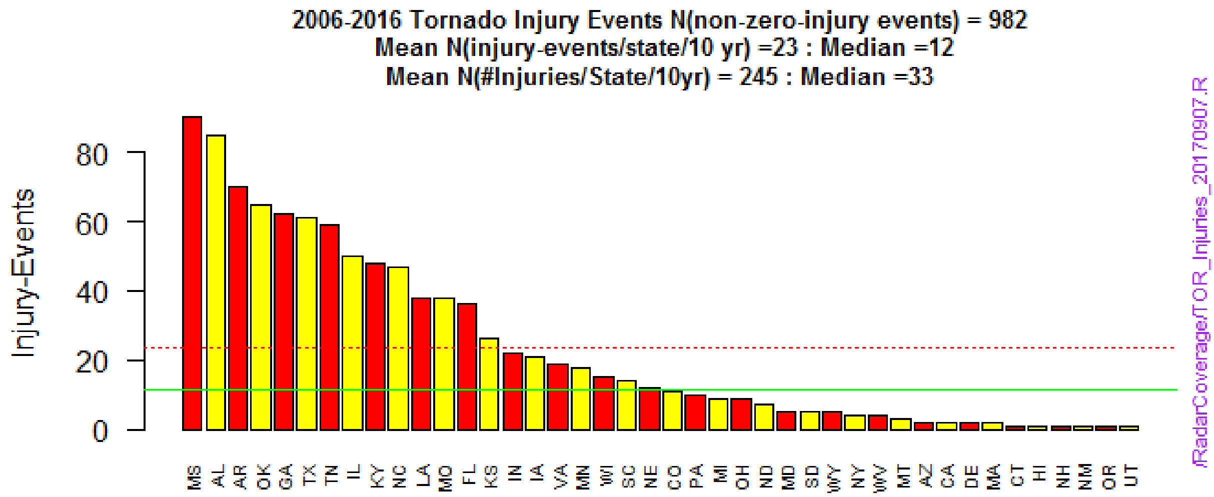


Figure B.20 - Total events with injuries between 2006-2016 per jurisdiction from the overall total of 982 events with one or more injuries. The mean injury per event (per ten years) is just below one, median is zero for the entire sample. The mean of injuries per state per ten years is 245, the median 33. The mean number of injury-events per state per 10 year is 23 (red dashed line), the mean is 12 (green line). Less than half of the jurisdictions shown carry the bulk of the injuries in the ten year record.

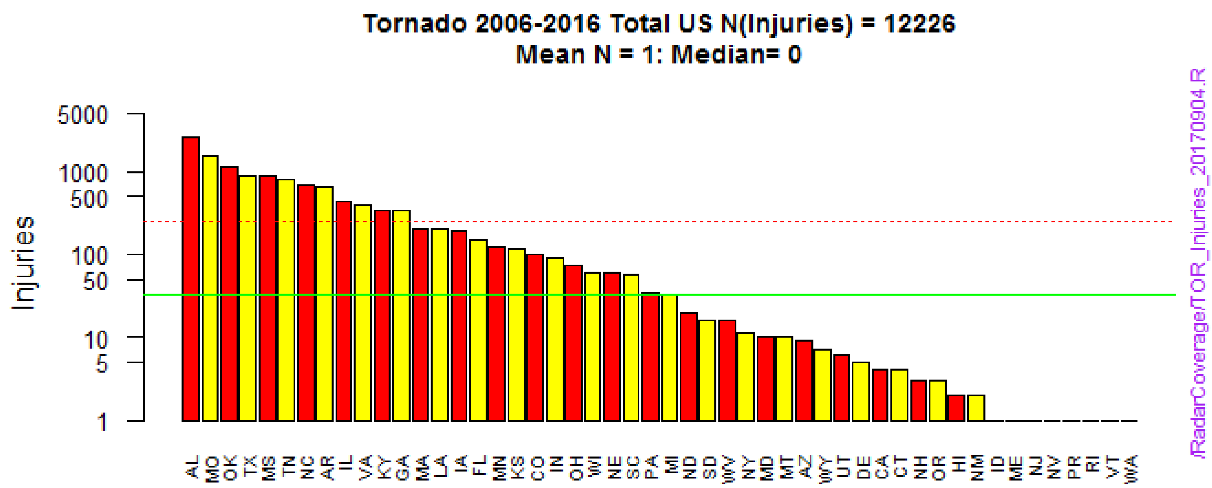


Figure B.21 - Total tornado injuries in 2006-16 per jurisdiction from a total of 982 events with one or more injuries totaling 12226. The mean injury per event (per ten years) is just below one, with a zero median in the whole sample. Mean injuries per state per ten years is 245 (red dotted line), median is 33 (green line). Less than half of the jurisdictions shown carry the bulk of the injuries in the ten year record. Note the compressed scale for injuries.

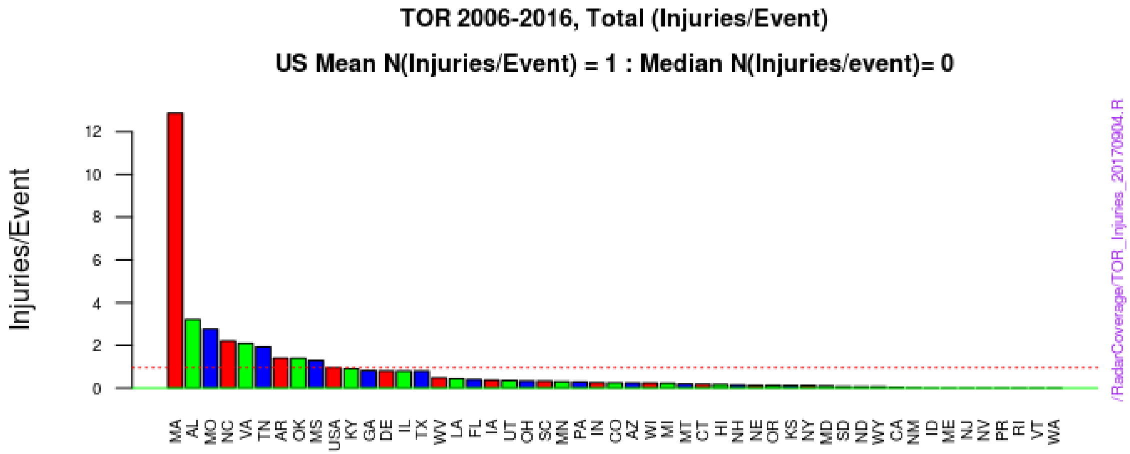
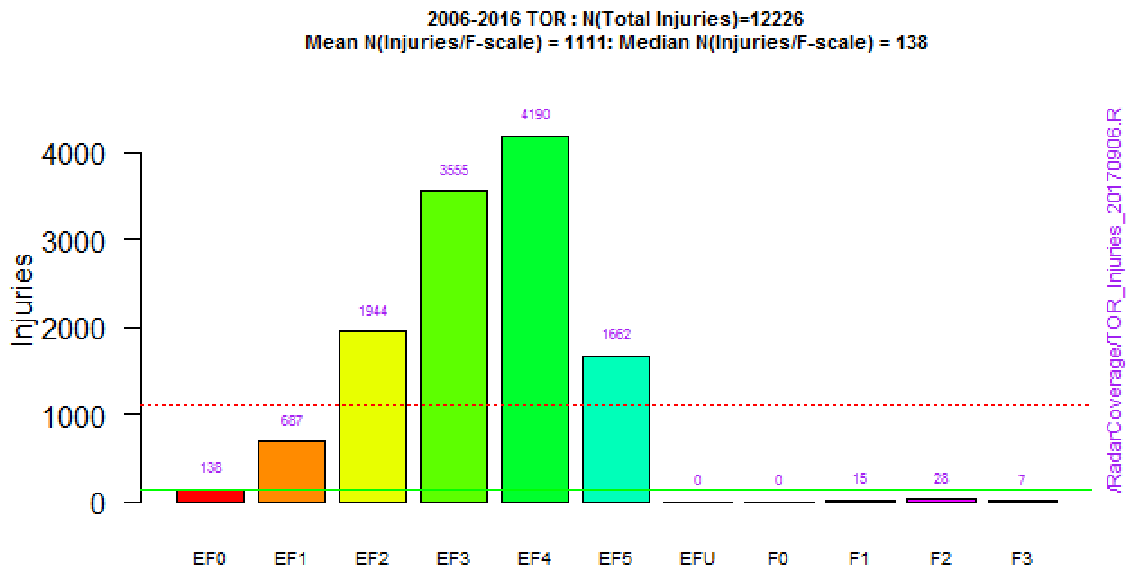


Figure B.22 - Injuries per event between 2006-2016 per jurisdiction from a total of 982 events with one or more injuries. Total injuries in the 10-year record is 12226. The mean injury per event per ten years (dotted red line) is just below one, median is zero (green line). A handful of jurisdictions have above average injuries per event in the ten year record since the majority have near zero injuries per event.

The distribution of injuries versus tornado intensity shows that the bulk of the injuries (~⅔) arise from EF3-EF4 tornadoes, as seen in Figure B.23, somewhat different than the fatality distribution where the more lethal tornadoes are also the more intense ones (Fig. B.16). Since the highest percentage of warned tornado events are also the more intense ones, the injury-producing events are therefore warned at a relatively high rate as well (Figs.B.6-B.8). The yearly breakdown of unwarned tornado injury-events resembles approximately the yearly breakdown of lethal events, peaking at 2008 and 2014 (compare Figs.B.14.a and B.24). Most unwarned injury-events are the weaker EF1 and EF2 events, as seen in Figure B.25. The injury-event rates largely follow the unwarned injuries (Figs. B.23 and B.25), and does not mirror the unwarned fatality distribution closely (Fig. B.18). Most unwarned injuries are seen with weaker tornadoes (which are relatively less warned – Fig.B.6), contrary to the overall distribution of injuries (and overall events) that are concentrated in the more intense tornado events (Fig.B.23). In other words, the unwarned injuries and unwarned injury-events fall preferentially in the weaker events, unlike the overall total injuries falling mainly in the EF3 and EF4 events (Fig.B.23). This suggests that unwarned injuries follow the overall distribution of tornado event counts overwhelmingly packing the less intense categories. Most unwarned injury-events are EF2s, accounting for 34% of the unwarned EF2 events, followed by EF0s at 15% of unwarned EF0s, and EF1s at 8% (Table B.1). Most of the unwarned injury-events are in the Texas panhandle, eastern and southern parts of the US, as seen in Figure B.26. Some of these localities have radar coverage gaps (Fig.B.1).



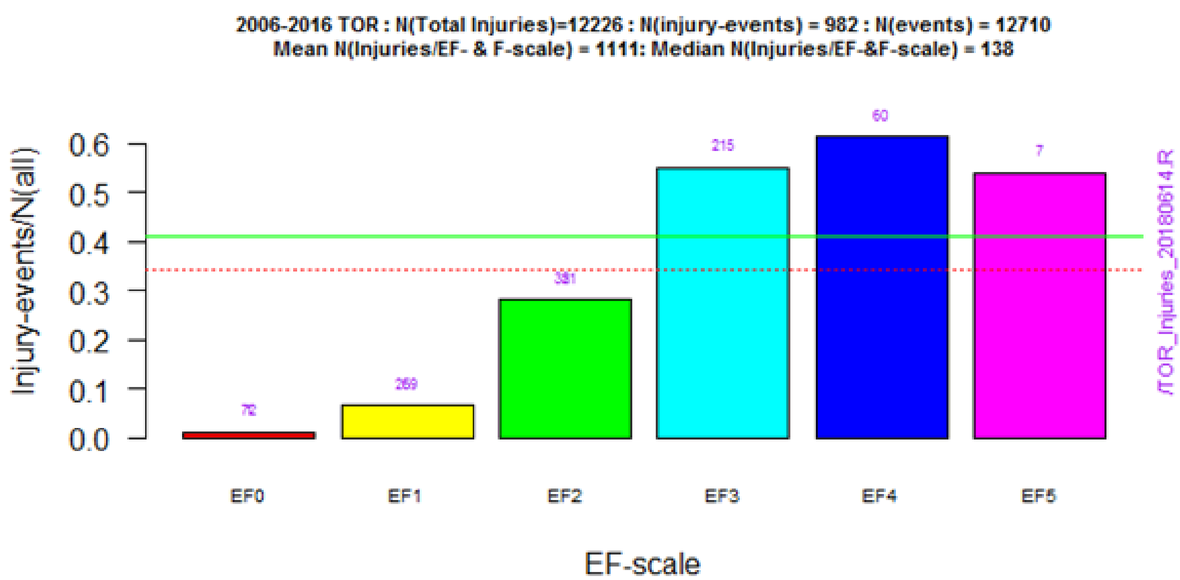
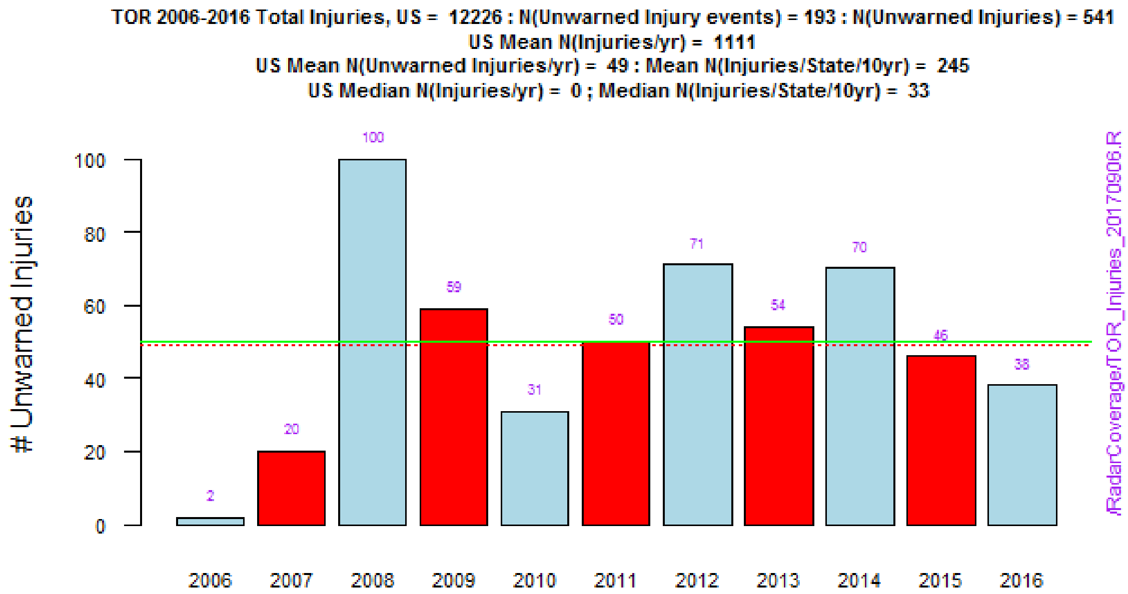


Figure B.23 – **(top)** Injury distribution as a function of tornado intensity (EF- and F-scale levels) for 2006-2016 arising from 982 injury-events totaling 12226 injuries. The mean number of injuries per category is 1111 per ten years (dotted red line), the median is 138 (green line). Injuries per category are in purple atop the color bars. **(bottom) –** Injury-event ratio (with respect to all events per EF-scale) as a function of tornado intensity (EF-scale levels) for 2006-2016 arising from 982 events with one or more injuries, from a total of 12226 injuries. There are 8 injury-events in the old F1 to F3 scale, accounting for 50 injuries (not shown). The mean injury event ratio is shown in red (0.34), the median in green (0.41). The mean number of injuries per category is 1111 per ten years, the median is 138. Non-zero event counts for each EF category are in purple atop the color bars.



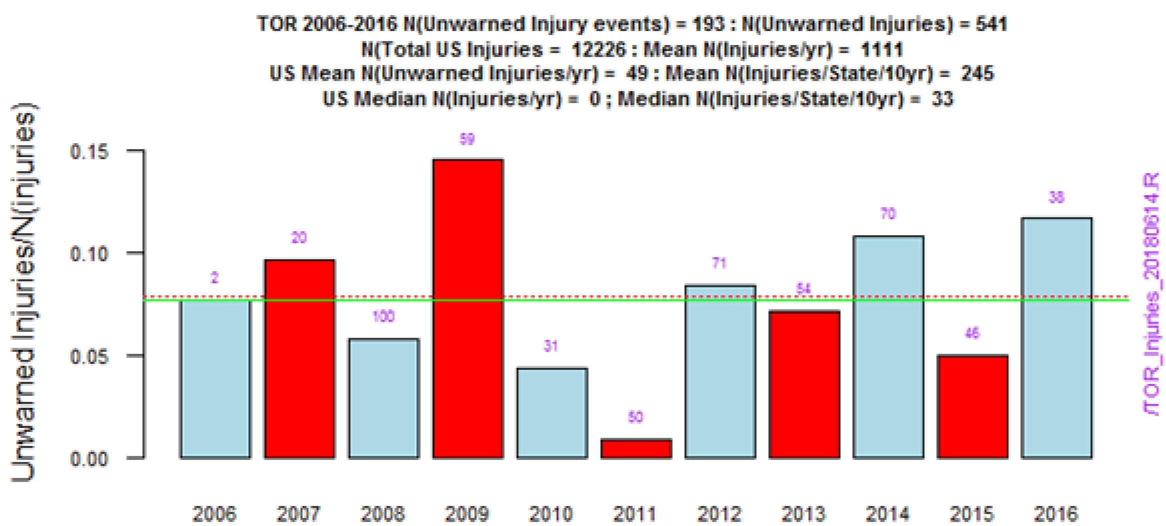
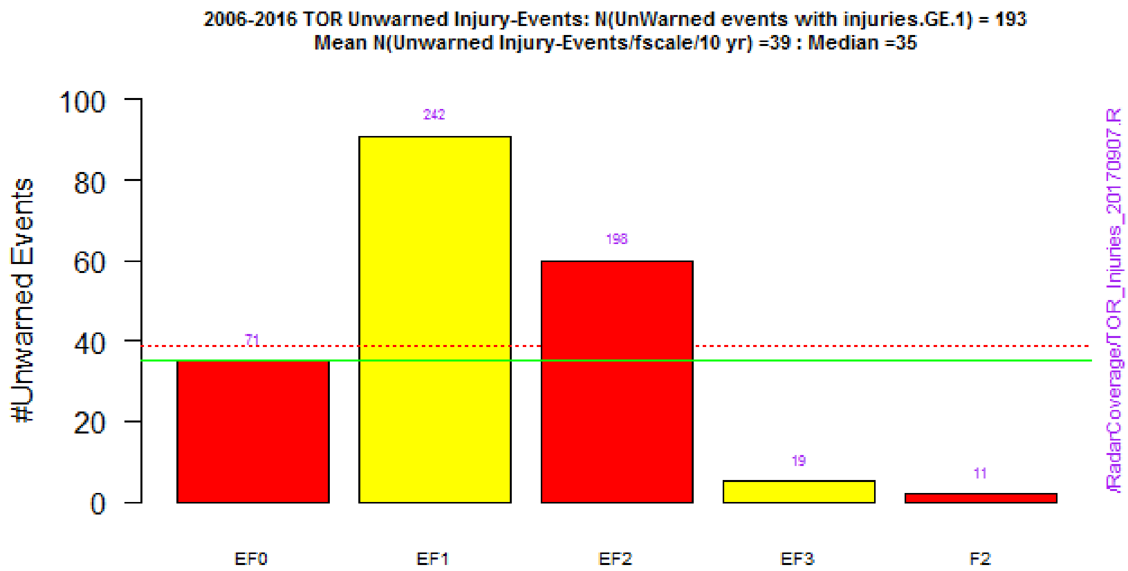


Figure B.24 – **(top panel)** Unwarned tornado injuries (direct and indirect) per calendar year between 2006-2016. The mean number of unwarned injuries per year is 49 (dotted red line), the median is 50 (green line). The injuries in each category are in purple on top of the color bars. There were 12226 injuries in the ten year period, 541 of which occurred in 193 unwarned events. **(bottom panel)** Ratios of unwarned injuries to overall injuries per year corresponding to the top panel.



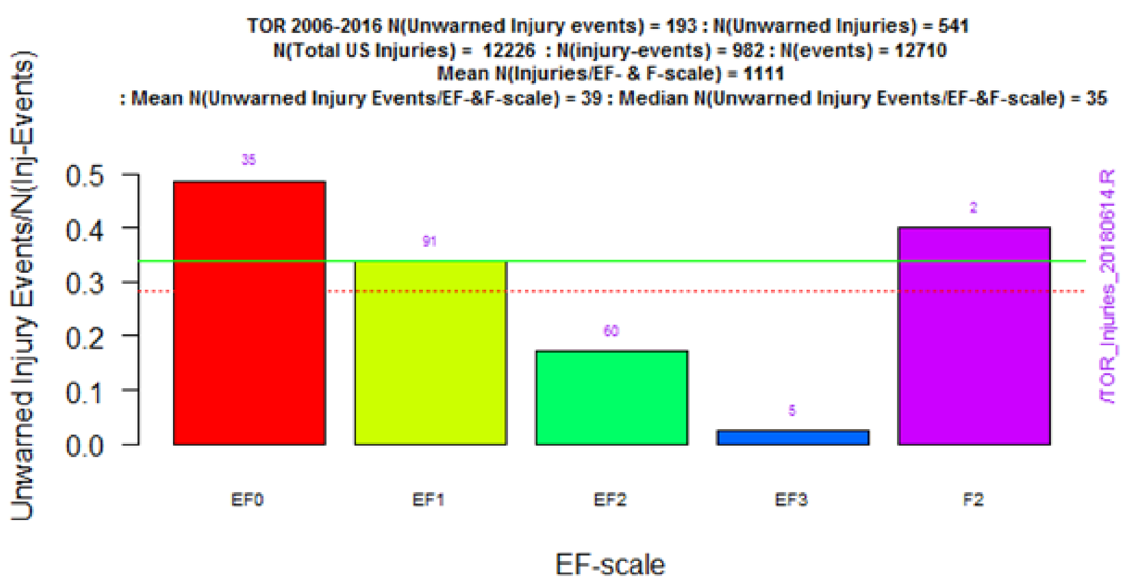


Figure B.25 – **(top)** Unwarned injuries per EF- and F-scale between 2006 and 2016 from a total of 193 unwarned injury-events. The mean number of unwarned injuries per intensity scale per 10 years is 39 (dotted red line), the median is 35 (green line). The total injuries in each category are in purple on top of the color bars. There are no reported unwarned injury-events in intensity levels not shown. The purple numbers on top of the color bars are the associated injuries. **(bottom)** Unwarned injury events per EF- and the earlier F-scale between 2006 and 2016 from a total of 193 unwarned injury-events. The mean ratio of unwarned injury events per intensity scale per 10 years is 0.28 (dotted red line), the median is 0.34 (green line). The total unwarned injury event counts in each category are in purple atop the color bars. There are no reported unwarned injury-events for EF- and F-scale levels not shown.

Table B.1 – Total and unwarned events in terms of tornado intensity (EF- and F-scale) as well as unwarned injury-producing and lethal events between 2006 and 2016.

Intensity	Total Events (N=12710)	Unwarned Events	Unwarned Injury-Events	Unwarned Lethal Events
EF0	6699	2315	35	1
EF1	4161	1182	91	10
EF2	1252	174	60	13
EF3	391	13	5	0
EF4	98	0	0	0
EF5	13	0	0	0
F2	8	2	2	0

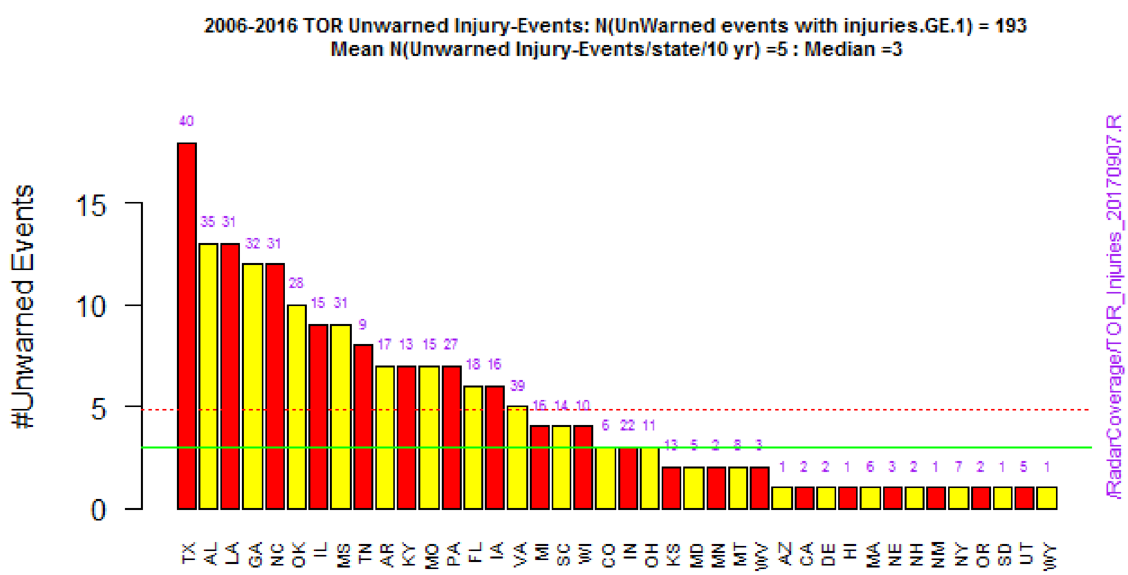


Figure B.26 – Unwarned injury-events jurisdiction between 2006 and 2016 from a total of 193 unwarned injury-events. The mean number of unwarned injury-events per jurisdiction per 10 years is 5 (dotted red line), the median is 3 (green line). The total unwarned injuries in each jurisdiction are in purple on top of the color bars. There are no reported unwarned injury-events in jurisdictions not shown.

Significant Property Damage

Significant property damage is here defined as any damage (direct and indirect) above the mean damage per event in Figure B.27 of about $1.55M. About 55% of all tornado events involve damage directly or indirectly (including crops), and 557 events carry damages above the mean damage value per event. There are far fewer significant damage events given the large number of zero-damage events (44% of the entire sample). Most of the damage is concentrated in the stronger tornado events in spite of their much lower frequency of occurrence, as seen in Figure B.28. In terms of total damage (not shown), the highest cumulative total for 2006-2016 are on the order of billions: EF4 events accumulated the most damage ($6,384,062k) followed by EF5s ($5,128,375k). Weaker tornadoes carry much less damage, as can be expected. As shown earlier (Fig.B.6), stronger tornadoes are warned at a higher rate than the weaker ones and produce the greatest damage per event so the probability of damage increase greatly with more intense tornadoes (a simple cost model developed by Meléndez et al., 2018, https://ams.confex.com/ams/29SLS/webprogram/Paper348262.html, has mean damage per event increasing logarithmically by several orders of magnitude with greater tornado intensity).

In terms of jurisdiction, just one state (MA) had much higher per event damages than the rest, showing the episodic nature of significant damages. Few jurisdictions had above average damage-events, as seen in Figure B.29. The majority of these are concentrated in the southeastern and central US, amounting to a few states. Unwarned events with significant damage occurred mostly in 2008, as seen in Figure B.30. That is, the significant damage has episodic yearly spikes not uniformly distributed in time or space, as in Figure B.31. Unwarned events with significant property damage peak in just a handful of states in central and eastern US, like unwarned lethal and injury-causing tornado events (Fig. B.17).

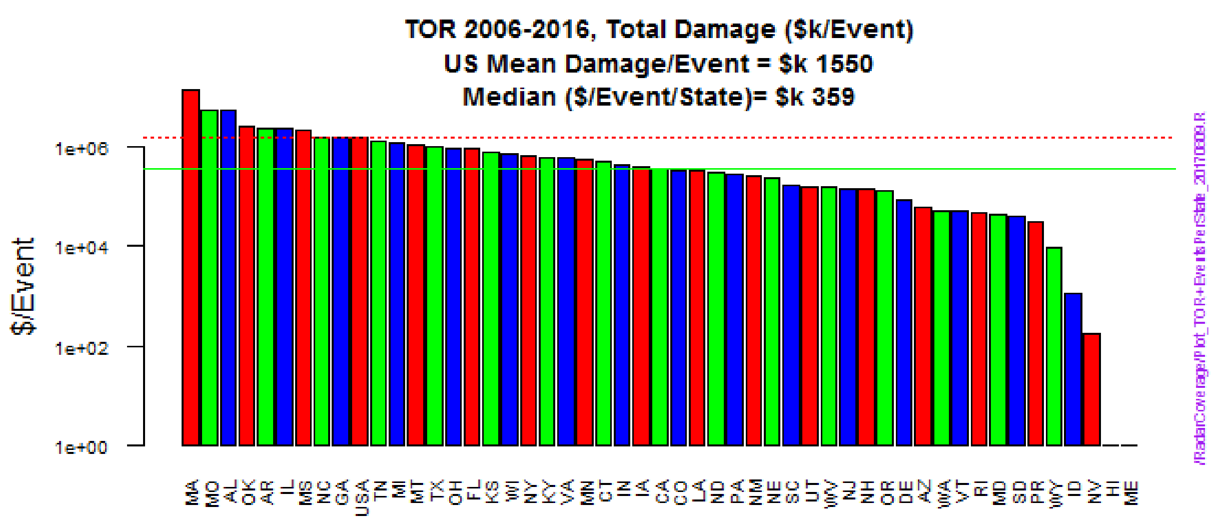


Figure B.27 – Mean tornado damage per event for 2006-2016 in the US from 7078 damage carrying-events (out of 12710 events). Mean damage per event per 10 years is $1.55M (red line); the median per event per jurisdiction is

$359k (green line). Some jurisdictions had no damage-events. Note the compressed $k/event scale, spanning from $1k to over $1B.

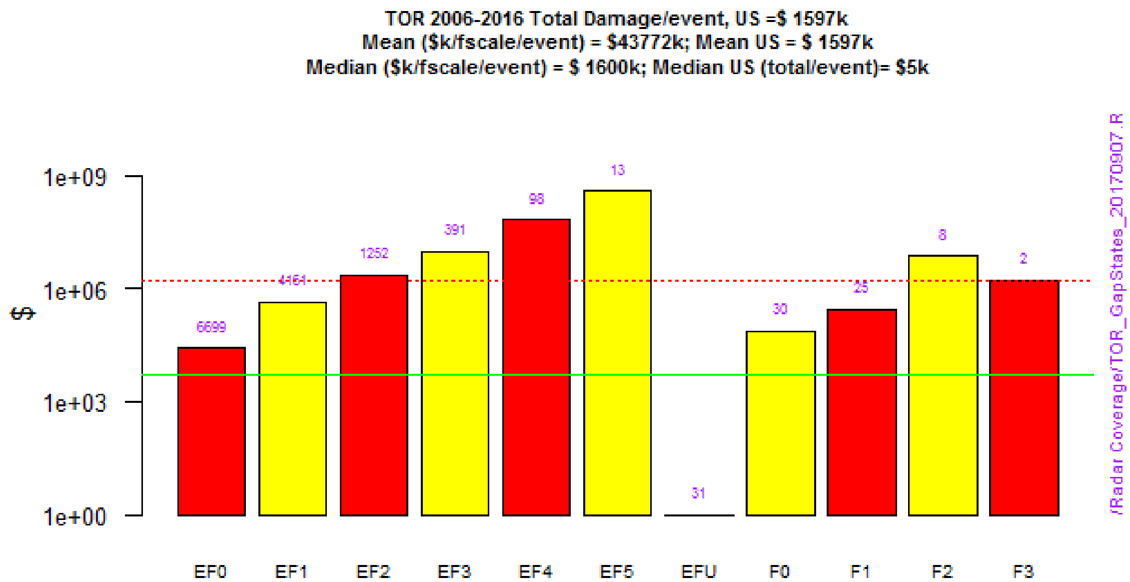


Figure B.28 – Tornado mean damage per intensity category (EF- and F-scales) between 2006 and 2016 from a total of 7078 damage carrying-events (out of 12,710 total). The mean damage per event per intensity category per 10 years $43.8M (dotted red line), and the mean per event per jurisdiction is $1.6M (green line). EFU refers to events that were not categorized in any scale level. The numbers above the color bars are total tornado events per EF/F-scale category.

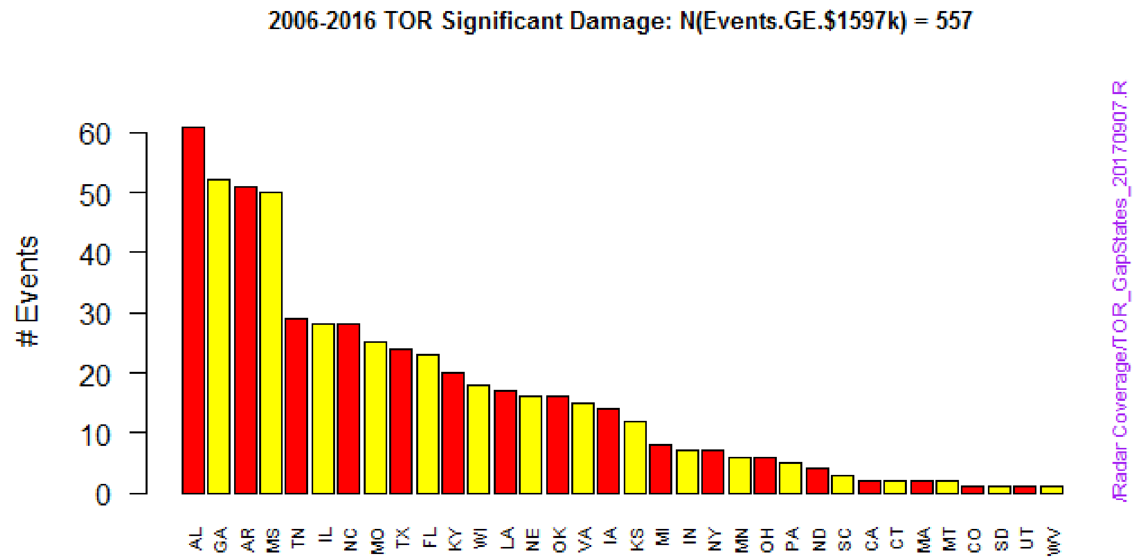


Figure B.29 – Tornado events with damage above the US mean damage between 2006 and 2016 for the jurisdictions reporting. From a total of 7078 damage carrying-events (out of 12,710 total), 557 events had above average damage. Jurisdictions not listed reported no events above the mean damage level.

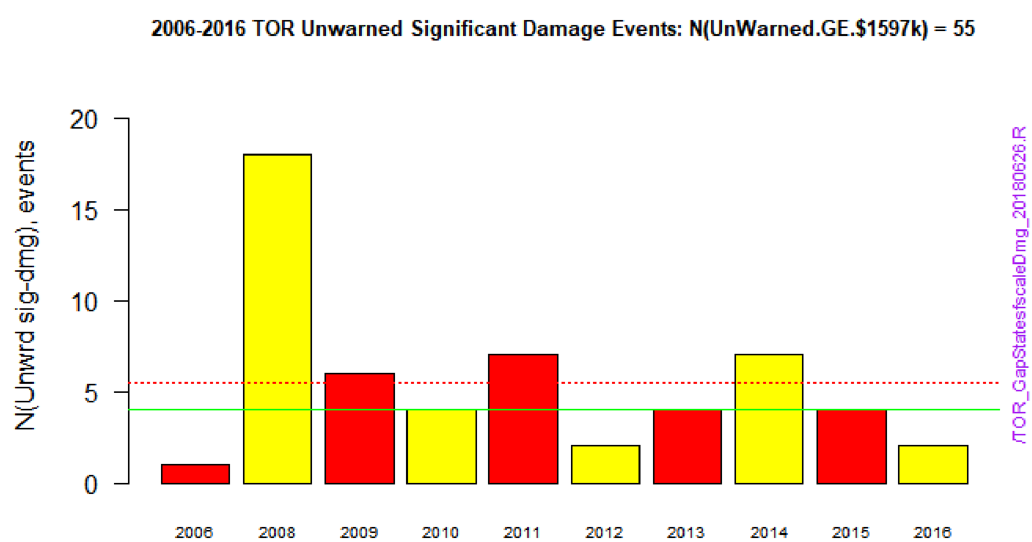


Figure B.30 – Unwarned tornado events (55) with damage above the US mean damage between 2006 and 2016. Most of the significant damage events took place in 2008.

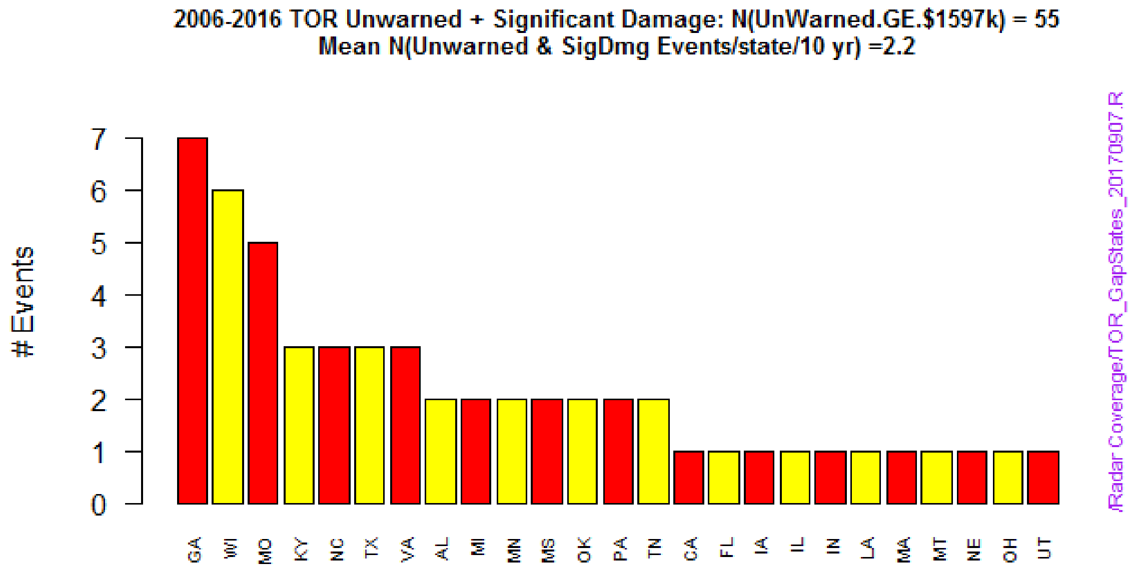


Figure B.31 – Unwarned tornado events with damage above the US mean damage between 2006 and 2016 across jurisdiction.

Appendix C – Tornado Warning Performance and Relative NEXRAD Area Coverage

[Writers: W/STIO - Daniel Meléndez]

- Describes relationship between probability of detection (POD), false alarm rate (FAR), critical success index (CSI), as well as new performance metrics versus percentage of NWS WFO surface area coverage under the NEXRAD 6 kft radar beam under a linear-response model.

This section examines tornado warning performance as a function of relative NEXRAD surface area coverage horizontally (range-wise). An objective measure of radar coverage, different from the conventional range or horizontal distance from the radar, is the percentage of a given jurisdiction or WFO under the NEXRAD bottom-of-the-beam height of 6 kft above ground level (AGL). The NEXRAD beam has a finite solid angle of about 1^{0} (which means that at 60 nm from the radar the beam is 1 nm wide). Since the beam altitude increases with more horizontal distance (range) from the radar antenna, a given altitude implies a range. Because the beam can be obstructed at any given azimuth (or elevation) by natural or human structures, a beam clutter pattern develops. This clutter is taken into account in computing the relative area covered as well as the overlap of different NEXRAD beams over the same area, which is here removed. The resulting coverage (percent jurisdictional surface area) under 6 kft AGL shows that states having above average relative coverage (65%) are in the eastern and portions of the central US while those with less than average coverage are mostly in the western US, as shown Figure C.1.

The introduction of the metric of relative surface area coverage in this technical study is different from the traditional range from the radar metric. The area metric has not been used before, thus warranting exploration and baselining, and it is an intrinsic coverage metric characterizing each WFO, which, in aggregate, provides a spectrum and sample of coverage values. This is a physically realistic measure anchored in the WFO as the basic service entity. A 100% relative area coverage value means that the entire WFO area of responsibility is covered by NEXRAD below the bottom-of-the-beam height of 6 kft AGL, including beam clutter/obstructions, whereas 0% means there is no NEXRAD coverage. There is no a priori reasoning that can be identified to disregard such coverage metric, any more than there is reason to discard fractional volume coverage or averaging in range (as done by Brotzge and Erickson, 2010, and others). The relative area metric reflects both another "moment" in beam spatial extent, conceptually analogous to fractional volume, but in terms of WFO. There is no claim or expectation that this metric is necessarily the globally optimal spatial variable against which to evaluate performance. But, as a physically realistic and legitimate descriptor of relative beam coverage, area coverage provides an eigen-framework for spatial analysis that warrants understanding, description, and further elaboration with this and future studies.

Another advantage of the relative area metric is that it reflects the existing NEXRAD surface area coverage distribution as it exists, and at the same time can be applied to any volumetric weather radar network. This metric also provides a rational basis for inter- and intra-WFO performance analyses. It is certainly possible and desirable to make further geospatial analyses using this and other metrics. Future work should include further comparison with range-only metrics and thresholding at not just 6 kft, but at other beam heights. The choice of 6 kft beam height is not entirely arbitrary, informed by congressional interest and the previous NAS/NRC study on NEXRAD Coverage and Flash Flood Performance in Complex Terrain (and references therein).

A recent change to the NEXRAD scanning protocol is to add a supplemental lower elevation angle at selected sites, below the established base elevation of 0.5°. This has the advantage of providing more low-level coverage of the planetary boundary layer, which is known to be where much severe weather can originate, become modified, and dissipate - causing a myriad of impacts. Currently, about ten NEXRAD sites have implemented a supplemental low elevation angle or will be implemented within the next year. The number of sites is likely to grow (depending on funding and no findings of environmental impacts.). However, since this has been in effect for about a year, it is not amenable to meaningful statistical evaluation, but is flagged for future work.

One question that has arisen in tornado event reporting (e.g., Brotzge and Donner, 2013) is whether it depends on population. Using the 2011 census data (approximately mid-way value in terms of the period of coverage of the data being 2008-2016), no statistically significant relationship between population and number of events is found, as seen in Figure C.2. The data is scattered widely in events-population phase space, so there is no strong correlation between events count and population at the state-scale, though there is a clustering in the lower population corner having clusters of both high and low counts. The lowest count cluster contains most jurisdictions with low tornadic activity as known from tornado climatology (e.g., VT, WY, MT, NM, PR). The non-relationship remains even with the state with most events and second highest population removed since the low-event states dominate the fit. The large scatter in the data greatly affects the quality of the fits, where a dramatically different regression arises by removing one populous point alone. Therefore, <u>population itself is not a significant or primary driver of reported events in a linear model;</u> other factors must be at play, though there is sensitivity to events in terms of WFO-area coverage (Figs.C,4 and E.33). While there is no strong correlation overall, there is some clustering of low events associated with low population counts nonetheless. A different statistical analysis may reveal a different or similar sensitivity to population, as exemplified by Brotzge and Erickson (2010), who find an increase in FAR with range sorted by population density.

The distribution of tornado events in terms of relative coverage area per state under the 6 kft AGL beam height as defined earlier is statistically insignificant in Figure C.3. However, a statistically significant relation is seen if instead of states/territories, the comparison is made to the relative coverage of the Weather Forecast Offices (WFOs) in Figure C.4. There is an intriguing clustering of high events for a set of WFOs having between 60% and 80% area coverage. This is interpreted to denote that as the spatial scale is reduced (from states to WFOs), the event counts show more sensitivity to spatial coverage, and that some WFOs are more sensitive than others. There is a potential role for factors related to experience, outreach, and emergency management that can influence event reporting in addition to warnings, the latter discussed in Brotzge and Donner (2013). A listing of WFO acronyms and locations can be found in Appendix S.

Compared to the event counts (Figs.C.3--C.4), the ratio of warned tornado events (warned ratio or probability of detection) as a function of relative NEXRAD coverage for both US jurisdictions and WFOs shows a much stronger relationship in spite of scatter in the data, as seen in Figures

C.5--C.6. The false alarm rate (FAR) or the number of false alarms divided by the total number of forecast events is a measure of reliability where 100% means all events forecasted did not occur. The distribution as a function of relative NEXRAD area coverage per WFO shows no statistically significant trend, meaning that FAR and coverage are independent under the linear model response to area coverage, as shown in Figure C.7. This is an unexpected result that points to the substantial difficulty in reducing the mean tornado FAR, which has held steady for years. The range in these metrics are as large as in the annual variations in Brooks and Correia (2018).

As found by Brotzge et al. (2011): for warnings within 50 km of an NWS radar, FAR increased with population density; however, for warnings beyond 150 km from radar, FAR decreased regardless of population density. In their Fig.8, the FAR increases with range beyond about 150 km, which corresponds closely to the threshold range of 165 km implied by the beam height cutoff in this study. Neither of these results are, therefore, in direct conflict. The relationship for the critical success index (CSI) or "threat score," defined as the hits divided by the sum of all hits, misses and false alarms, relates to how well the forecast "hits" matched the observed hits, with one as perfect score. This is another conventional, or traditional, measure of skill, along with FAR, lead time and POD, shown here for completeness. As a function of relative area coverage, CSI increases with more radar coverage in Figure C.8 with a statistically significant slope. In spite of a zero mean when all WFO CSI values are averaged, there is relative improvement in the overall skill with increasing coverage. A note of caution: CSI as a statistical measure can be biased in proportion to the frequency of the event forecasted [Schaefer, 1990; https://doi.org/10.1175/1520-0434(1990)005%3C0570:TCSIAA%3E2.0.CO;2]. In other words, trends in CSI are likely driven by event frequency, and in this case, events increase some with more coverage (Fig.C.4). It should also be noted that increases in CSI were found to occur with the deployment of NEXRAD compared to the FAA ARSR-centered skill values in DOT/FAA report by Dunbar and Mittelman (1993)

Tornado lead time is the time of the warning at or before the event was verified to occur (there are negative lead times also that refer to events verified before a warning was even issued). The relationship between lead time and relative WFO-area under radar coverage is also subject to considerable scatter but, compared to the probability of detection (POD), CSI, and FAR discussed previously, has some dependence on relative area coverage, as shown by the regression in Figure C.9. NWS practice includes the zero-lead time events as warned for the purpose of POD and Warned Ratio metrics (NWS Performance Directive 2017). Events warned with non-zero lead time have a small but positive contribution to the probability of detection (which is rigorously different but closely related to the warned ratio). When the regression in Fig.C.9 excludes the zero-lead time events, the slope is nearly-flat and statistically insignificant (not shown), a result consistent with the flat annual fluctuation in lead time of Brooks and Correia (2018). Note that the latter work looks at the temporal variability, whereas this study is centered on the spatial variability.

Taken together, there is linear sensitivity to radar area coverage in the traditional tornado metrics of POD, CSI, and lead time but not in FAR. The warned ratio and lead time have perhaps the strongest dependence on relative area coverage of the set yet suffering from high scatter in the data. At best, it can be said that increased radar coverage raises skill but may not affect the false alarms and does not seem to be as predictive of warning skill as is the number of events (related to experience and statistically marginal to coverage, given the mild sensitivity of events with area coverage). Of course, the experience factor is in itself enabled by NEXRAD so the two are not mutually exclusive.

Fatalities

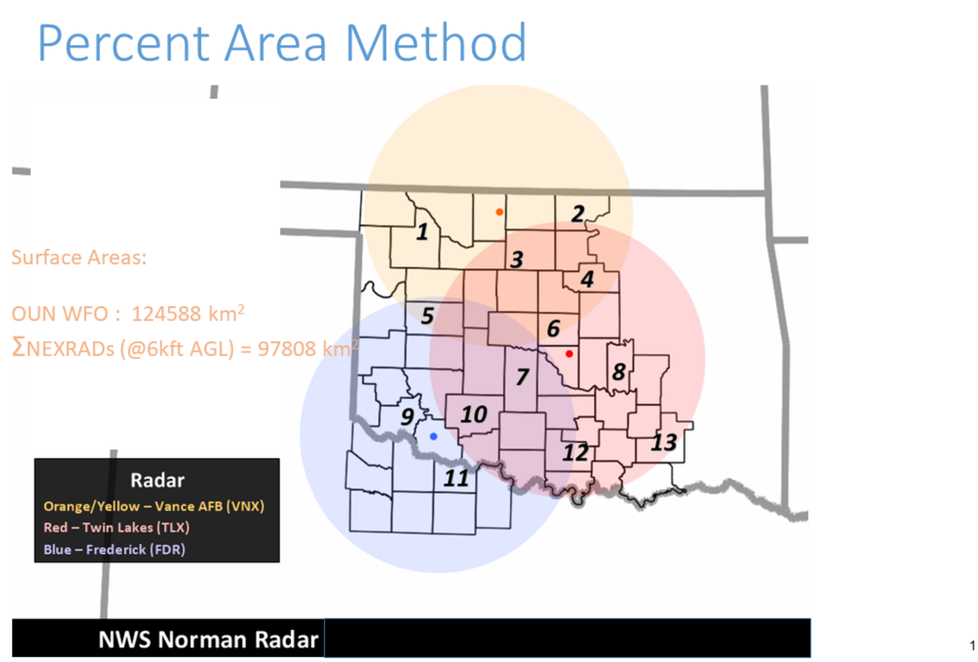
There is a small increase in the number of fatalities, lethal events, and the fraction of lethal to all events with increasing percent of radar area coverage, as seen in Figures C.10--C.12. The linear fits to the data are, like most other ones, weak given the large scatter in the data. The strongest relationship appears to be the increase in the fraction of lethal events with greater relative radar coverage. Thus, these results suggest a secondary response to relative radar coverage. The weak association arises from the fact that fatal events are a very small fraction of the entire sample (271 or 2% of the events), and from the wide variation with coverage in the non-lethal events itself. There were only 24 unwarned fatal tornado events equally distributed across 20 WFOs with either one or two such events per WFO (not shown). Therefore, there is no association with radar coverage and unwarned fatalities for any inference could be drawn with a linear response model.

Injuries

There were 12,226 injuries associated directly or indirectly with tornado events during 2006-2016 and 982 injury-events, about 8% of all events, as shown in Figure C.13. Neither the number of injuries or injury-events have a strong relationship with radar coverage though the dependence of injury-events with coverage is slightly stronger. However, the ratio of unwarned injury events to non-zero injuries decreases with more radar coverage, as can be expected, and the linear fit is statistically significant (Fig.C.14) though again with large scatter in the data and unwarned event counts in single digits. From the analytical angle, this shows that some metrics are more sensitive to coverage than others but in all cases metrics with low overall counts should be understood as indicating secondary effects. Injuries, and fatalities are the result of a complex interplay between warnings, human behavior, and other material factors such that there is no a priori foundation to expect much if any variation with radar coverage. Injury event statistics do not fully mimic those of fatalities so they should be evaluated separately. There were 193 unwarned injury events out of 2845 unwarned events (7% of unwarned events; 22% unwarned event ratio), as shown in Figure C.14. The unwarned injury- to unwarned event ratio shows even less sensitivity to relative radar coverage than the unwarned events count (and is probably the cause for the insensitivity). Therefore, injury-events, injuries and relative radar coverage are mostly independent from radar coverage; the unwarned injury to total injury ratio decreases with more radar coverage but weakly so due to the low number of such events under the linear model.

Significant Property Damage

The fraction of tornado events incurring direct or indirect damage to all events per WFO increases with more radar coverage, as well as in the fraction with significant property damage (defined as the mean of the direct and indirect damage) is seen in Figure C.15. Because low or no damage events dominate the distribution, there are only 557 events above the significant damage threshold of nearly $1.6M. Compared to the other fits, the linear response models for damage and significant damage do a better job of accounting for the variance or spread in the data and are statistically significant. Therefore, there is a statistical sensitivity to radar coverage for both nonzero and significant property damage per event. This deserves further investigation since there may be more vulnerability to damages in areas of higher relative coverage since the bulk of the low coverage areas in the intermountain western US. As shown before, population is larger in areas with greater radar coverage so the exposure to damage can be expected to follow population. The distribution of total damage as a function of relative radar coverage (Fig.E.33) clocks low damages below 50% coverage. There is only a handful of very large damage events above that, which can explain the above relationships. Linear fits to both the nonzero damage event ratio to all events per WFO and the significant damage to damage event ratio are statistically significant and show greater sensitivity to more radar coverage, which is likely due to higher population.



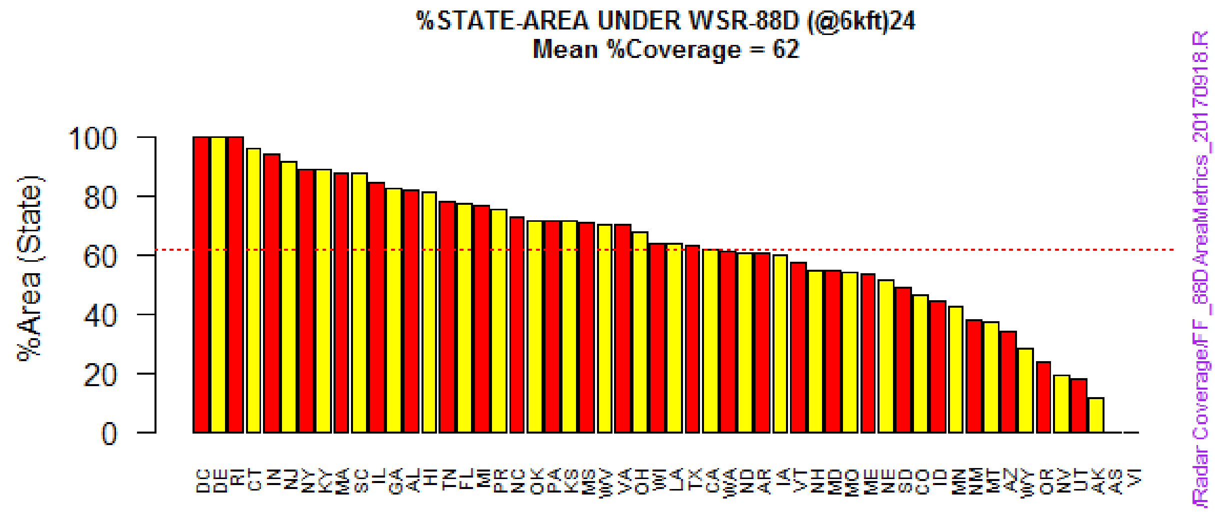


Figure C.1 – **(top panel)** Example of the "percent area" method over a Weather Forecast Office or state area as covered by any number of NEXRADs under the bottom-of-the-beam height at 6 kft AGL. In this example, three NEXRADs cover 97808 km2 of the OUN WFO surface area of 124588 km2 for a coverage ratio of 78.5%. **(bottom panel)** Same as above but computed per NWS jurisdiction, showing the mean coverage is 62%, including Alaska (AK), American Samoa (AS), PR and USVI (VI).

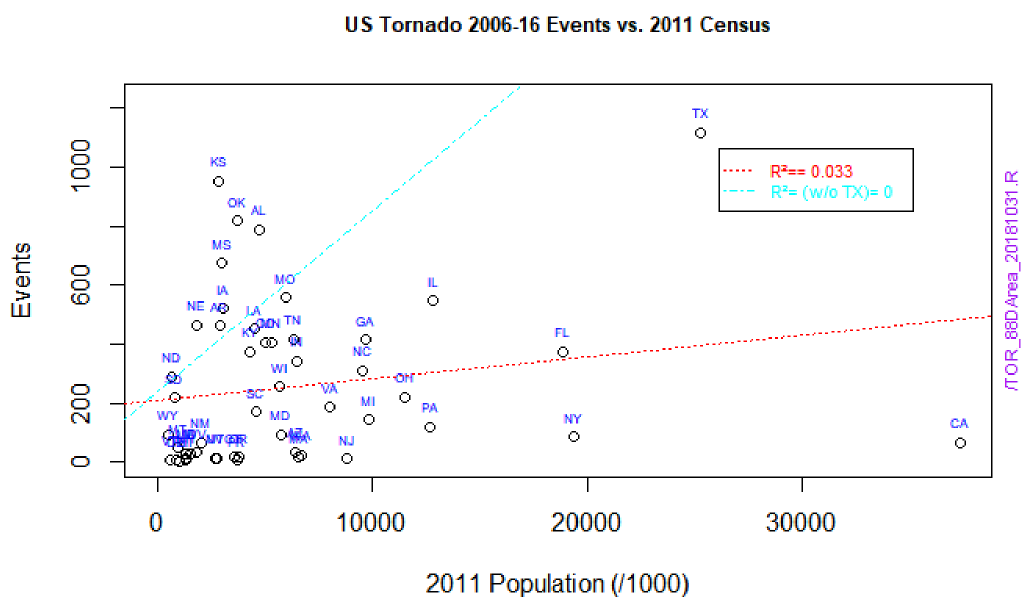


Figure C.2 – Tornado events in 2006-16 (N = 12710) as a function of population per 2011 US Census. A linear fit to the data (red dotted line) is not statistically significant ($p = 0.2$) and increases with more population with an index of determination of $R^2 = 0.033$. Sensitivity to population is further explored with a fit excluding the state with most events and population (TX), which is not statistically significant ($p = 0.99$) and has a coefficient of determination $R^2 = 0$. Neither regression is statistically significant so events and population are not well explained by a linear relation.

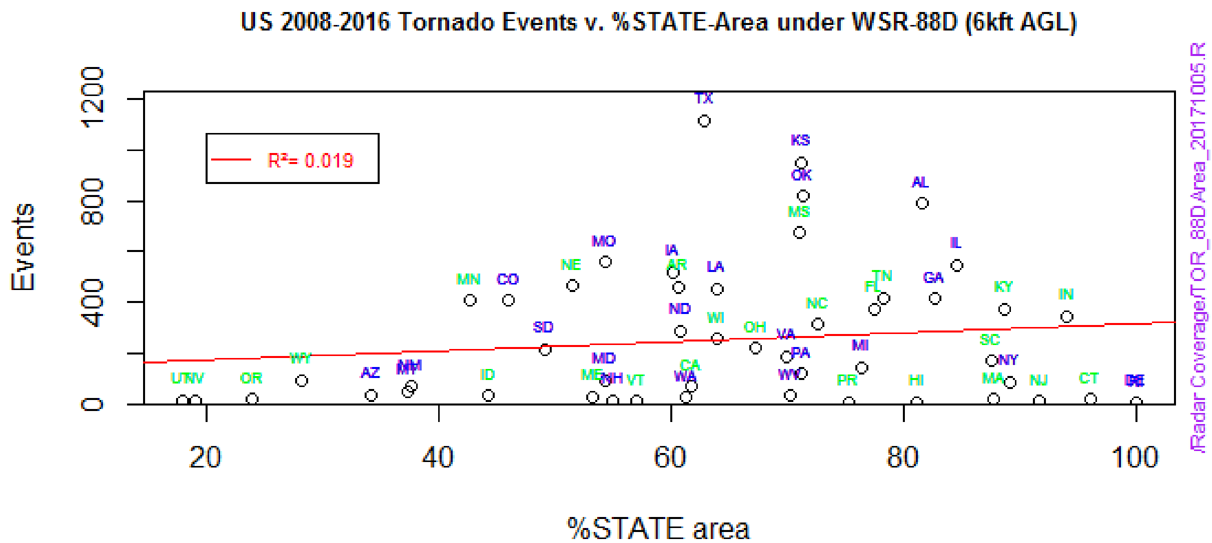


Figure C.3 – Tornado events reported between 2008 and 2016 as a function of the relative area covered by the 6 kft AGL radar beam. Each circle corresponds to a particular jurisdiction. A linear fit to the data (red dotted line) shows a small increase with increasing NEXRAD coverage that is statistically insignificant (p = 0.3) with an index of determination of only 0.02.

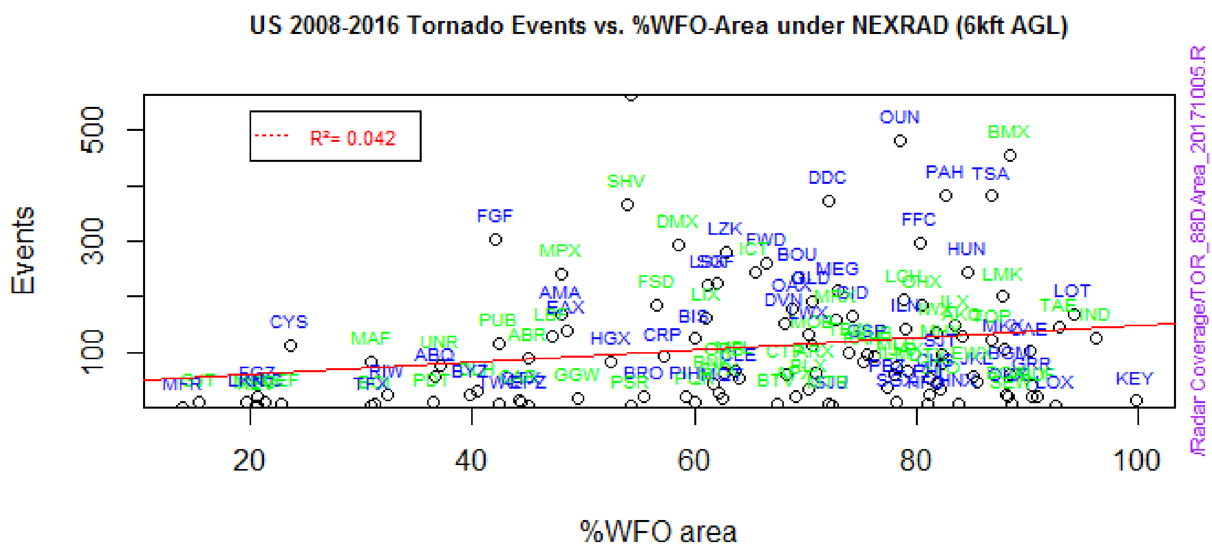


Figure C.4 – Tornado events reported between 2008 and 2016 as a function of the relative Weather Forecast Office (WFO) area covered by the 6 kft AGL radar beam. Each circle corresponds to a particular jurisdiction. A linear fit to the data (red dotted line) shows a small but statistically significant (p = 0.027) increase with more radar coverage with a coefficient of determination of 0.04. See Appendix S for a listing of WFO identifiers and locations.

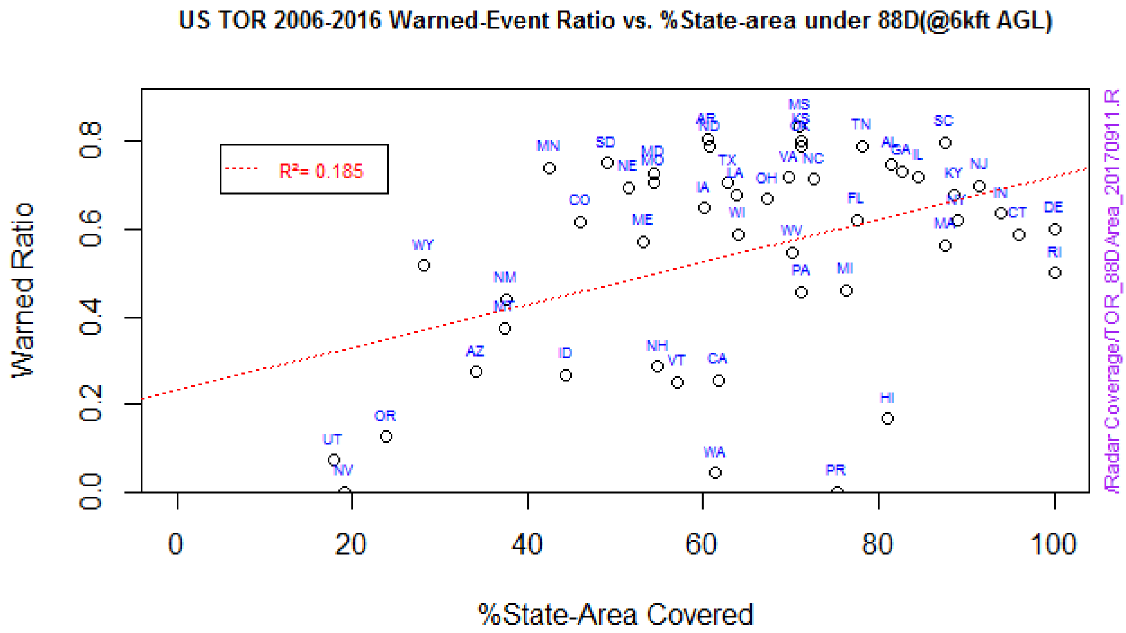
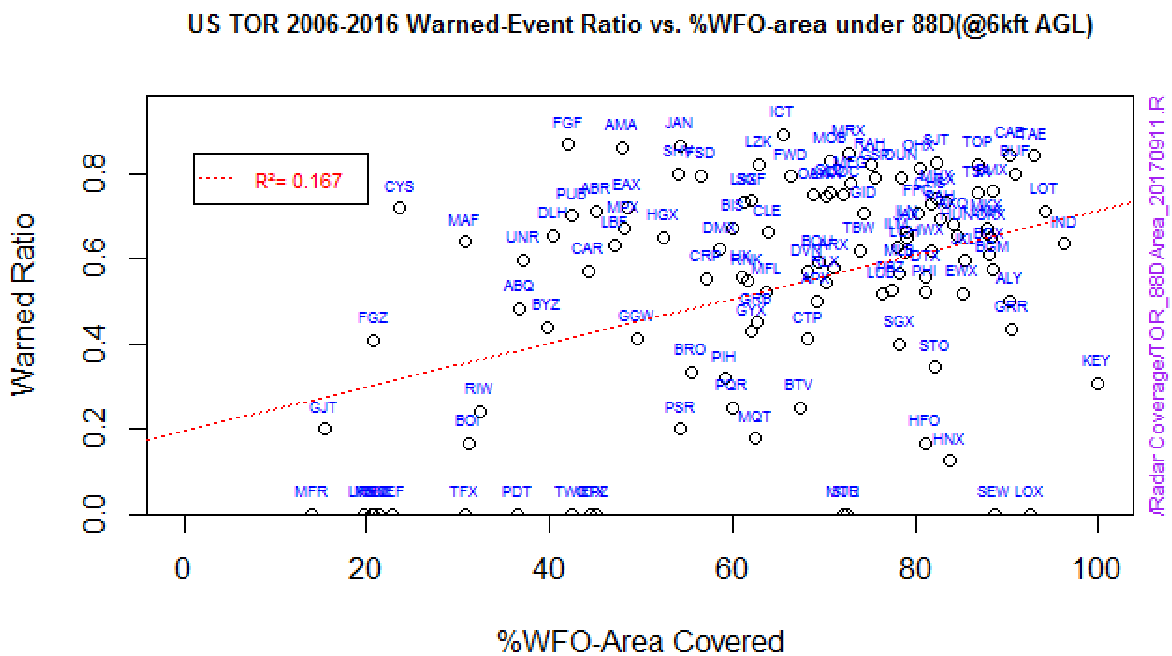


Figure C.5 – Fraction of warned tornado events reported between 2006 and 2016 as a function of the relative state area covered by the 6 kft AGL radar beam. Each circle corresponds to a particular jurisdiction. A linear fit to the data (red dotted line) shows a statistically significant (at better than 99% level of significance) increase with more radar coverage with a variance of 0.185.



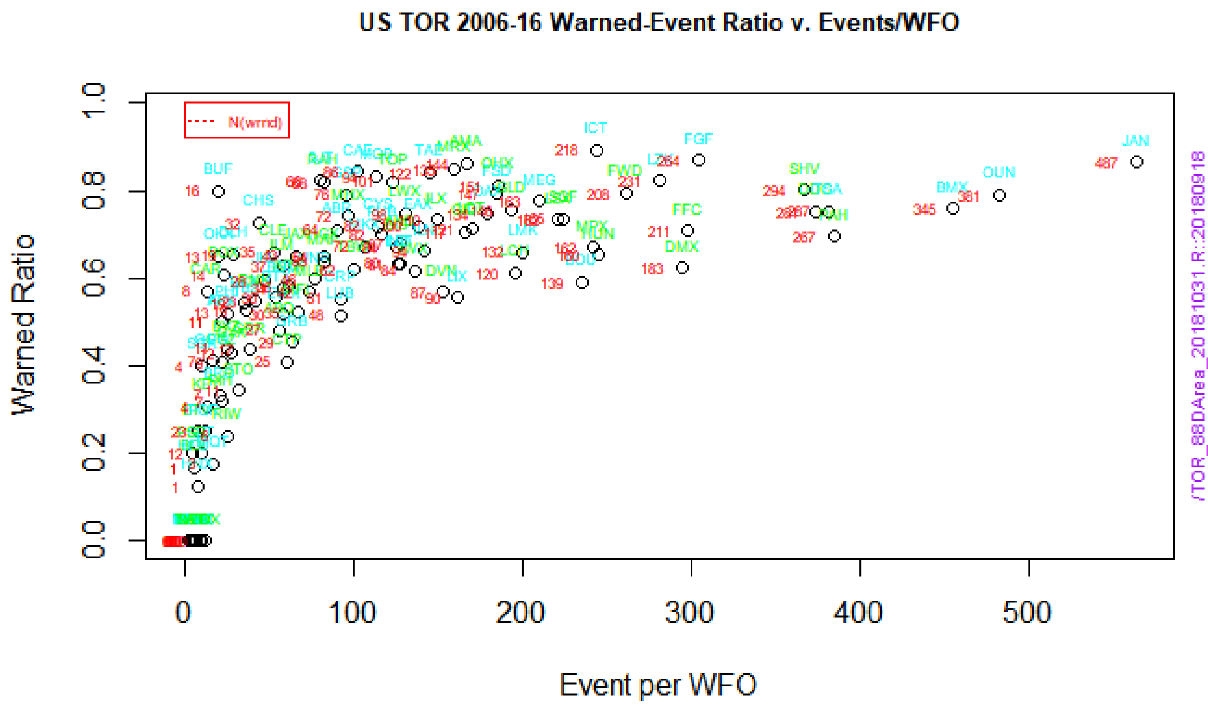


Figure C.6 – **(top panel)** Fraction of warned tornado events for 2006-16 as a function of the relative Weather Forecast Office (WFO) area covered by the 6 kft AGL radar beam. Each circle corresponds to a particular WFO. A linear fit to the data (red dotted line) shows a statistically significant increase (at better than 99%) with more radar coverage with a coefficient of determination near 0.17. **(bottom panel)** Same ratio as a function of the number of events per WFO, with the red value to the left of each point indicating the number of warned events.

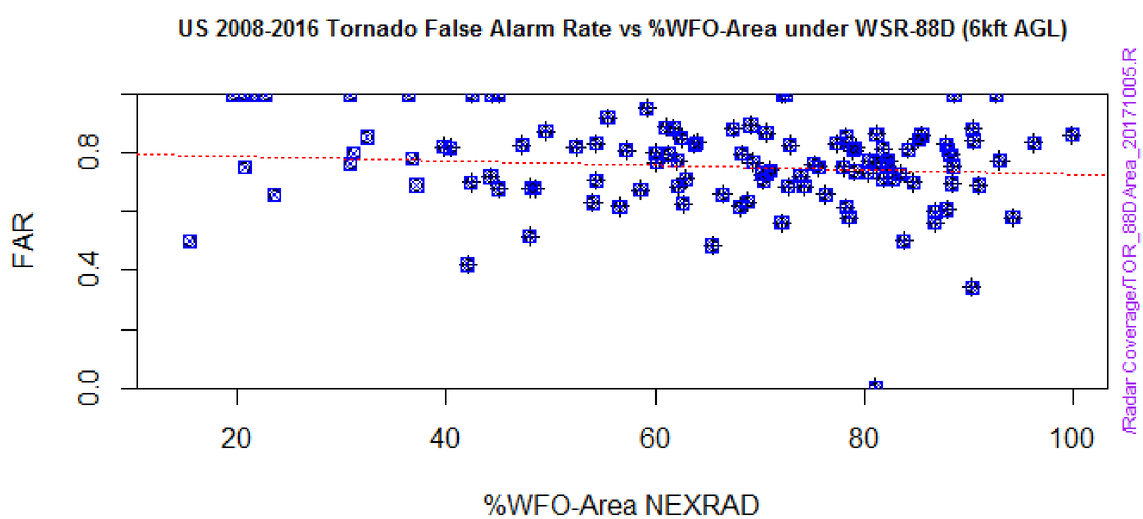


Figure C.7 –Tornado false alarm ratio between 2006 and 2016 as a function of the relative Weather Forecast Office (WFO) area covered by the 6 kft AGL radar beam. Each square corresponds to a particular WFO. A linear fit to the data (red dotted line) has a near-zero coefficient of determination ($R^2 = 0.006$) and is not statistically significant ($p = 0.44$).

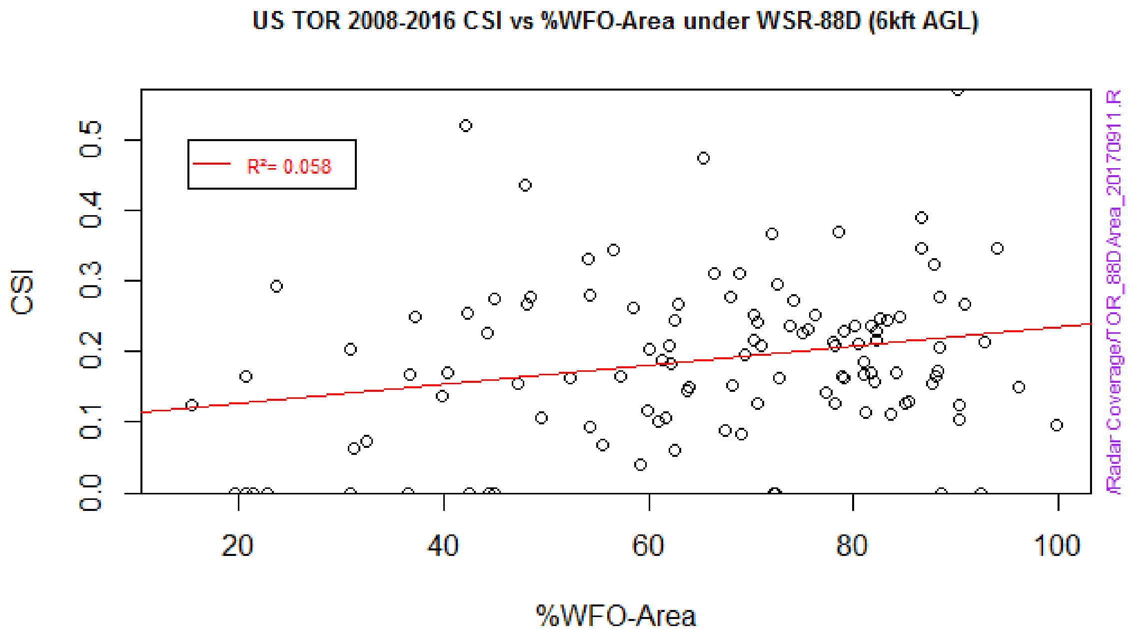


Figure C.8 –Tornado critical success index (CSI) between 2008 and 2016 as a function of the relative Weather Forecast Office (WFO)-area covered by the 6 kft AGL radar beam. Each circle corresponds to a particular WFO. The mean CSI for the sample is zero. CSI is calculated according to current NWS practice. A linear fit to the data (red dotted line) is statistically significant at better than 99%, increasing with more radar coverage with a coefficient of determination (R^2) about 0.06.

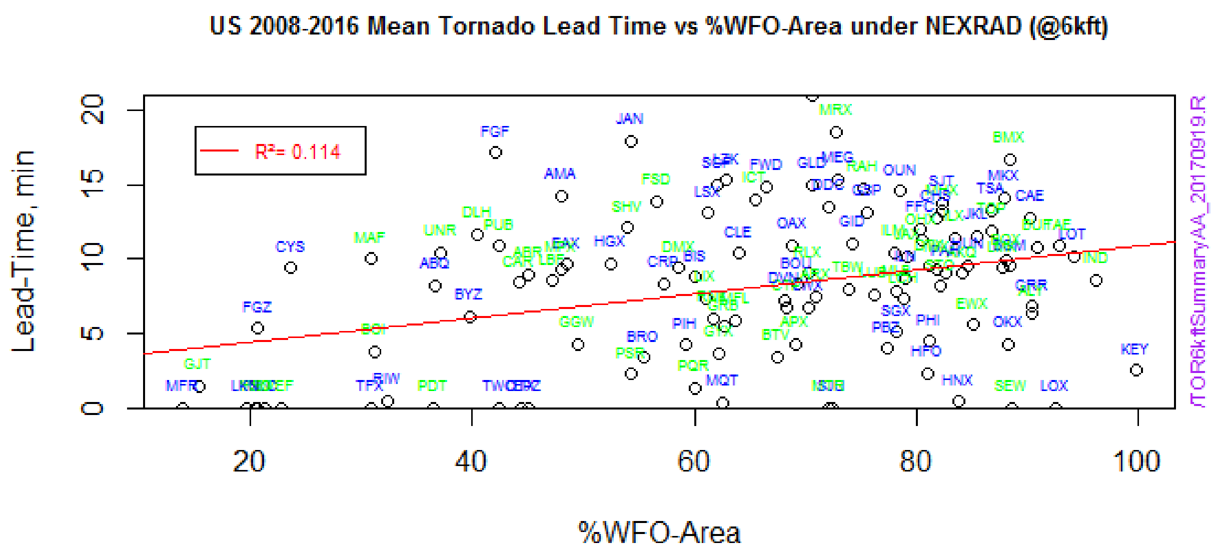


Figure C.9 –Tornado mean warning lead time between 2008 and 2016 as a function of the relative Weather Forecast Office (WFO)-area covered by the 6 kft AGL radar beam. Each circle corresponds to a particular WFO. A linear fit to the data (red dotted line) is statistically significant (at better than 99%) and increases with more radar coverage with a coefficient of determination $R^2 = 0.114$. Mean lead time for the sample is 8 min, median is 9 min. Lead times are calculated using the NWS formulation that includes zero-lead time events. If zero-lead time events are excluded, a statistically insignificant (p=0.14) nearly-flat slope is obtained (not shown).

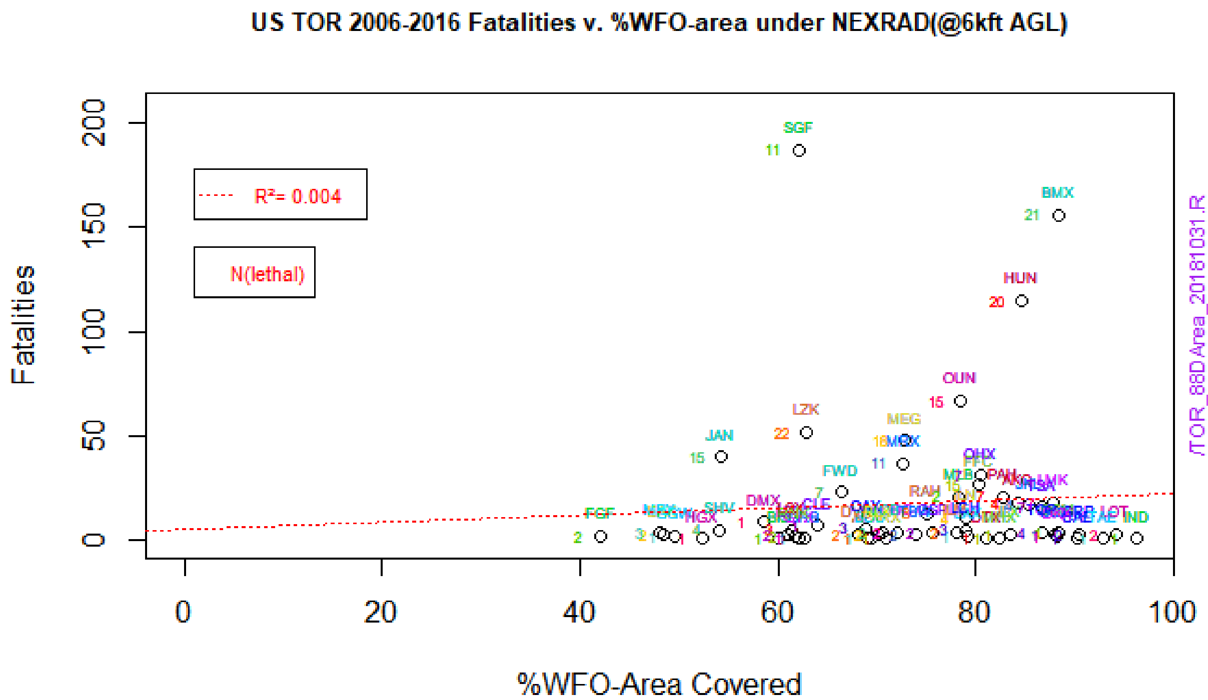


Figure C.10 –Tornado fatalities (1032) for 2006-2016 as a function of the relative Weather Forecast Office (WFO)-area covered by the 6 kft AGL radar beam. Each circle corresponds to a particular WFO. The number to the left of the point corresponds to the number of lethal tornado events at each WFO. A linear fit to the non-zero data (red dotted line) is not statistically significant and has a coefficient of determination $R^2 = 0.026$.

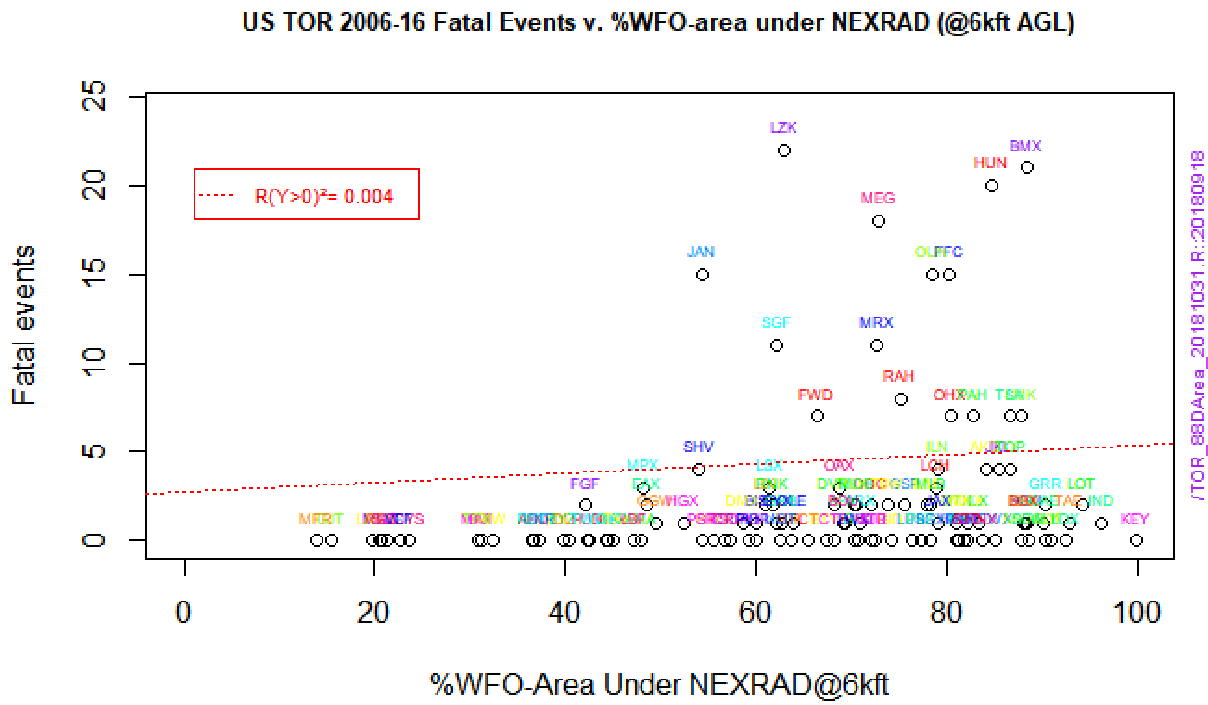


Figure C.11 –Lethal tornado events (271) totaling 1032 fatalities between 2006 and 2016 as a function of the relative Weather Forecast Office (WFO)-area covered by the 6 kft AGL radar beam. Each circle corresponds to a particular WFO. A linear fit to the non-zero events (red dotted line) is not statistically significant and shows a small increase with more radar coverage with a coefficient of determination of $R^2 = 0.04$.

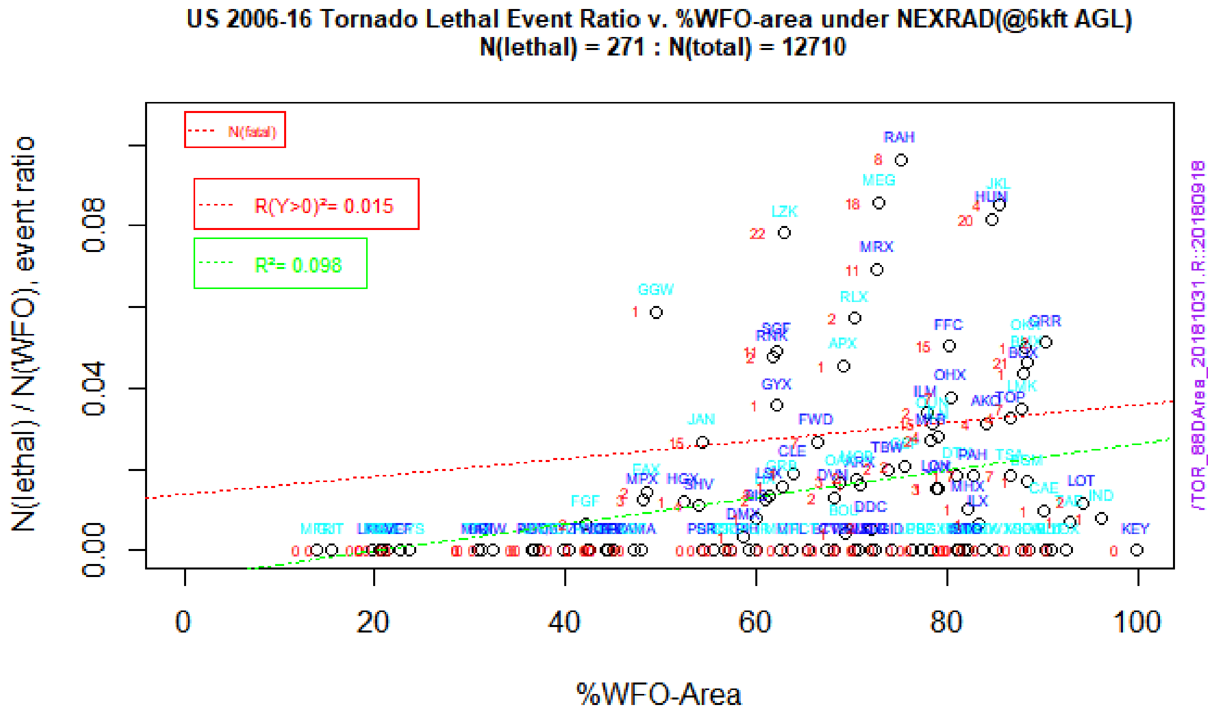
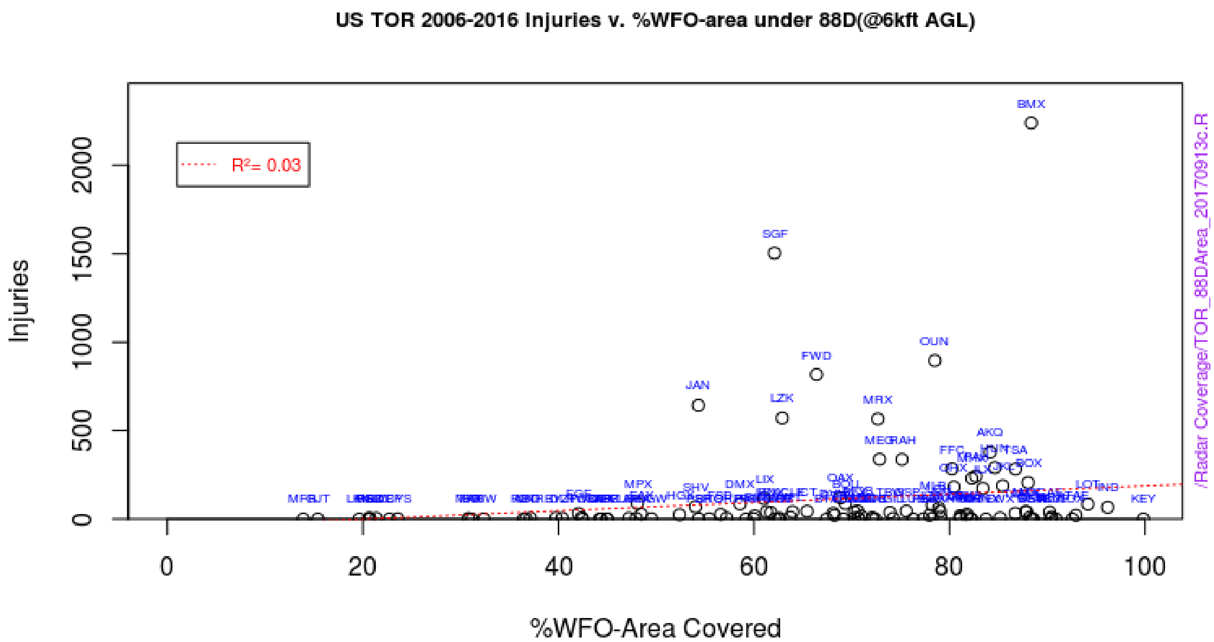


Figure C.12 –Lethal tornado event ratios for 2006-16 in terms of events per Weather Forecast Office (WFO) vs. area covered under the 6 kft AGL radar beam. Each circle corresponds to a particular WFO. The red number to the left is the number of lethal events. A linear fit to the non-zero ratios (red dotted line) is not statistically significant and increases with more radar coverage with a coefficient of determination of $R^2 = 0.015$. A fit to all the ratios (green dotted line) is statistically significant (at better than 99.9%) and has $R^2 = 0.098$.



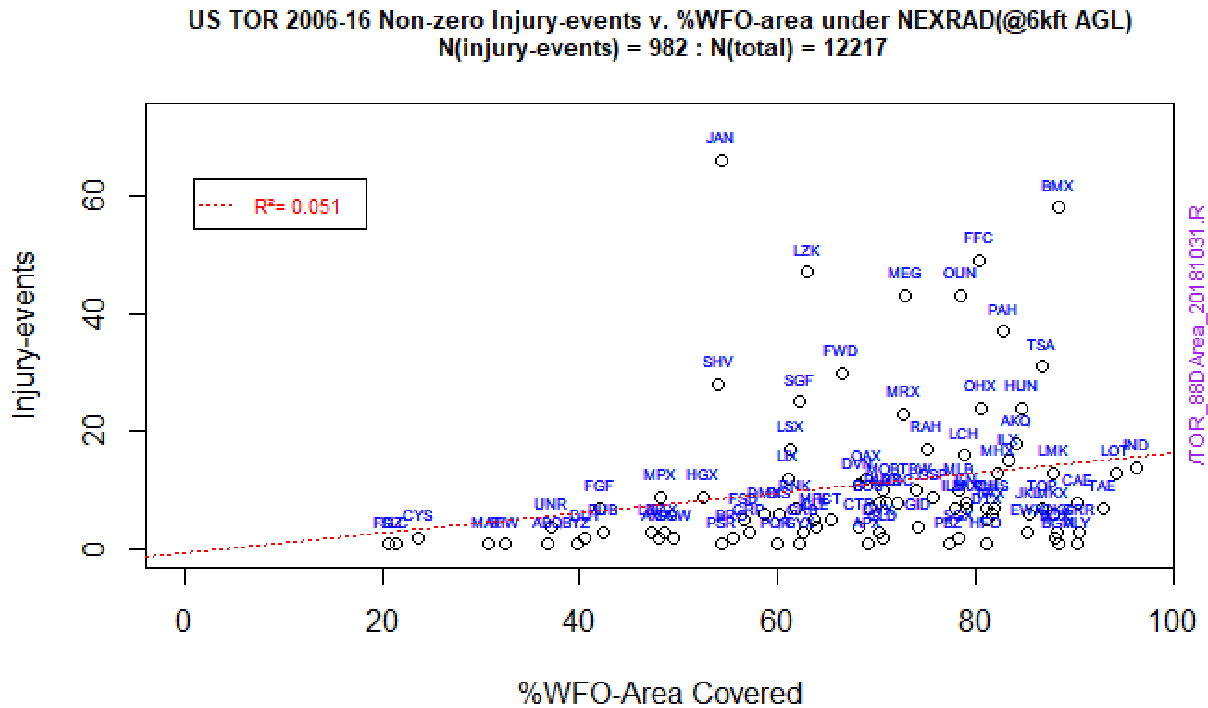
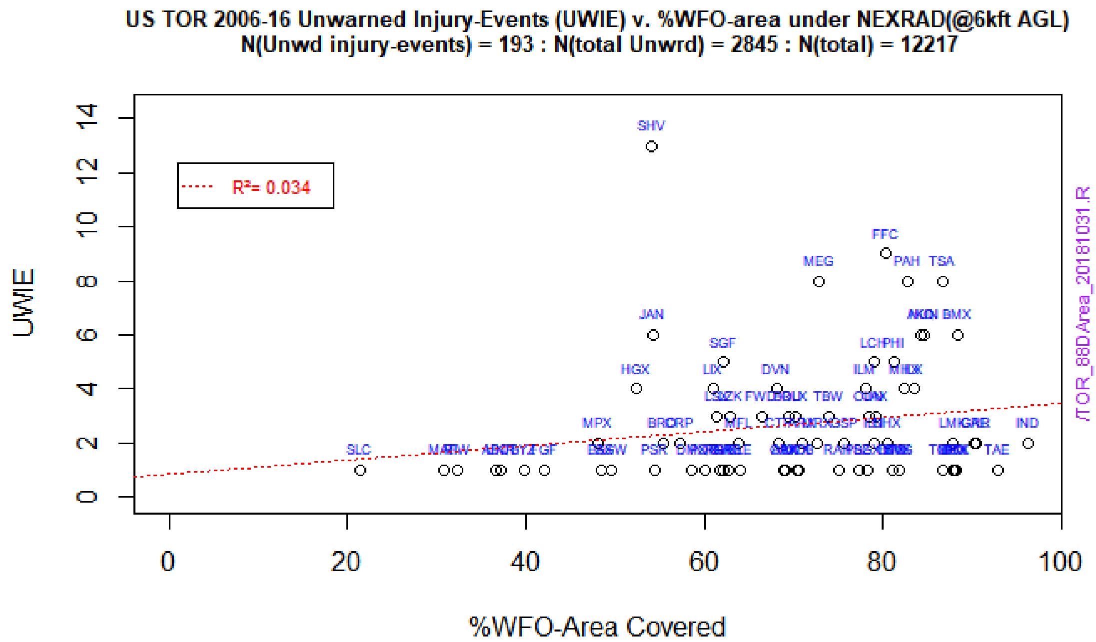
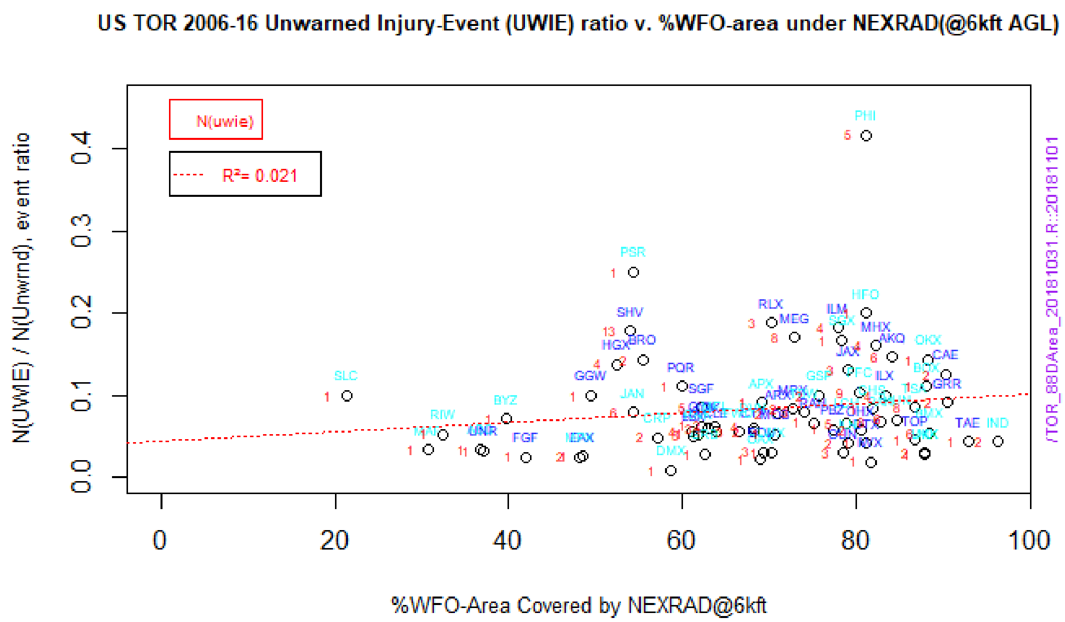


Figure C.13. **(top panel)** Direct and indirect tornado injuries, and **(bottom panel)** non-zero injury-events for 2006-16 as a function of the relative Weather Forecast Office (WFO) area covered by the 6 kft AGL radar beam. There were 982 injury-events out of a sample of 12217. A linear fit to the top plot has marginal statistical significance ($p=0.06$) and a coefficient of determination $R^2 = 0.03$. There were 12226 such injuries in 982 events (7% of all tornado events). Each circle corresponds to a particular WFO. A linear fit to the injury-events (red dotted line) is statistically significant (p = 0.03) and increases with more radar coverage with $R^2 = 0.051$.





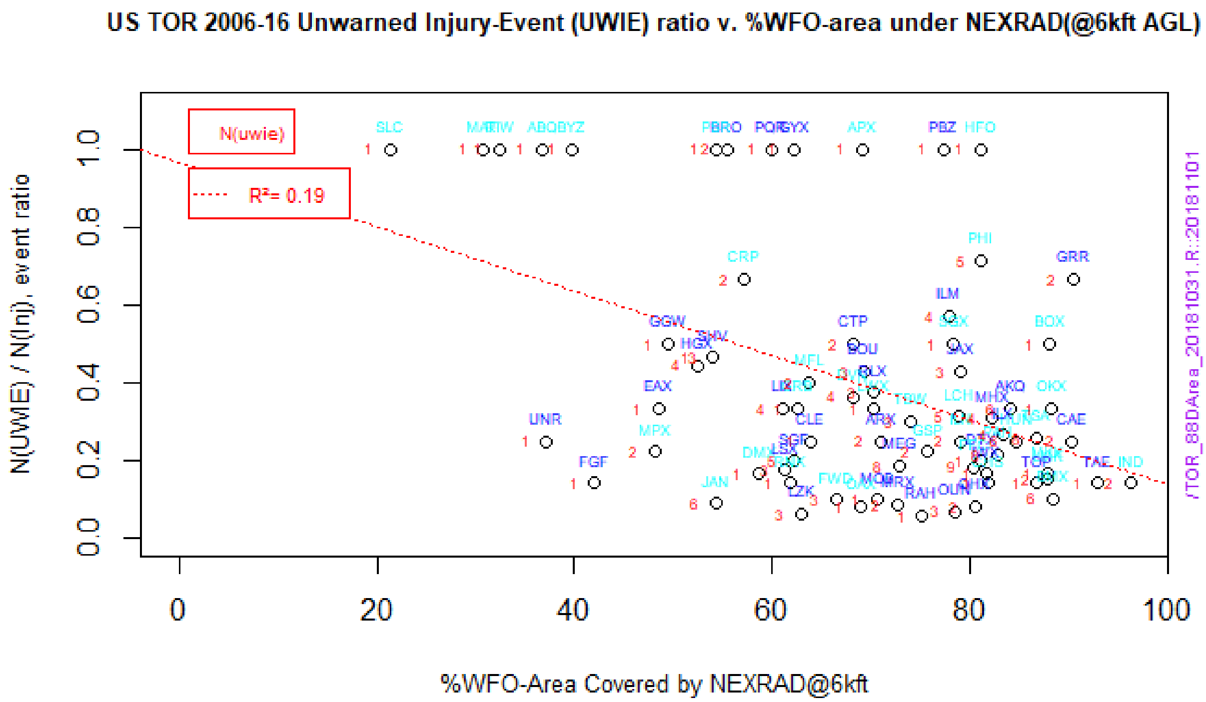
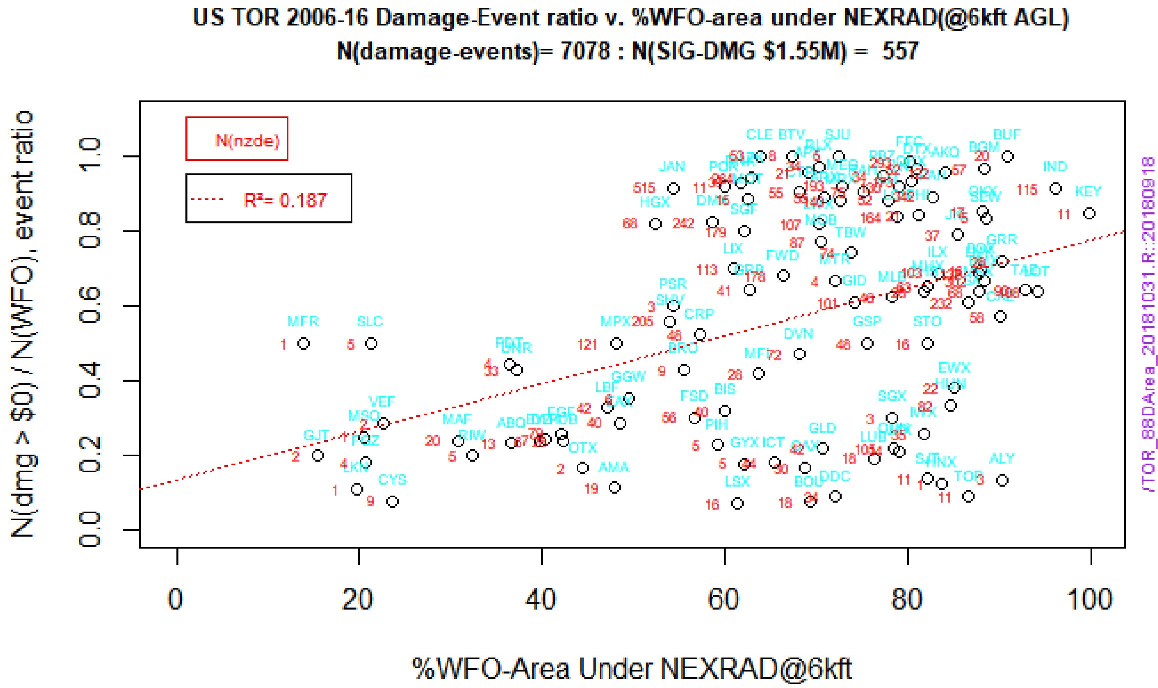


Figure C.14. (top panel) Unwarned tornado injury events (UWIE), **(middle panel)** unwarned injury-event ratio (with respect to unwarned events) and **(bottom panel)** ratio of unwarned injury-events to all injury events for 2006-16 as a function of the relative Weather Forecast Office (WFO)-area covered by the 6 kft AGL radar beam. There were 193 unwarned injury events in 2845 unwarned events (22% of unwarned events out of 12,710 total or less than 1.5% of all events). Each circle corresponds to a particular WFO. A linear fit to the UWIEs (red dotted line) is not statistically significant ($p = 0.2$) and increases with more radar coverage with a coefficient of determination R^2 values of 0.03. The regression to the ratio of UWIEs to unwarned events is not statistically significant either and has a low R^2 =0.02 in the middle panel. The linear fit to the ratio of UWIEs to injury events per WFO is statistically significant at better than the 99% level. The number of unwarned injury events is plotted in red next to each point.



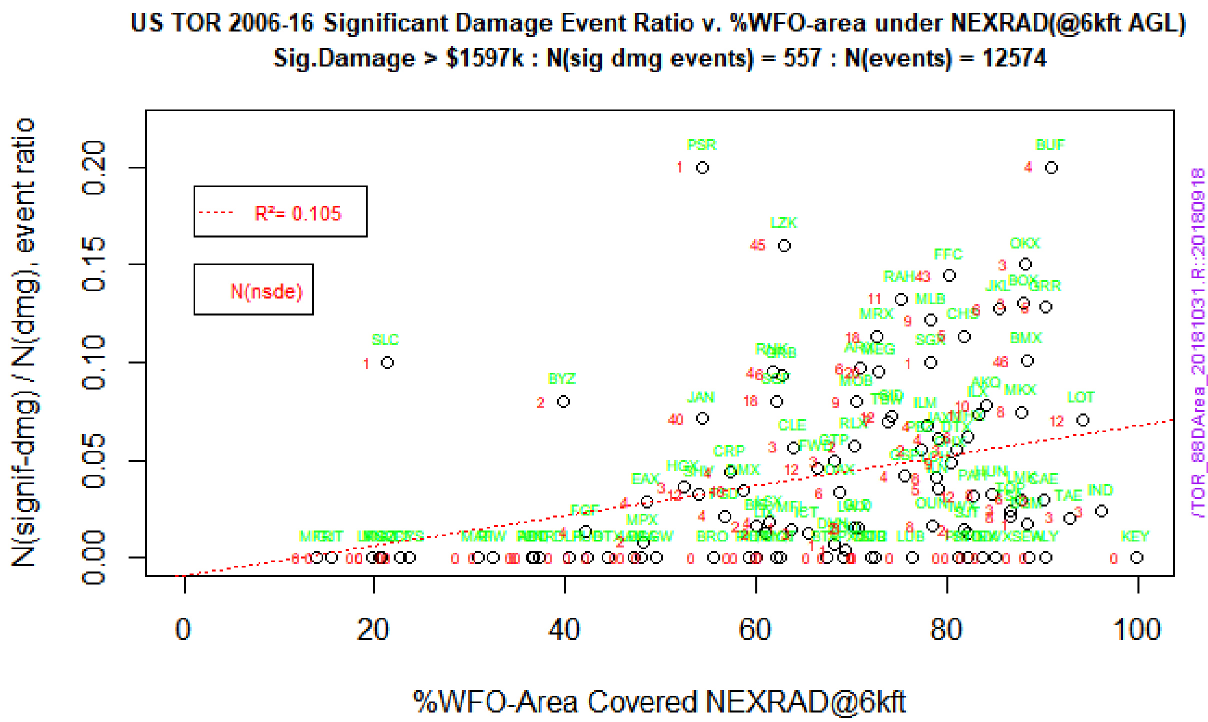


Figure C.15 – **(top)** Fractions of non-zero damage tornado events, and **(bottom)** of significant damage events relative to all events per Weather Forecast Office (WFO) in 2006-16 as a fraction of the surface area covered under the 6 kft AGL radar beam. There were 7078 damage- and 557 significant-damage events out of 12,710, defined as events with damage over the mean of $1.597M/event. Each circle corresponds to a particular WFO. A linear fit to the ratio of non-zero damage events to all WFO events (red dotted line, top panel) is statistically significant at better than 99% and increases with more coverage with fit R^2 values of 0.187. The linear fit to the ratio of significant damage to all damage events per WFO (bottom plot) is also statistically significant at better than 99% with coefficient of determination of 0.1. The red numbers indicate the event counts associated with each WFO: nonzero damage events, N(nzde), in the top panel and the number of significant damage events N(nsde) at the bottom panel.

Appendix D - Operational Considerations in NWS Warning and Forecasting of High Impact Weather (Tornadoes) and Non-NEXRAD Data Sources

[**Writers:** AFS/Greg Schoor]

Tornado Warnings Begin with Forecasting:
In most cases, the decision-making process behind Tornado Warnings (TOR) issued by meteorologists in local NWS offices begins well before a thunderstorm forms. The process typically begins within a few days before the event, through the forecasting efforts of the NWS NCEP Storm Prediction Center (SPC) which issues probabilistic and categorical risk-related thunderstorm outlooks on a national-scale, up to 8 days in advance. The information can be localized to a particular NWS office which may have varying levels of risk on a certain day from one end of their area of responsibility to the other. The desired effect is a continuous stream of well-coordinated forecast information between SPC, WFOs, and the recipients of the message before and during a severe weather event. Even just a few hours before the start of an event, forecasters at SPC and the WFOs continue to be refined, as newer forecast guidance arrives, based on updated weather observations.

Forecast Coordination Before High-Impact Events:
In the hours-scale before a severe weather event occurs, SPC alerts large areas (e.g. entire states or portions of states within a singular regional-sized area) by issuing Severe Thunderstorm and/or Tornado Watches. These types of alerts are meant for broad socialization of the forecast risk for this type of weather to occur within the Watch area and valid time, so that preparations can be made and ready for execution, should a thunderstorm present localized severe impacts, like a tornado, or a combination of large hail and damaging winds. No two severe weather episodes or even storms are the same and severe weather can occur anywhere, any time of the year. Effective collaboration between the national center (SPC) that issues the official forecast information and affected NWS offices that issue the official warning information, is key to a successful communication of the severe weather threats in a fast-evolving, high-impact event and provides a more holistic depiction of how a forecaster is led to issuing a Tornado Warning with more background information than just real-time radar data.

Severe Thunderstorm Interrogation:
Warning meteorologists at local NWS offices determine severity of thunderstorms through the visual "interrogation" of individual cells visible from radar data, NEXRAD WSR-88D Radar being the primary tool. Even at the storm-scale, warning meteorologists work to get a full picture of the potential threats, ideally from multiple available data sources. Radar data is the primary tool for warning meteorologists to investigate a thunderstorm from top to bottom (forward and backward in time) watching the trends of each thunderstorm cell. Aggregating these scans together gives the meteorologist a general picture of the thunderstorm's anatomy and potential for severe impacts. Radar data provide a finite number of "characteristics" of the targets within a thunderstorm cell (e.g. raindrops and hail), like how reflective raindrops are and how fast they are moving. Decades of research and operational usage of radar data have yielded well known signatures for a variety of hazardous weather, providing at times 10s of minutes of lead time prior to impacts at the ground. Satellite and lightning detection systems can provide additional thunderstorm characteristics, like initiation of the cloud, growth/evolution of

thunderstorm tops, and characteristics of lightning (e.g. flash rate). Lightning detection, in particular, is independently obtained, radar is not required. Additionally, computer algorithms use the base data from these sources to quantify specific elements of thunderstorms are available for both radar data, satellite, and a fusion of the two that add to the fuller picture of thunderstorm severity in the mind of a warning meteorologist.

Tornado-Producing Thunderstorm Modes:
Tornadoes are a unique meteorological phenomenon that span a wide range of atmospheric "turbulent eddies" or rotating columns of air. On the lowest end of intensity spectrum, there are dust devils, landspouts, and gustnadoes with wind speeds well under "severe" wind criteria. Although rare, the most powerful of tornadoes can grow to be over 2 miles wide and contain wind speeds over 300 mph, while a vast majority of tornadoes are short-lived and reside on weakest end of the intensity spectrum. Many of the strongest tornadoes develop within large thunderstorms, called "supercells" that contain a rotating updraft and the classic "hook" feature that is normally well-represented in radar data, although not all supercells produce tornadoes and not all strong tornadoes develop from supercells. Adding to this challenge, a large percentage of yearly tornadoes, primarily those in the Midwest, appear within squall lines, otherwise known as Quasi-Linear Convective Systems (QLCS). A QLCS can produce mesovortices that may lead to a brief tornado and normally multiple brief intermittent tornadoes along the leading edge of the forward-propagating line. These tornadoes are typically known for their quick "spin-in" nature, meaning that they usually form from the bottom of the cloud, skyward, as opposed to most other tornadoes that descend from the base of a cloud. QLCS mesovortex tornadoes are usually short-lived, 1 to 5 minutes typically, and also contain wind speeds on the order of a marginally-severe thunderstorm. Minor roof damage (displaced shingles), downed large tree limbs, downed small trees, and/or other minor property damage such as broken fence lines, are common with these types of tornadoes with the damage path length around 2 to 4 miles, on average. On radar, these tornadoes usually form with limited precursor evidence and are challenging to spot as they are usually wrapped in heavy rain and/or hail and may fall in between scans or be too far away from the radar, as the velocity structure will only be visible up to around 5 kft AGL.

Outside of supercell thunderstorms and squall lines, tornadoes also develop out of unconventional thunderstorm types, adding to the overall challenges for NWS warning meteorologists. Throughout the summer months, tornadoes form nearly anywhere across the country in relatively weak and disorganized thunderstorm activity. These tornadoes can form from subtle features not easily forecasted even minutes in advance because of their quick evolution and limits in detectability. Tornadoes that form from landfalling tropical cyclones also present challenges for NWS warning meteorologists not only with detection but communication since the main threat focus is on the tropical system and its multiple other associated hazards. Areas near and along the coast of the Southeastern US are particularly prone to these types of tornadoes, not only from landfalling tropical cyclones but in the "cool season" (winter) months.

Tornado Warning Performance Overview:
At its core, a Tornado Warning issued by the NWS is a forecast of an imminent threat that can either be deduced from data sources, such as radar, or credible visual reports. In the absence of credible visual reports, NWS warning meteorologists must rely on remotely-sensed data sources, like radar. Limitations in these data sources can elevate the challenges that are inherent with

such a complex phenomenon. The normally lower-end intensity tornadoes do not exhibit the same precursor signals or features in radar data that tornadoes typically do in more organized thunderstorms, like supercells, and can also occur in a relatively shallow portion of the thunderstorm which may be missed by the radar if the storm is too far away.

More Options Possible with the Same Radar:

Over the past several years, the WSR-88D radars have had critical enhancements that have provided NWS warning meteorologists with more data for use in real-time fast-paced decision-making scenarios. In the late 2000s, higher-resolution versions of both of the staple radar base products, reflectivity and velocity, provided a better visualization of thunderstorm cells, right down to the portion of a thunderstorm that may contain a tornadic signature. Additional enhancements within the past few years have decreased the amount of time for a full volume scan. Before these enhancements, NWS warning meteorologists had to wait nearly a full 5 minutes before receiving updates from the radar. Now, there are a number of choices available to radar operators that allow for updates at certain scanning angles to appear nearly every minute. There are still some trade-offs in terms of slower updates for the upper-level tilts, if a choice is made for more low-level tilts, but now these decisions are in the hands of the experts in the field who are charged with the protection of lives and property within the NWS.

NWS forecast offices that have access to a nearby TDWR have the benefits of 1-minute lowest tilt scan updates, fine-scale resolution for the Reflectivity and Velocity products, and a varied vertical scanning strategy from the WSR-88Ds to potentially fill-in some vertical interrogation gaps, should the storm(s) be close enough to the radar. The tradeoff however, is that for higher-resolution products, the WSR-88D range is just under twice the distance from the radar than the TDWR, so WSR-88Ds can provide higher-resolution products at longer ranges. There is also the knowledge that WSR-88Ds are more powerful than TDWRs and are therefore less subject to attenuation (reduction in signal strength) due to rain or water vapor, which is essentially the scrambling of the reflectivity signal either when it is raining on the radar or the radar is attempting to scan through an intense storm to see a storm on the other side and does not have enough power to identify it properly. NWS warning meteorologists are trained on these topics, the advantages and disadvantages associated with each, the tradeoffs, and any enhancements or additions to the radar networks.

Trusted Sources for Tornado Warning Decision-Making

NWS offices surveyed under NOAA Observing System Integrated Analysis (NOSIA - https://nosc.noaa.gov/tpio/) indicate that the primary interrogation tool utilized in warning operations is the WSR-88D by about a 3 to 1 margin compared with TDWRs. Only about one-third of NWS offices have access to a TDWR and even fewer have access to multiple TDWRs (some of the larger metropolitan areas with multiple high-traffic airports or military bases). Closely following the contribution from TDWRs is "on-the-ground" reporting from spotters trained through the NWS-sponsored SKYWARN® network, and volunteers across the country trained by NWS employees to report specific weather conditions and phenomena to their local NWS office. Data from the GOES-series of satellites have always been used by NWS warning meteorologists for elements of the warning process, such as early-stage thunderstorm growth/late-stage decay, intensification/dissipation, and low-level boundary detection. Even with the enhanced products and increased temporal resolution from GOES-16, satellite data provides forecasters with visualizations of cloud-top characteristics but little information about the contents of the cloud, from the base to the anvil. Therefore, satellite data can only provide supplemental information that may be used to generally connect or assert that a specific thunderstorm-related phenomenon will occur based on this data but not be able to detect it. Together, satellite and radar data provide gap-filling information that the other cannot supply and work well together in a complimentary format in the warning decision-making process. In recent years, with the advent of social media accounts for individual NWS offices (Facebook and Twitter), there have been an increasing number of real-time reports (in message form or in pictures with captions) for all severe weather, particularly tornadoes and funnel clouds, that offices will receive and corroborate with other data, such as radar and surface observations, to validate the reports. Despite this and other sources of information, radar data and WSR-88D data in-particular, continues to dominate all other information sources to support the warning decision-making process.

The State of Tornado Science and Technology:
In terms of the weaker, short-lived tornadoes that form out of disorganized thunderstorms, giving warning forecasters more data has not necessarily led to increased lead times for Tornado Warnings. A vast majority of these tornadoes impact the surface for an average only a couple of minutes, causing relatively minor damage (the median is $50k/event and accounts of 44% of non-zero-damage events, well below the mean of $1.5M/event) and even less damage than nearby downburst thunderstorm wind gusts. There is ongoing research to characterize aspects of lightning (density, flash rates, etc.) and even rapidly updating satellite imagery (of thunderstorm cloud tops) in addition to fast weather scanning with phased array radar (e.g., http://journals.ametsoc.org/doi/pdf/10.1175/WAF-D-14-00042.1). There are instances where this information may add a few minutes to the pre-tornado signals but more research should be done to determine the whether this is the case across all convective modes, times of year, and areas of the country.

Appendix E – NWS Flash Flood Warning Performance Inside and Outside Areas of NEXRAD Radar Coverage

[Writers: AFS/Abshire, STIO Meléndez, AFSO Mullusky; NSSL/Martinaitis, Howard]

This appendix examines national warning performance of flash flood events as a function of radar coverage. Radar coverage is defined similarly to that for the tornado analysis (see Appendix B for full methodology and Appendix A for a discussion on previous radar coverage studies, especially as they relate to tornado warning performance), with the addition of a category for flash flood event polygons which "cross" the area of radar coverage, that is, that the geospatial analysis indicated the event may partially be within the area of radar coverage and may partially lie outside. The analysis herein takes into account all flash flood events between 2008 and 2016, a time period which encompasses NWS-wide use of polygon-based flash flood warnings instead of county-based warnings.

The geospatial analysis (GIS) was completed by comparing the location of the NWS flash flood event polygons to that of the radar coverage. The first step was to select the event polygons which fell completely within the radar coverage polygons. A new file was exported which only included these event polygons completely within the radar coverage polygons. A switch selection was then performed to select the event polygons that were either completely or partially outside radar coverage which was exported to create an intermediate file for the remainder of the GIS analysis. From this file the polygons which intersected the radar coverage polygons were selected and exported as a file to indicate warnings that crossed the radar coverage files. Finally the selection of the intersecting files in the intermediate warning file was switched and the new selection was exported to create a file of warning that were completely outside of radar coverage. The event files were then subdivided by their warned (yes or no) attribute to create the 6 final files and counts - warned within radar, warned outside of radar, warned crossed radar, unwarned, within radar, unwarned outside of radar and unwarned crossed radar.

Warning Performance and Relationship to Radar Coverage

Overall, most events, fatalities, and damages occur within NWS warning polygons, whether within, outside, or crossing areas covered by radar, at similar proportions, as shown in Figures E.1--E.4. The only exception is for unwarned injuries, as illustrated by Figure E.3. More than 80% of all events, fatalities, and damages are warned, regardless of radar coverage. A similar or greater warned proportion is observed for injuries inside or crossing radar coverage, however, only 40% of injuries occurring outside radar coverage are warned. It is important to note that flash flood injury statistics during this time period are dominated by a single flash flood outbreak in Oklahoma which injured 136 people. With the already small sample size (only 484 total injuries from 2008-2016), and more than 25% of all injuries during this single event, the role of radar coverage and injury events is complicated.

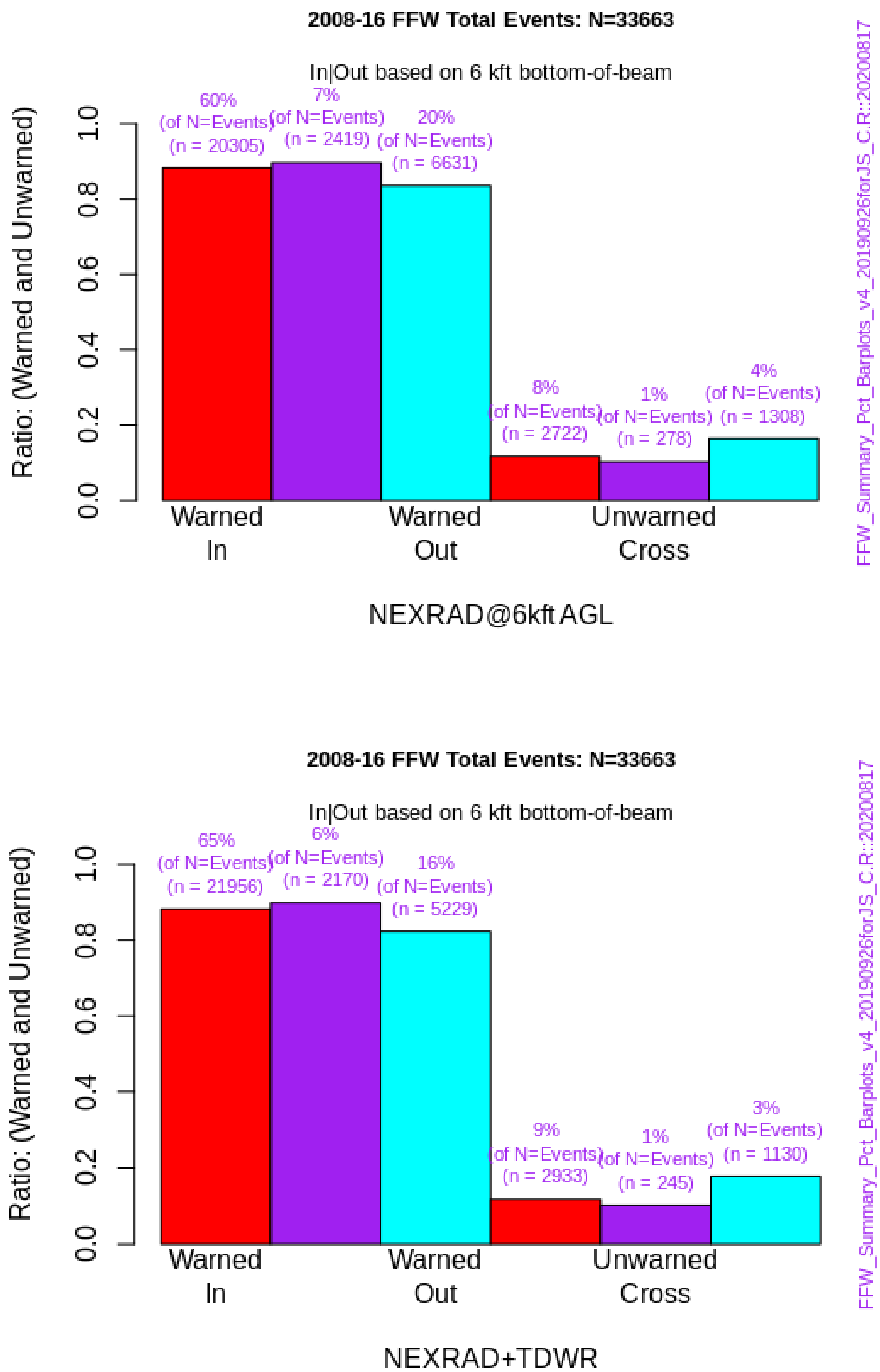


Figure E.1 – Flash flood events from 2008 to 2016 by warned or unwarned status within, outside of, or crossing radar coverage provided by (a) WSR-88D only and (b) WSR-88D plus TDWR. Regardless of radar coverage, more than 80% of all events are warned. For (a), the fraction of events warned inside is 88.2% while the fraction of events warned outside is 83.5%. The fraction unwarned inside is 11.8% while that unwarned outside is 16.5%. For (b), the fraction warned inside is 88.2% while that warned outside is 82.2%. The fraction unwarned inside is 11.8% while that for unwarned outside is 17.8%.

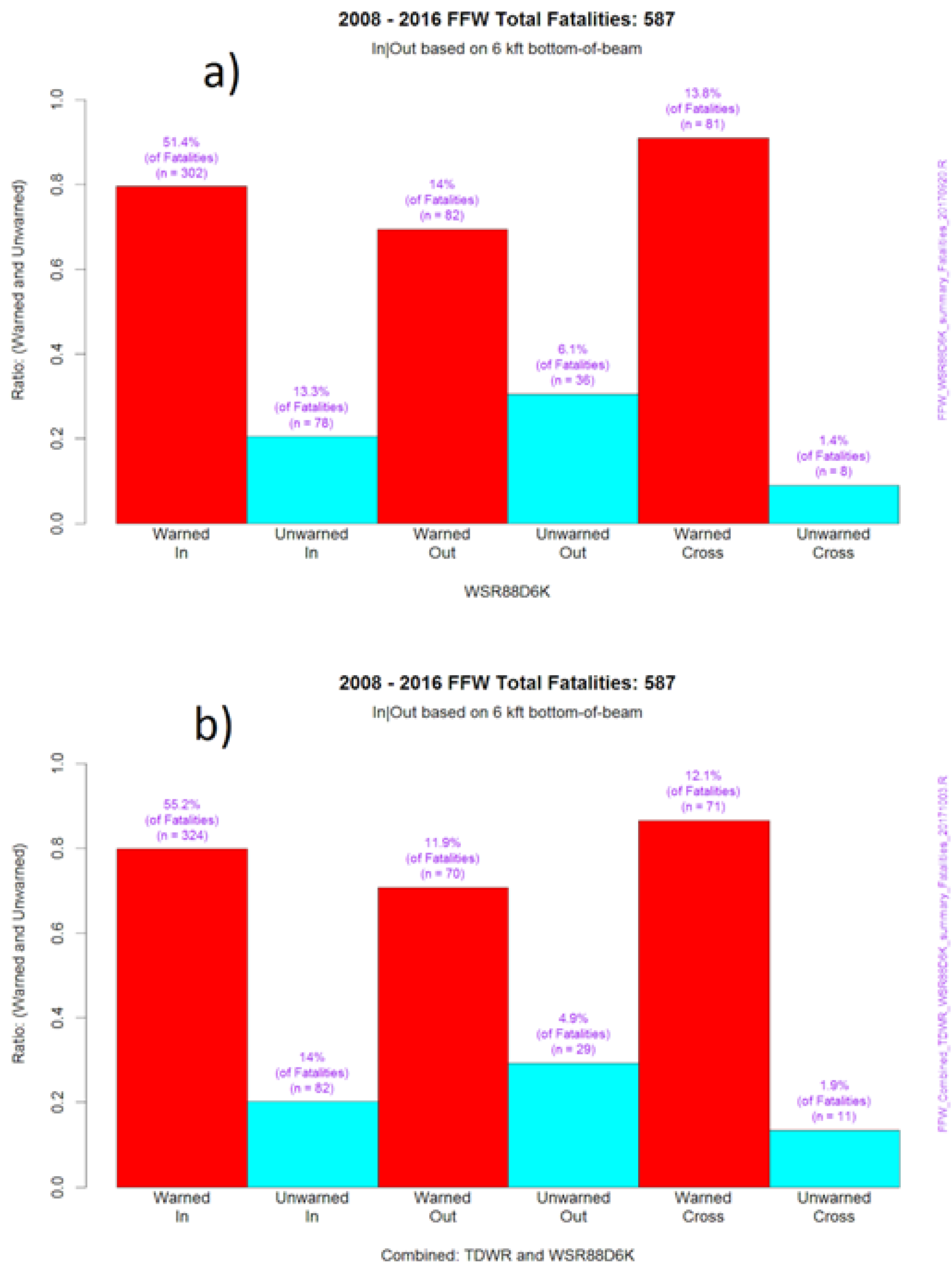


Figure E.2 – Flash flood-related fatalities (587) from 2008 to 2016 by warned or unwarned status within, outside of, or crossing radar coverage provided by (a) WSR-88D only and (b) WSR-88D plus TDWR. Regardless of radar coverage, more than 80% of all fatalities occur during warned events. For (a), the fraction of fatal events warned inside is 79% while the fraction of events warned outside is 69%. The fraction unwarned inside is 21% while that unwarned outside is 31%. For (b), the fraction warned inside is 80% while that warned outside is 71%. The fraction unwarned inside is 20% while that for unwarned outside is 20%.

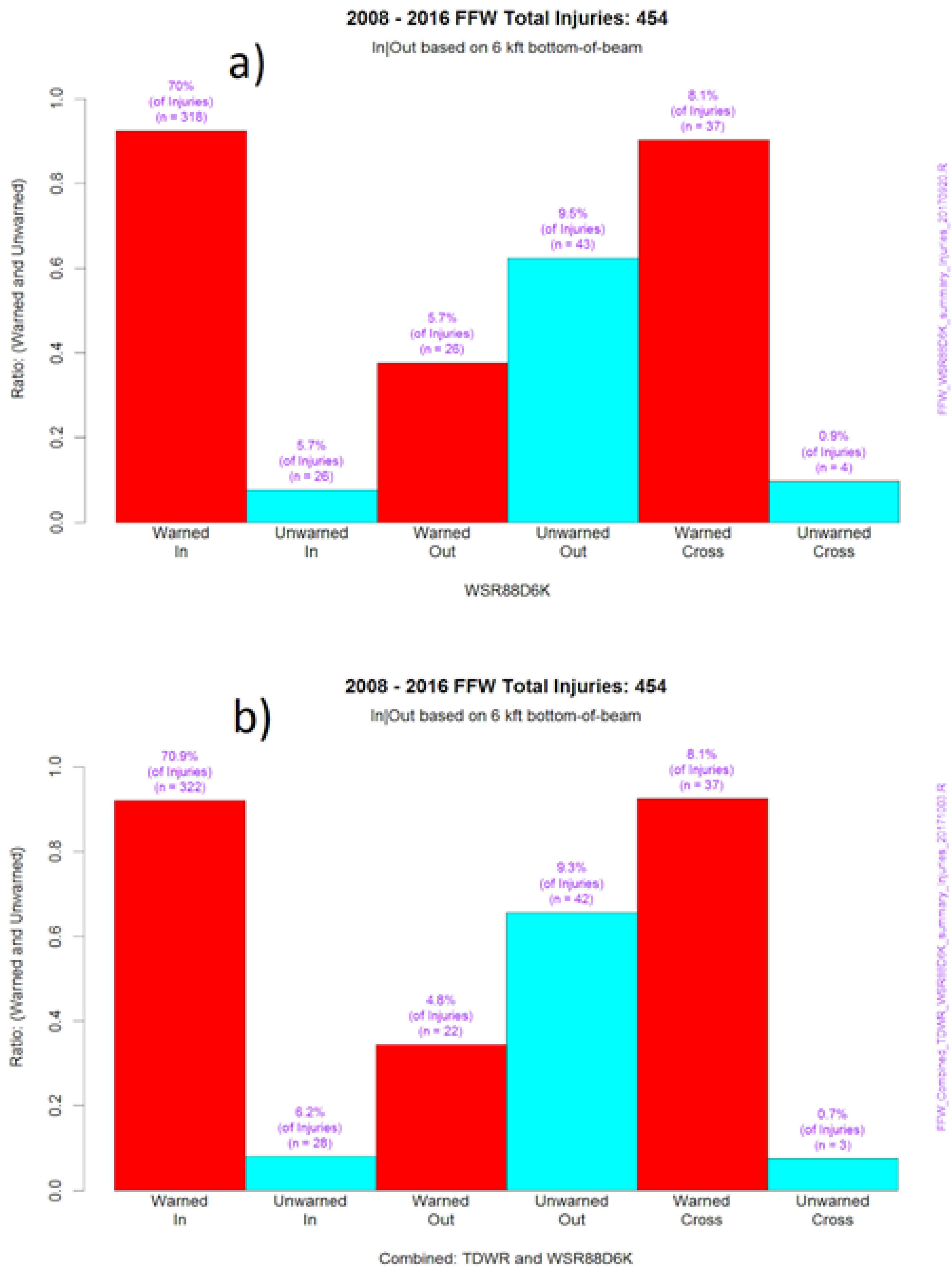


Figure E.3 – Flash flood-related injuries (454) from 2008 to 2016 by warned or unwarned status within, outside of, or crossing radar coverage provided by (a) NEXRAD only and (b) NEXRAD plus TDWR. For injuries that occurred within radar coverage or in in areas at the transition between radar coverage and no coverage, more than 80% of all injuries occur during warned events. Proportion between warned and unwarned fatalities changes very little between the coverage provided by WSR-88D only and the additional coverage provided by taking TDWR into account. For (a), the fraction of injury events warned inside is 92% while that warned outside is 38%. The fraction unwarned inside is 8% while that for unwarned outside is 62%. For (b), the fraction of injury events warned inside is 92% while the fraction of events warned outside is 34%. The fraction unwarned inside is 8% while that unwarned outside is 66%.

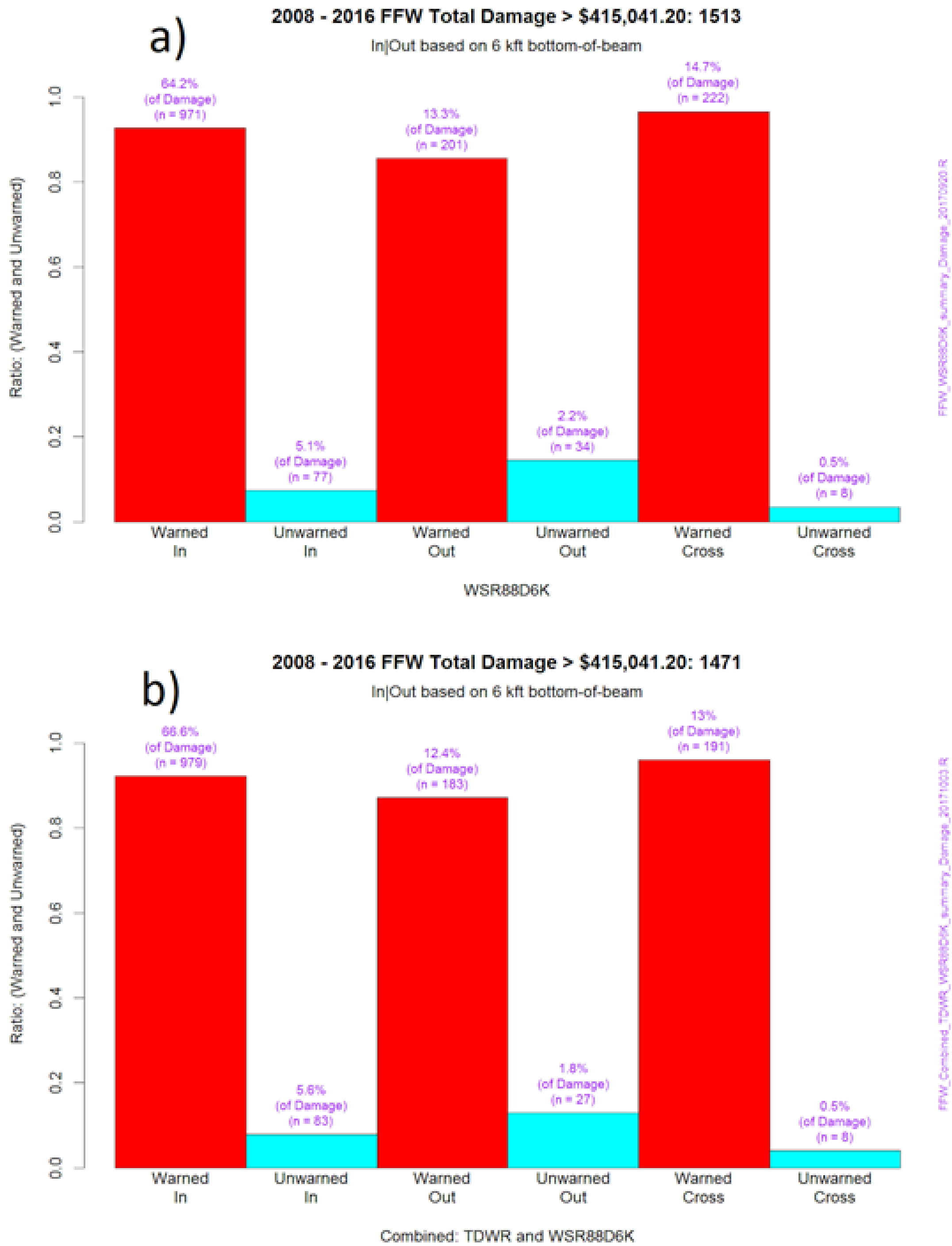


Figure E.4 – Flash flood-related damages from 2008 to 2016 by warned or unwarned status within, outside of, or crossing radar coverage provided by (a) WSR-88D only and (b) WSR-88D plus TDWR. Regardless of radar coverage, more than 80% of all damages occur during warned events. For (a), the fraction of significant damage events warned inside is 93% while that warned outside is 86%. The fraction unwarned inside is 7% while that for unwarned outside is 14%. For (b), the fraction of significant damage events warned inside is 92% while the fraction of events warned outside is 87%. The fraction unwarned inside is 8% while that unwarned outside is 13%. There were 1471 significant damage events.

Verification Statistics and Relationship to Radar Coverage

Traditional flash flood verification statistics considered herein (probability of detection, false alarm ratio, critical skill score, and mean lead time) are defined similarly to those for tornados; however, new metrics are deployed to analyze performance. See Appendix C for a full discussion of these metrics.

The full set of these metrics were calculated by WFO and compared to the percent of WFO area covered by the 6 kft AGL radar beam for each office. Probability of detection as expressed by warned event ratio (Figure E.5), critical success index (Figure E.7), and mean lead time (Figure E.8) all increase with more WFO radar coverage. There is a corresponding decrease in false alarm rate with increasing radar coverage (Figure E.6). That is to say, there is a positive slope showing fewer false alarms for WFOs with more radar coverage (unlike the tornado FAR discussed in Appendix C). While the coefficient of determination is not very high, it does suggest some positive relationship between flash flood verification statistics and radar coverage, and is one of the highest.

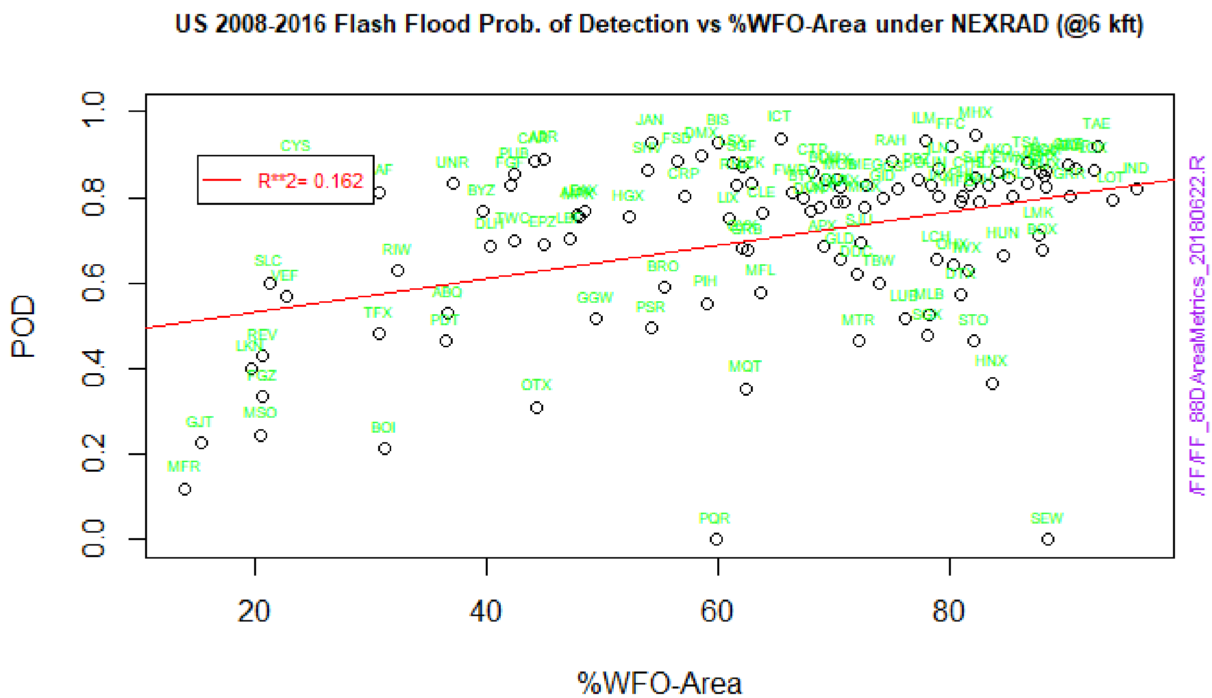


Figure E.5 – Fraction of warned flash flood events reported between 2008 and 2016 as a function of the percent WFO area covered by radar. The probability of detecting a flash flood event increases with more radar WFO area coverage with a statistically significant fit (better than 99% level). WFO identifiers can be found in Appendix S.

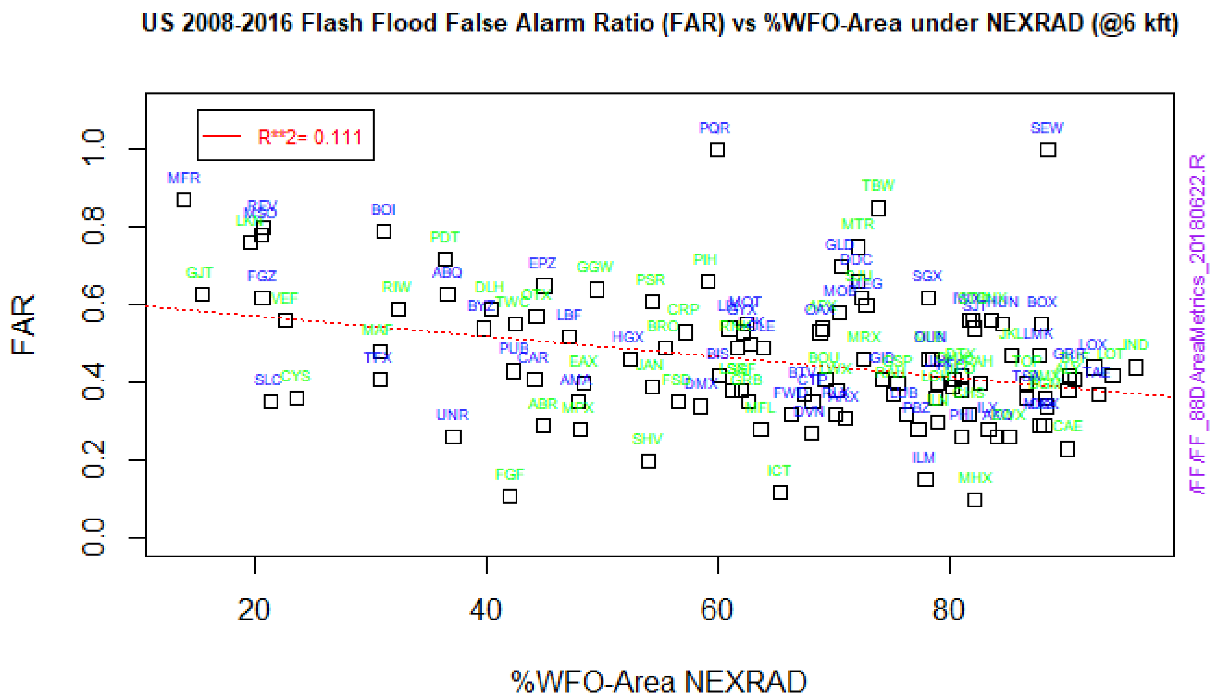


Figure E.6 – False alarm rate of flash flood events reported between 2008 and 2016 as a function of the percent WFO area covered by radar. False alarm rate is somewhat negatively correlated with increasing percent WFO area covered by radar. The linear fit is statistically significant at better than the 99% level with a coefficient of determination of 0.11.

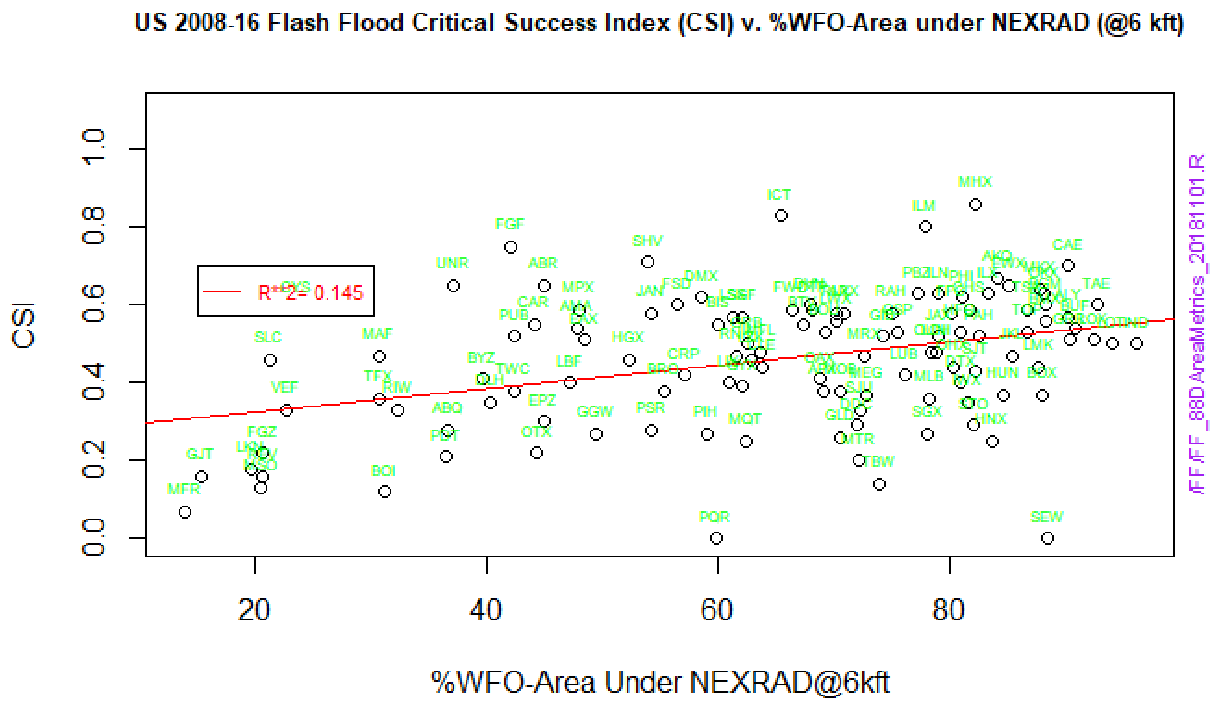


Figure E.7 – Critical success index of flash flood events reported between 2008 and 2016 as a function of the percent WFO area covered by radar. The critical success index is positively correlated with a statistically significant fit (> 99% level) increasing with percentage WFO area covered by radar with a coefficient of determination of 0.145.

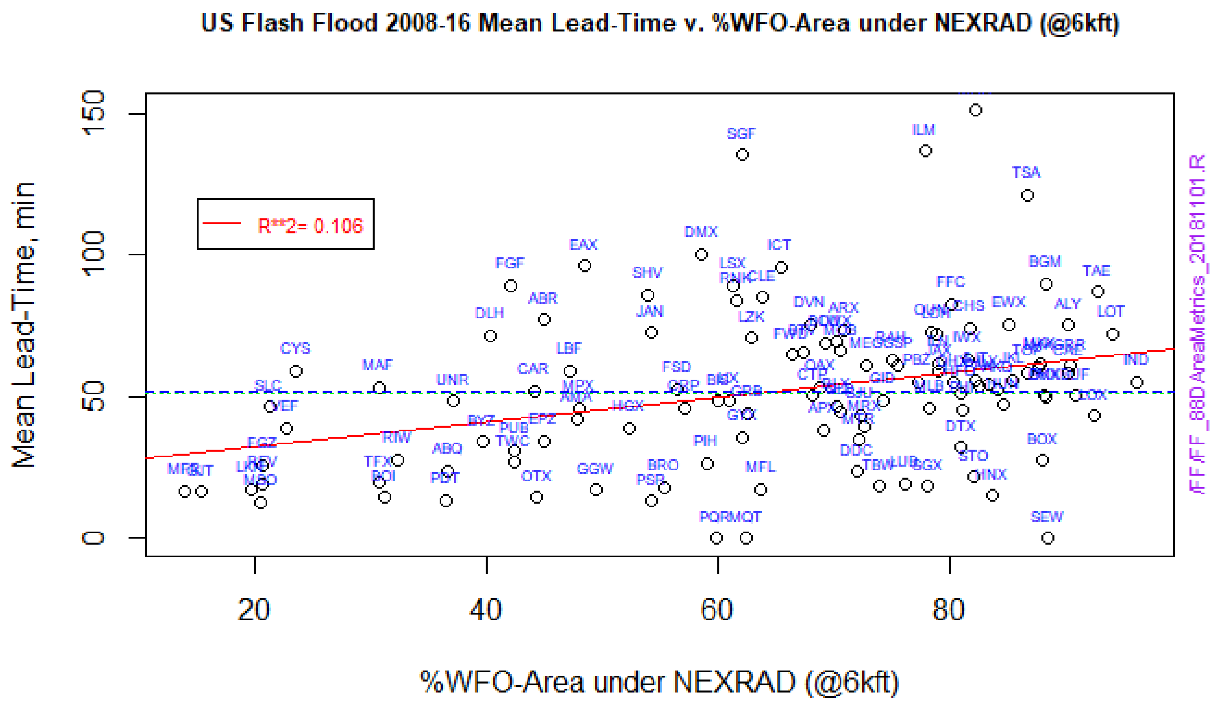


Figure E.8 – Mean lead time of flash flood events reported from 2008 through 2016 as a function of the percent WFO area covered by radar. Mean lead time increases with radar coverage in a statistically significant linear fit. The green line is the median and mean lead time of 52 min.

Probability of detection, as expressed by warned event ratio, was calculated by state and the percent of each state covered by radar as previously defined (Figure E.9). The higher coefficient of determination again indicates a positive relationship between flash flood probability of detection and radar coverage, which is to say that states with more radar coverage generally experience a greater percentage of warned flash floods as a proportion of total warned and unwarned events. This relationship appears to be stronger at the state level than at the WFO level. As performance metrics were not determined by state, additional analyses of these data are needed to understand the full relationship between radar coverage and flash flood warning performance, and whether this varies significantly between the WFO and state level.

Figure E.9 – Fraction of warned flash flood events reported between 2008 and 2016 as a function of the percent state area covered by radar. This is among the strongest correlations calculated between verification statistics and radar coverage, with a coefficient of determination of 0.362 and a statistically significant linear regression.

Additionally, warned ratios are analyzed for events within radar coverage (i.e., inside the 6 kft threshold) and events outside of such coverage in terms of number of events per state in Figures E.10--E.13. Most states have probabilities of detection above 80% (warned ratio greater than 0.8) in Fig. E.10, with some states in the western part of the United States generally having lower warned ratios for the same number of events as states in other parts of the country. The relationship is similar for events inside of radar coverage in Figure E.11, where most states but a handful from the West again have a probability of detection above or around 80%. For events outside of radar coverage in Figure E.12, several western states noticeably drop to a probability of detection around 60% while other states remain higher. So, some western states show lesser warning performance than others comparable in terms of event rate in the outside category. An overall warned bias computed as *bias = N(warned inside)/N(inside) - N(warned outside)/N(outside)* is shown in Fig. E.13.

Zero bias means similar warning ratios inside and outside the 6 kft beam height or equal skill at warning on either side. Positive values indicate more skill at warning under (inside) the 6 kft AGL radar coverage. This does not show a systematic clustering of negative warning bias (greater ratio of events warned beyond the 6 kft beam altitude) for US western states though a few of those states have negative biases, suggesting more warnings outside radar coverage relative to events outside. The lack of clear clustering can be seen in the fact that dry and wet states have comparable bias values (e.g., CO and PR). This bias calculation is not inconsistent with that shown in Figs. E.11-E.12 since those biases consider separately events inside/outside the 6 kft beam height. Moreover, Fig.E.13 shows that the overall bias and confidence intervals taper to zero as the total number of events increases, suggesting that the total number of events (i.e. forecaster experience) seems to be a stronger determiner of warning skill overall than percent radar area coverage. As before, the number of events is not completely independent from coverage, overtly and covertly, so the two are not exclusive. Though western states seem to warn less well with events outside, there does not seem to be a clear clustering in the overall bias that balances warning ratios inside and outside. Said differently, the lower biases seem to arise from lower warning ratios in the outside. More regional analysis is warranted in order to better to understand what is driving these bias trends.

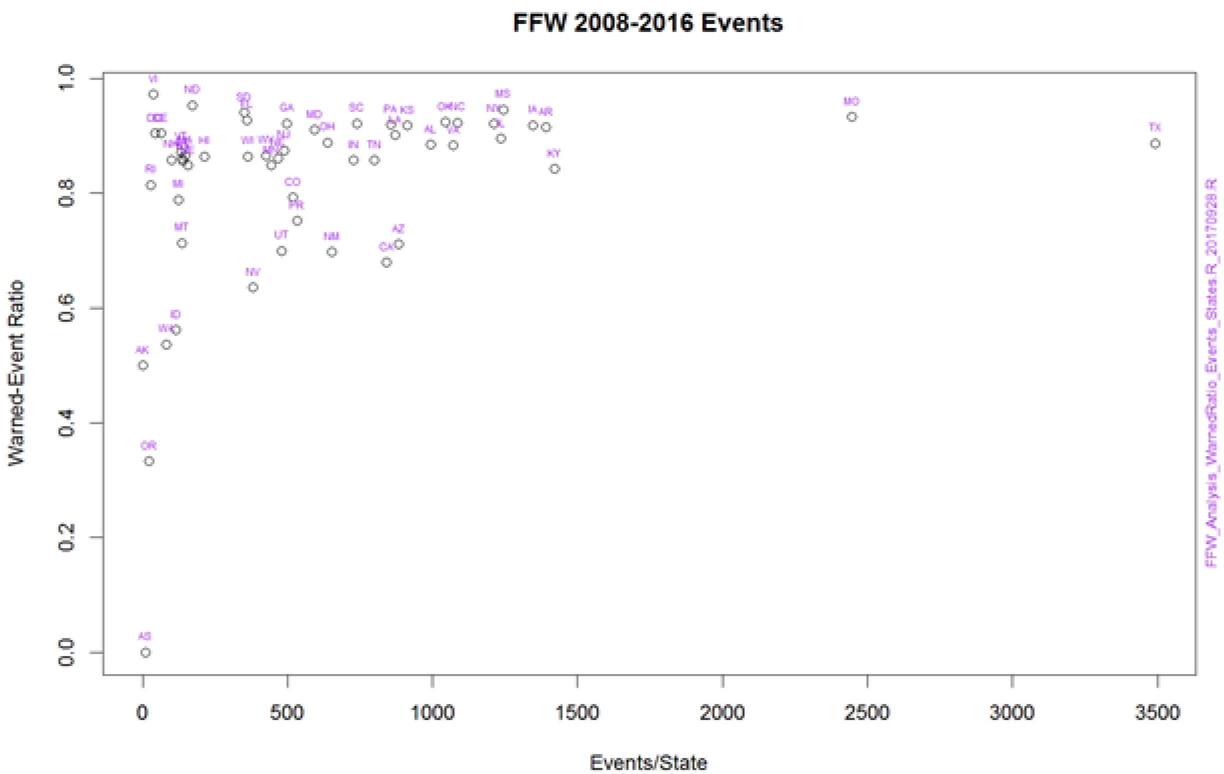


Figure E.10 –Warned flash flood event ratios as a function of the number of events reported per state between 2008 and 2016. There is considerable variability between states with similar numbers of events and their calculated warned event ratio.

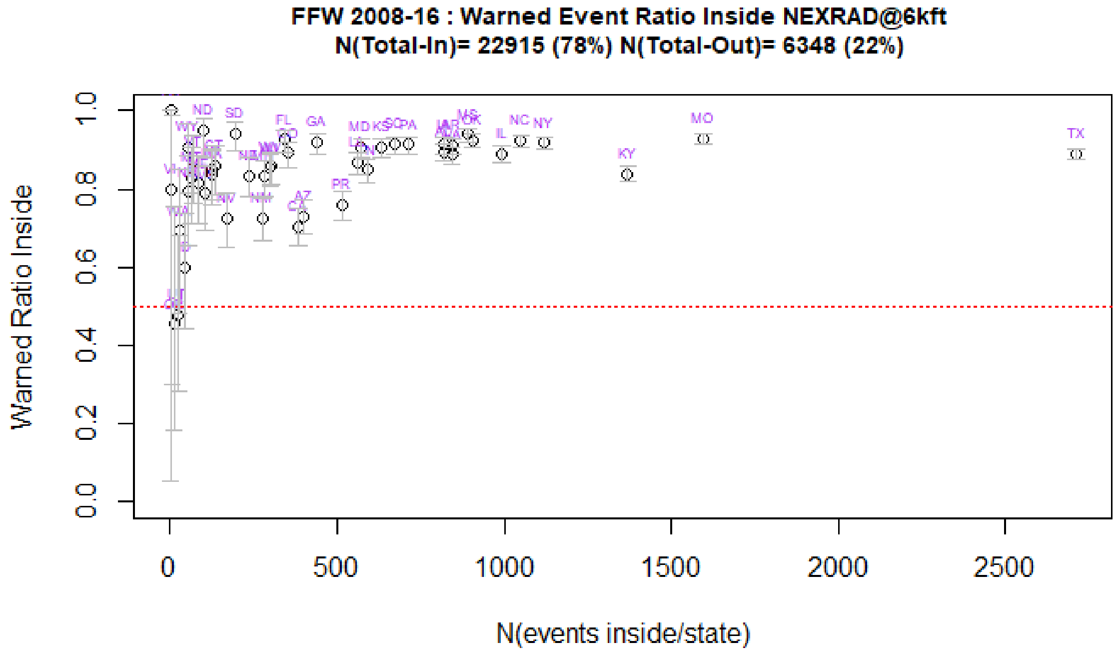


Figure E.11 – Fraction of warned flash flood events inside NEXRAD radar coverage at 6 kft AGL as a function of the number of events inside per state for 2008-2016. Confidence intervals (95% level) are drawn in gray. Some western US states have lower warned ratios inside as compared to others with the same number of inside events.

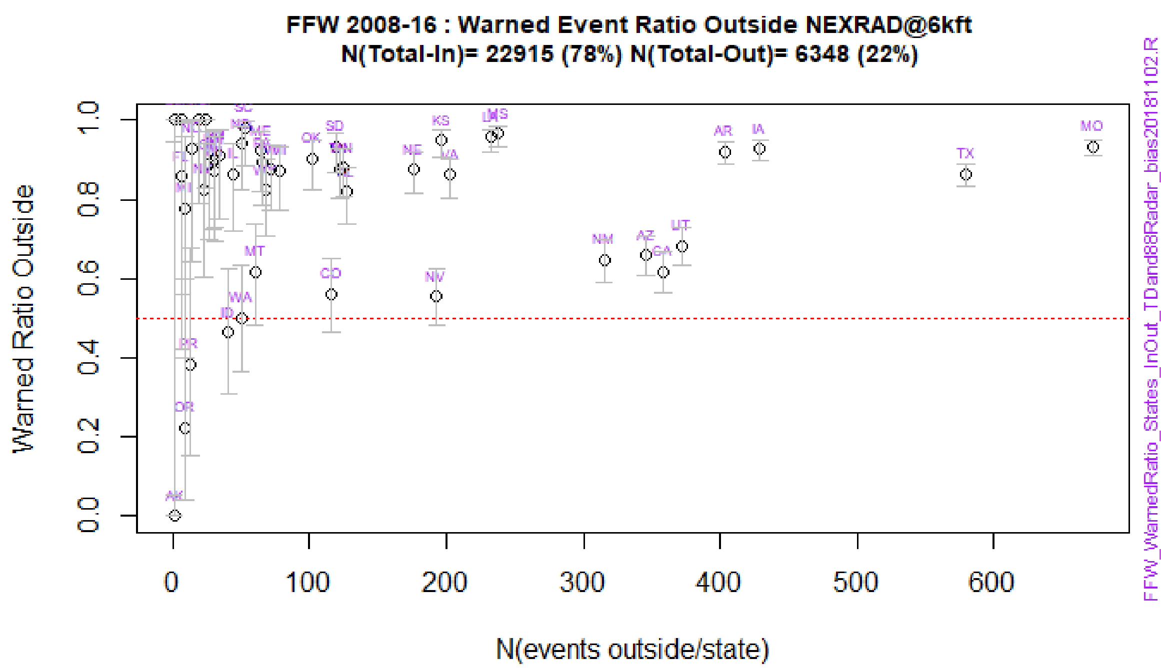


Figure E.12 – Fraction of warned flash flood events outside of radar as a function of the total number of events outside per state between 2008 and 2016. Gray vertical error bars are the 95% confidence intervals. Some states in the western part of the country suffer a greater drop in warned event ratio outside radar coverage as compared to counterparts elsewhere.

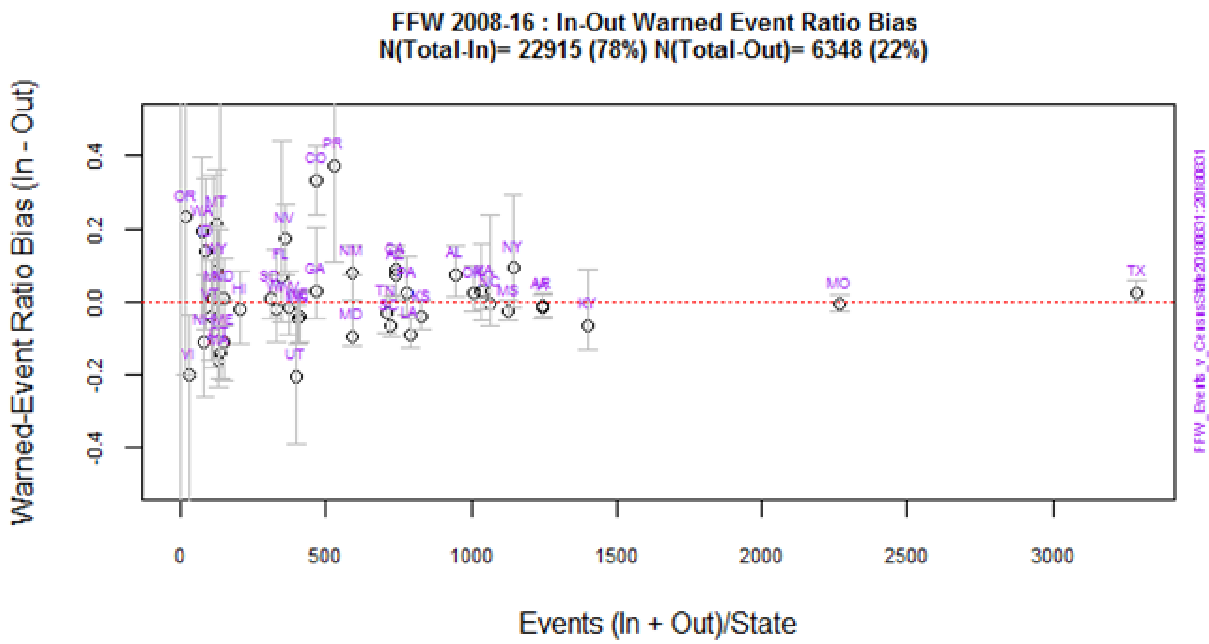


Figure E.13 – Bias in warned ratios by state for all events inside and outside of radar coverage normalized by total event counts inside or outside in the category considered (see text). A positive bias means a state has higher warned ratio for events within (inside) radar coverage while a negative bias means a state has a larger outside warned ratio. Western states have both high positive and negative biases. Confidence intervals (at 95th percentile) are denoted by vertical error bars (gray). Of all events, 78% fall inside the 6kft AGL bottom-of-the-beam height. With more events the bias tapers toward zero with increasing statistical confidence.

Trends in Flash Flood Events, Fatalities, Injuries, and Damages

From 2008 to 2016, there were 33663 flash flood events, 585 fatalities, 454 injuries, and nearly \$14 billion in combined property and crop damages. While the number of events per year in Figure E.14 holds relatively steady, fatalities, injuries, and damages in Figures E.15--E.17 are each dominated by a single above-average year, although this year does not have other similar impacts. There is little overlap among flash flood-related fatalities and injuries; there is only one event which recorded both double digit fatalities and injuries. Among all flash flood-related injuries, the dataset is dominated by a single flash flood outbreak in Oklahoma which injured more than 100 people. Given the limited sample size and high proportion of injuries occurring in association with a single flash flood event, it is difficult to assess the significance of analysis on this dataset. Moreover, the nature of flash flood fatalities is comparatively different from those in tornadoes, since flash floods are generally less sudden and are often the result of poor judgement (as evidenced in recurrent local storm reports).

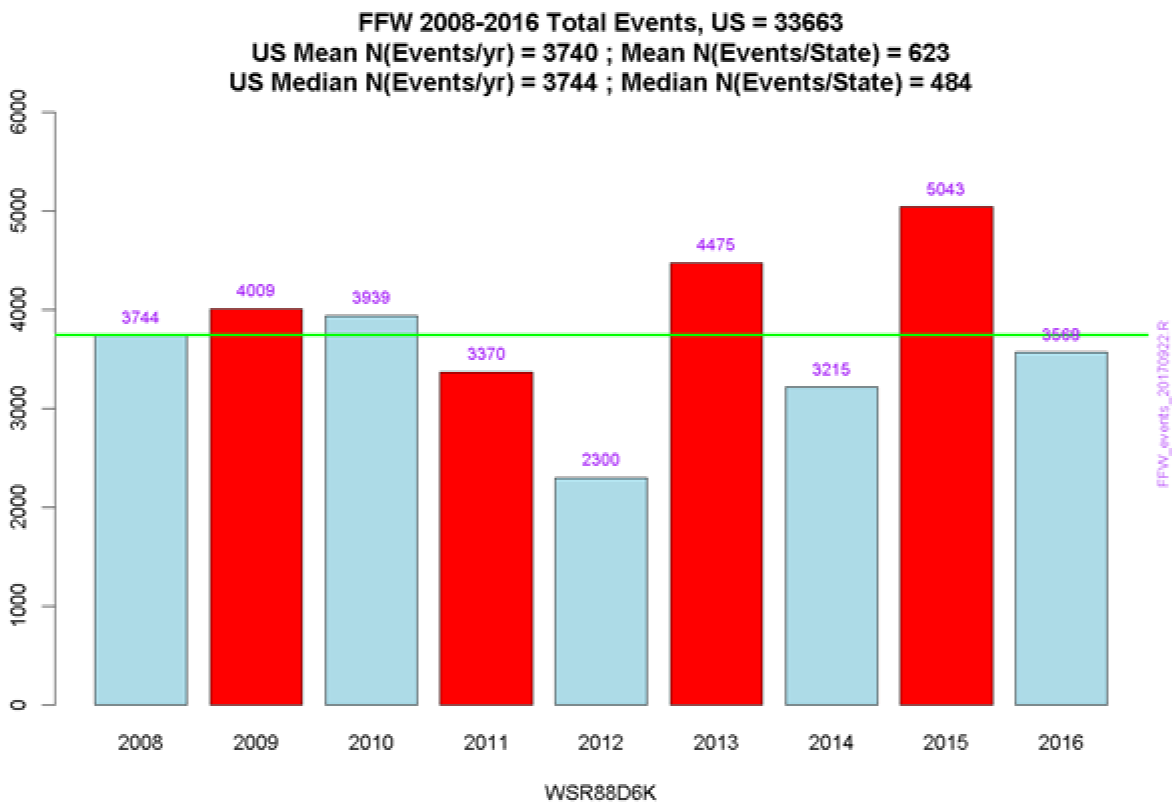


Figure E.14 – Flash flood events per year from 2008 to 2016. 2013 and 2015 both recorded an above average number of events. 2012 was the year with the least number of flash flood events during this time period.

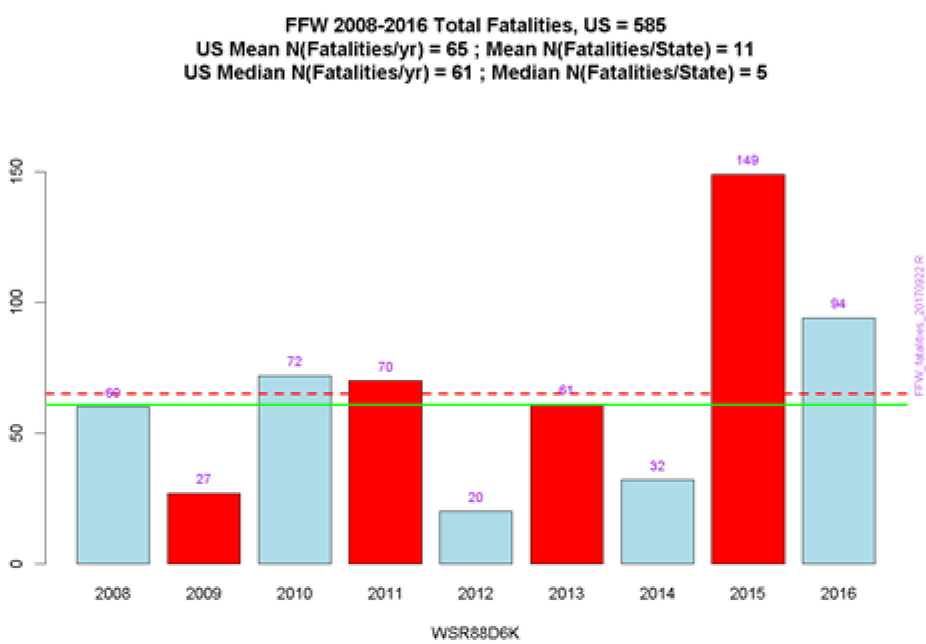


Figure E.15 – Flash flood-associated fatalities per year from 2008 to 2016. 2015 recorded a much above average number of fatalities.

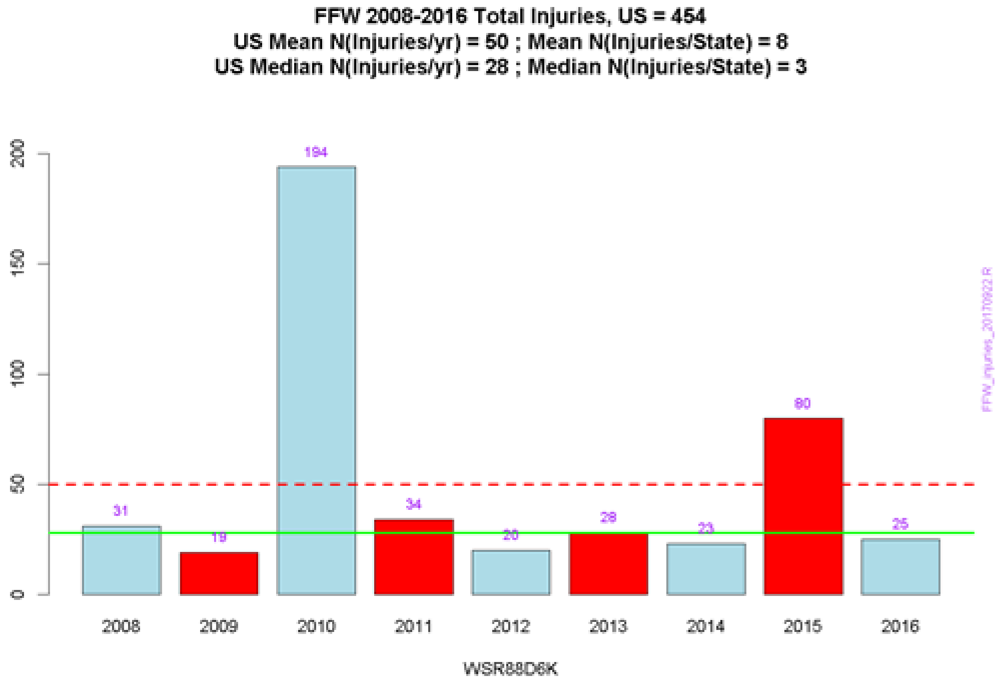


Figure E.16 – Flash flood-associated injuries per year from 2008 to 2016. 2010 recorded an above average number of injuries, dominated by a single flash flood outbreak in Oklahoma which injured more than 100 people.

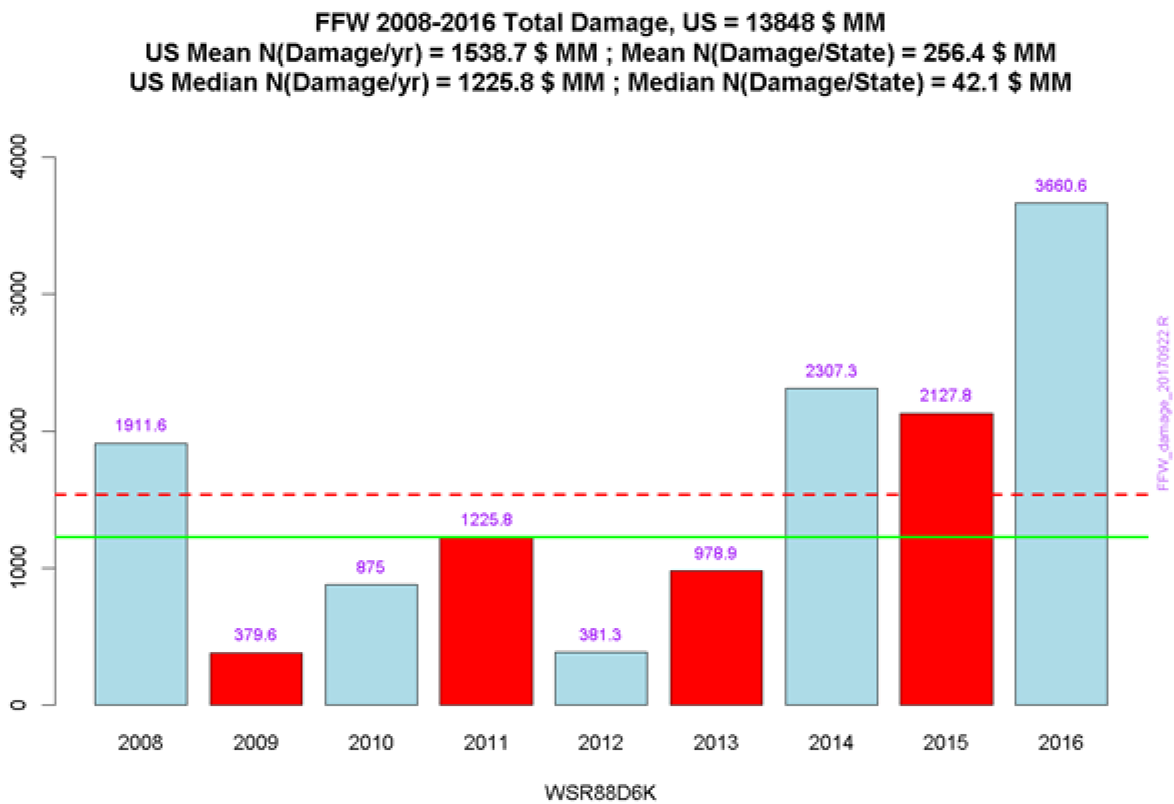


Figure E.17 – Flash flood-associated damages per year from 2008 to 2016. While 2016 had a slightly below normal number of flash flood events, more flash flood-associated damages were recorded in this year than any other.

While flash flood events are relatively evenly distributed by year, a few states account for the majority of events, fatalities, and injuries. As can be seen in Figure E.18, Texas and Missouri had many more events from 2008-2016, encompassing almost a third of the total events in the US during this time period. Texas also recorded more flash flood-related fatalities than any other state, as shown in Figure E.19. As previously discussed, Oklahoma experienced the most flash flood-related injuries, made obvious by Figure E.20. Flash flood related damages are relatively more widespread geographically, as shown in Figure E.21: more states experience damages than either fatalities or injuries.

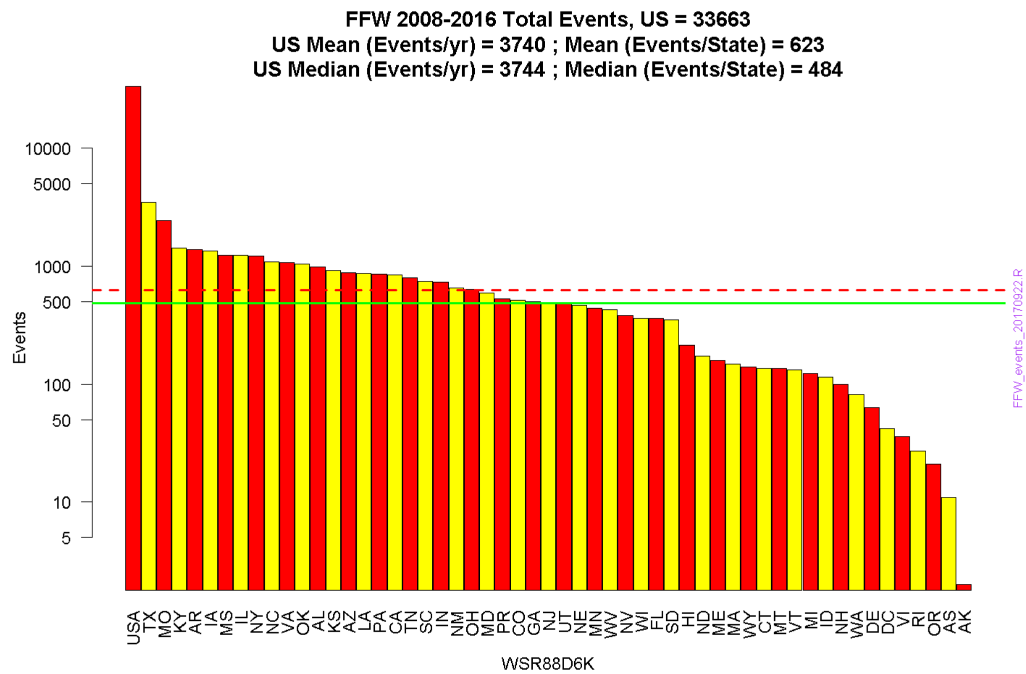


Figure E.18 – Flash flood events by state from 2008 to 2016. Texas and Missouri lead the nation in flash flood events during this time.

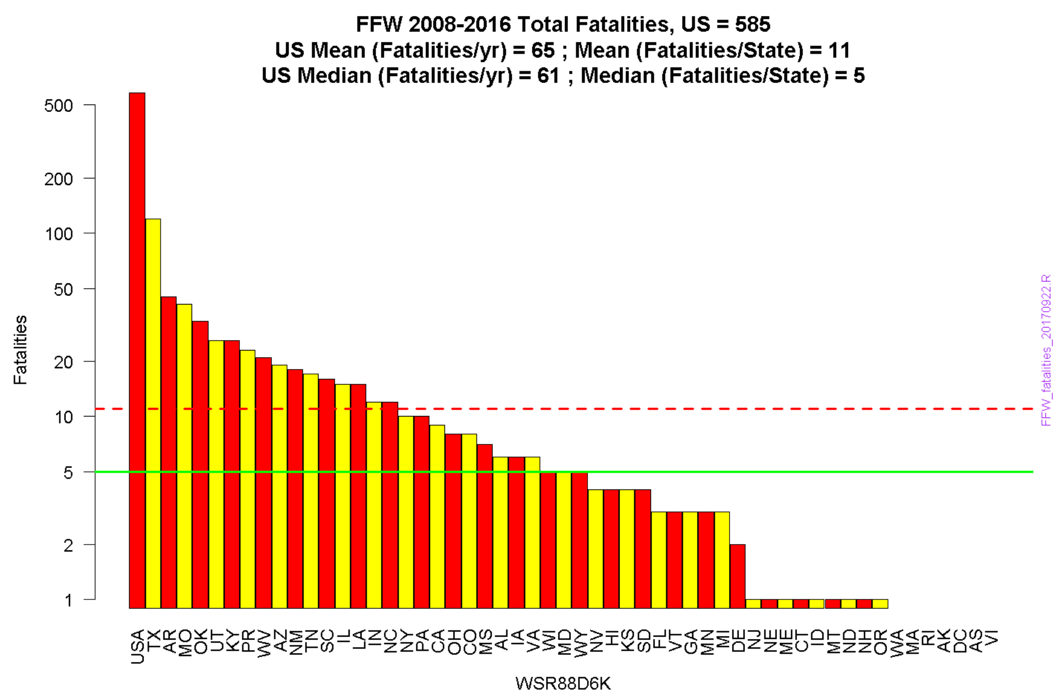


Figure E.19 – Flash flood-associated fatalities by state from 2008 to 2016. Fatalities in Texas are nearly a fifth of the nationwide total during this time. The mean is 11 (red line), and the median five (green line).

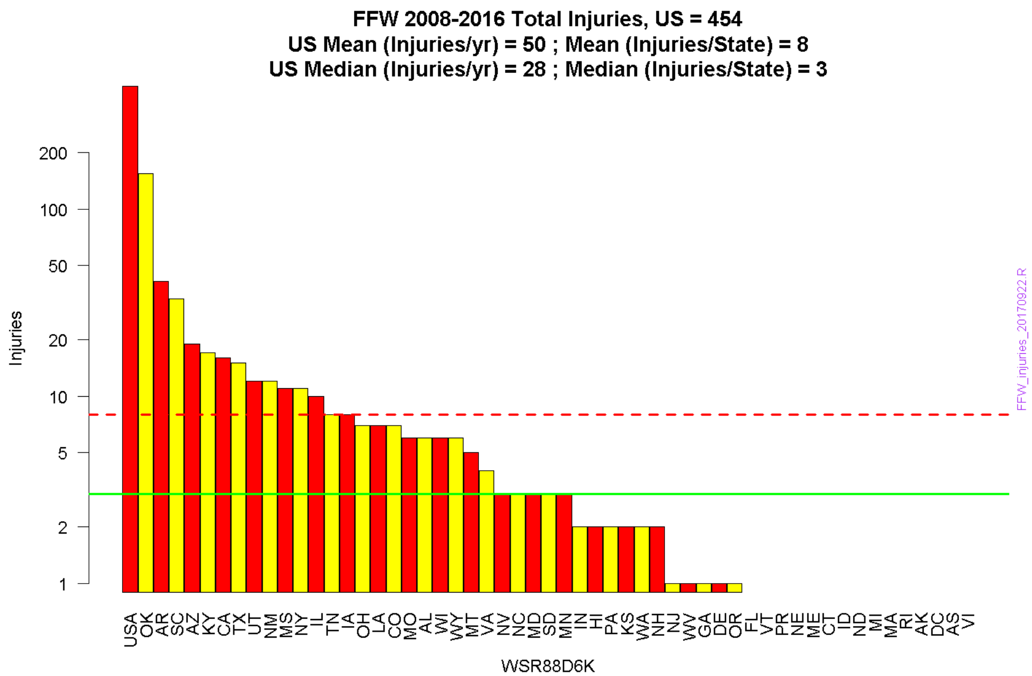


Figure E.20 – Flash flood-associated injuries by state from 2008 to 2016. Injuries in Oklahoma are nearly a quarter of the nationwide total during this time. The mean is 8 (red line), and the median three (green line).

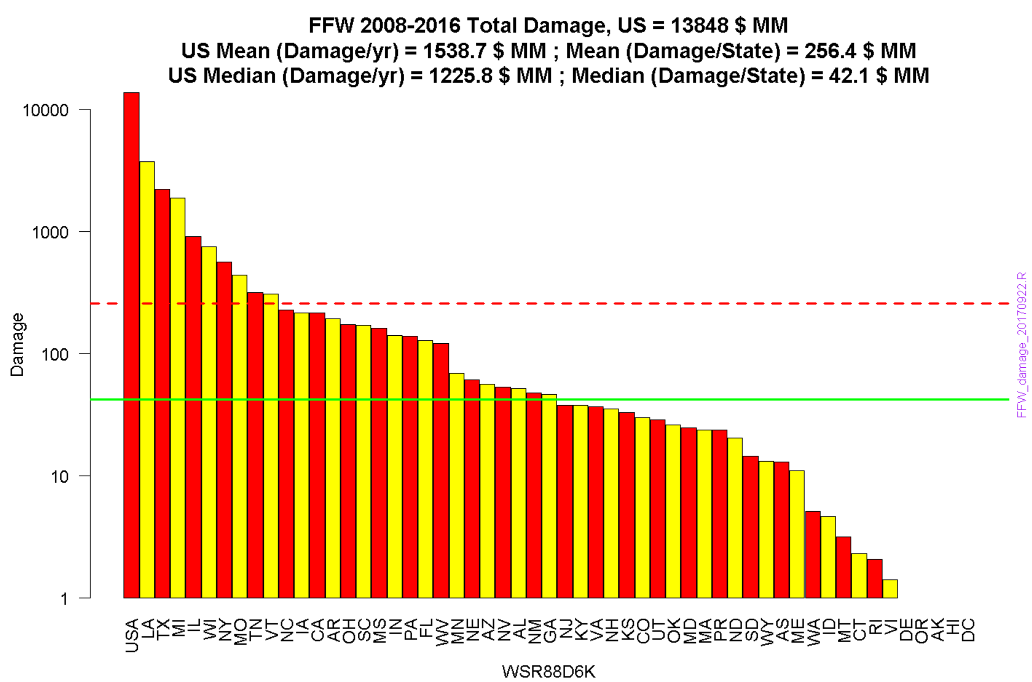


Figure E.21 – Flash flood-associated cumulative damages ($M) by state from 2008 to 2016. There is large variability in total damages recorded among states. The state with the greatest amount of damages during this period was Louisiana. Mean damage per state per decade is $256M (red line), the median is $42.1M.

A brief seasonal analysis was also performed. Nearly twice as many events are recorded in summer (mean = 1859) as in spring (mean = 984), and almost three times as many as in fall (mean = 640). Due to the highly skewed seasonal occurrence of flash floods, further detailed seasonal analysis will not be presented here, though it is a potential area for additional analysis. However, Figure E.22 illustrates clearly why Texas and Missouri are states at the top of events nationally, as they are among the top states experiencing flash floods in all seasons.

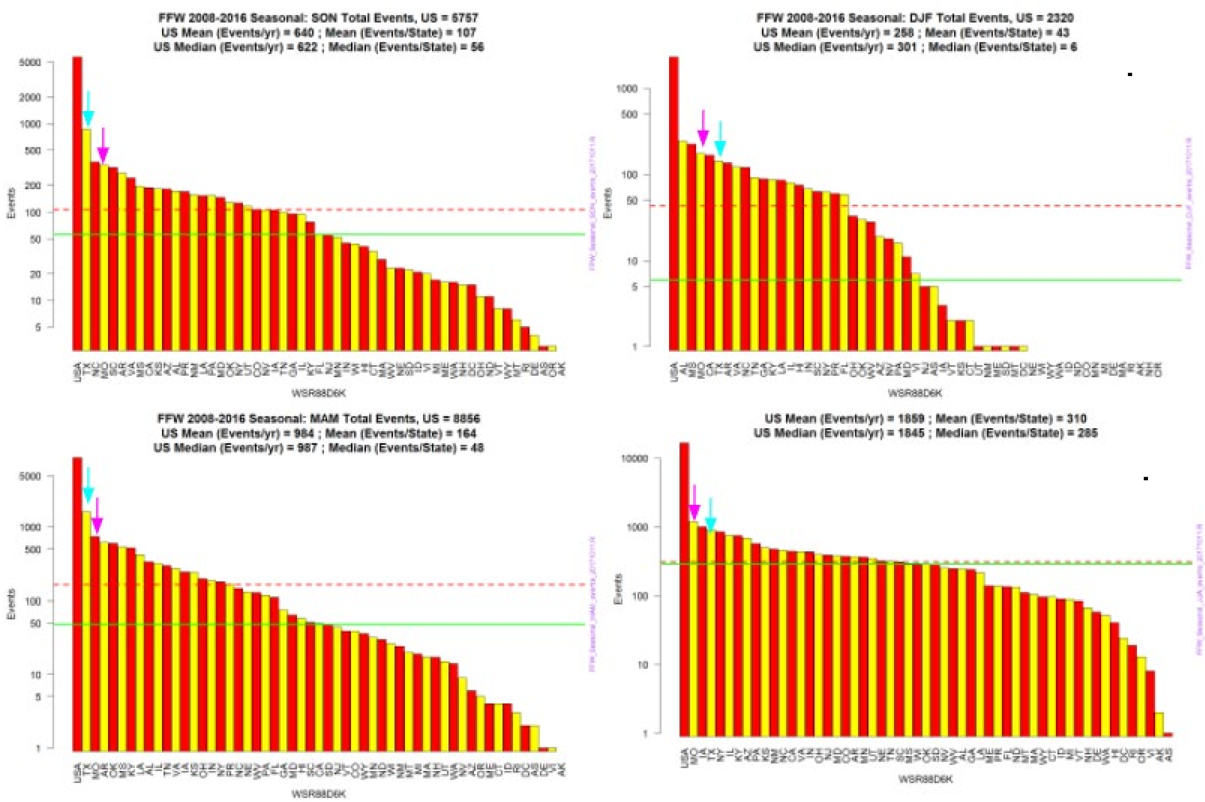


Figure E.22 – Flash flood events by state for (a) fall, (b) winter, (c) spring, and (d) summer. Texas is indicated by the cyan arrow and Missouri is indicated by the magenta arrow.

Fatalities, Injuries, and Damages per Event, and as a Ratio of All Events

Fatalities, injuries, damages and significant damages were also analyzed on a per event basis by year. From 2008 to 2016, there were around 17 fatalities and 13 injuries per thousand flash flood events. Damages per event averaged around $410,000 in combined property and crop damages. While the number of events per year during this time is relatively steady (Figure E.14), fatalities (Figure E. 23), damages (Figure E.25), and significant damages (Figure E.26) are dominated by a couple years with much above average rates of fatalities or damages, and injuries (Figure E.24) are dominated by a single above-average year. Among all flash flood-related injuries, the dataset is dominated by a single flash flood outbreak in Oklahoma which injured more than 100 people. Given the limited sample size and high proportion of injuries occurring in association with a single flash flood event, it is difficult to assess the significance of analysis on this dataset.

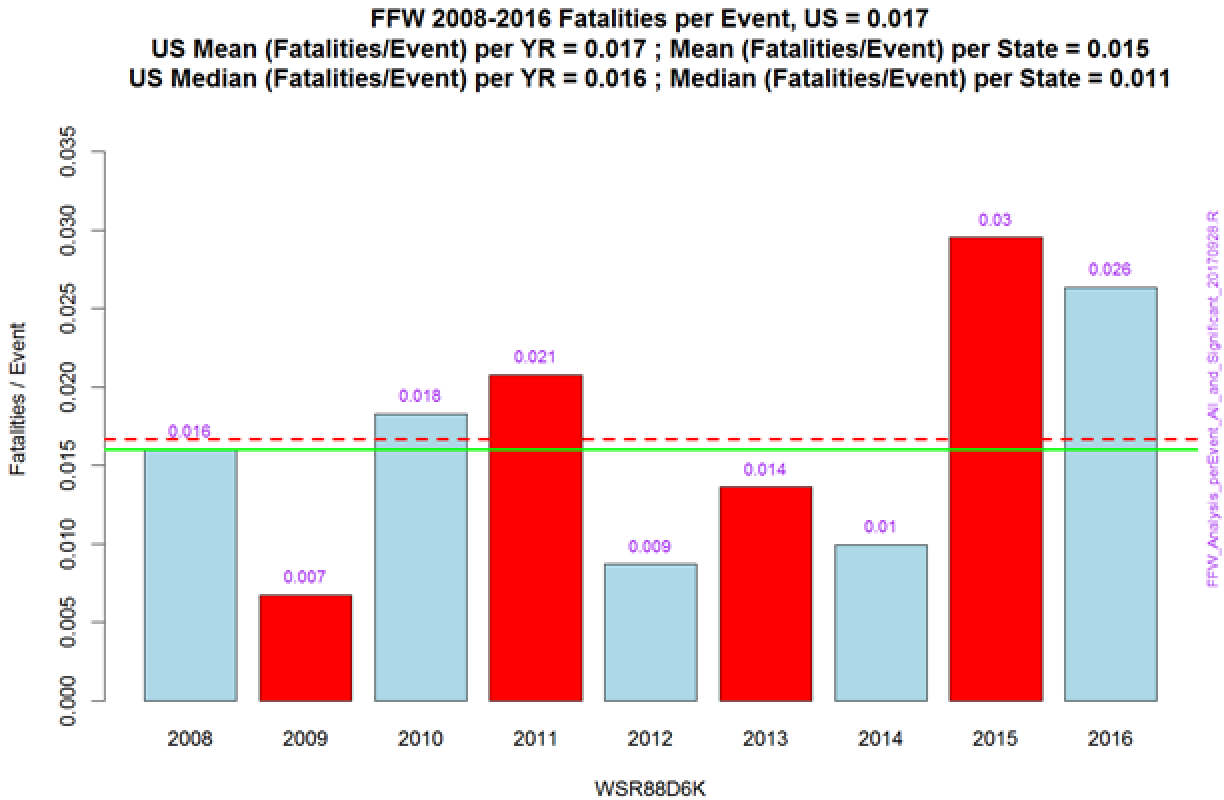


Figure E.23 – Fatalities per flash flood event by year from 2008 to 2016. Both 2015 and 2016 were much above average in fatalities per event, even as 2016 experienced a slightly below average number of events. Over this time period, there were an average of 17 fatalities per every thousand flash flood events.

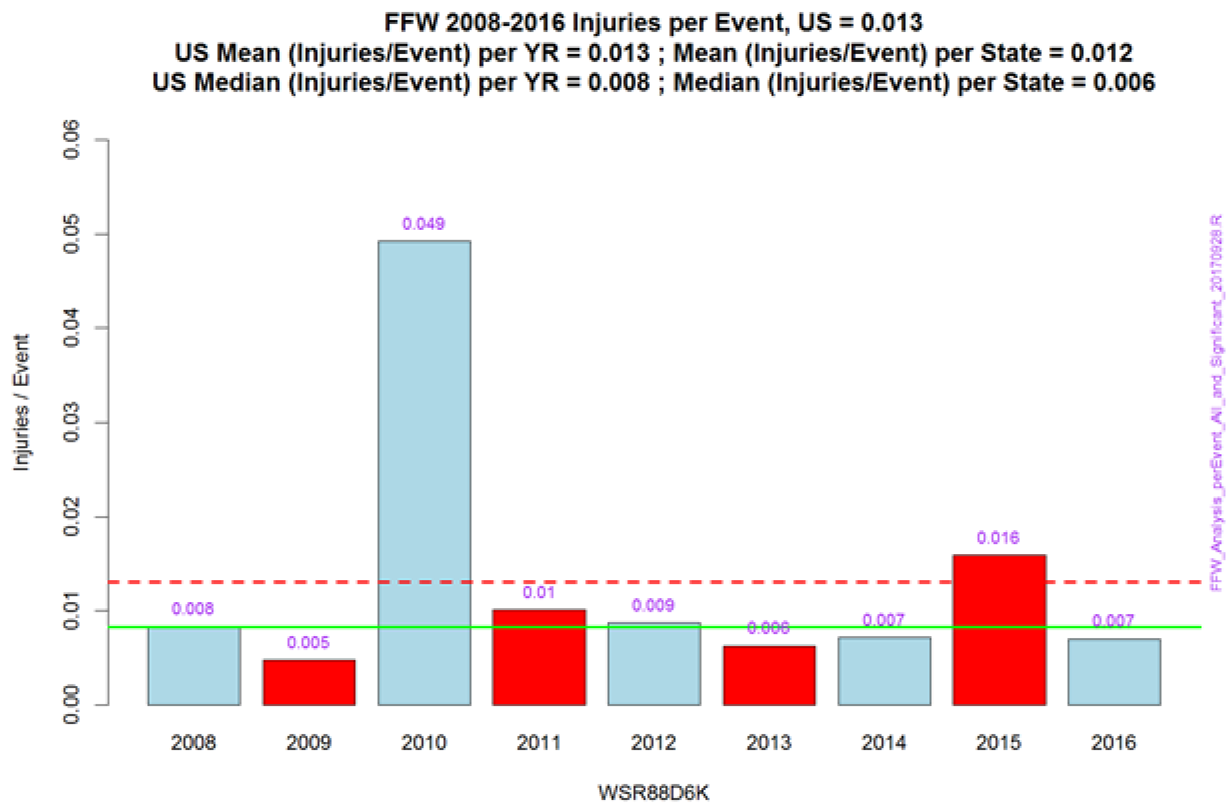


Figure E.24 – Injuries per flash flood event by year from 2008 to 2016. As previously discussed, 2010 saw an anomalous number of injuries due to a single event. Over this time period, there were an average of 13 fatalities per every thousand flash flood events, though variability among years is high and there was only a median of 8 people injured per every thousand flash flood events.

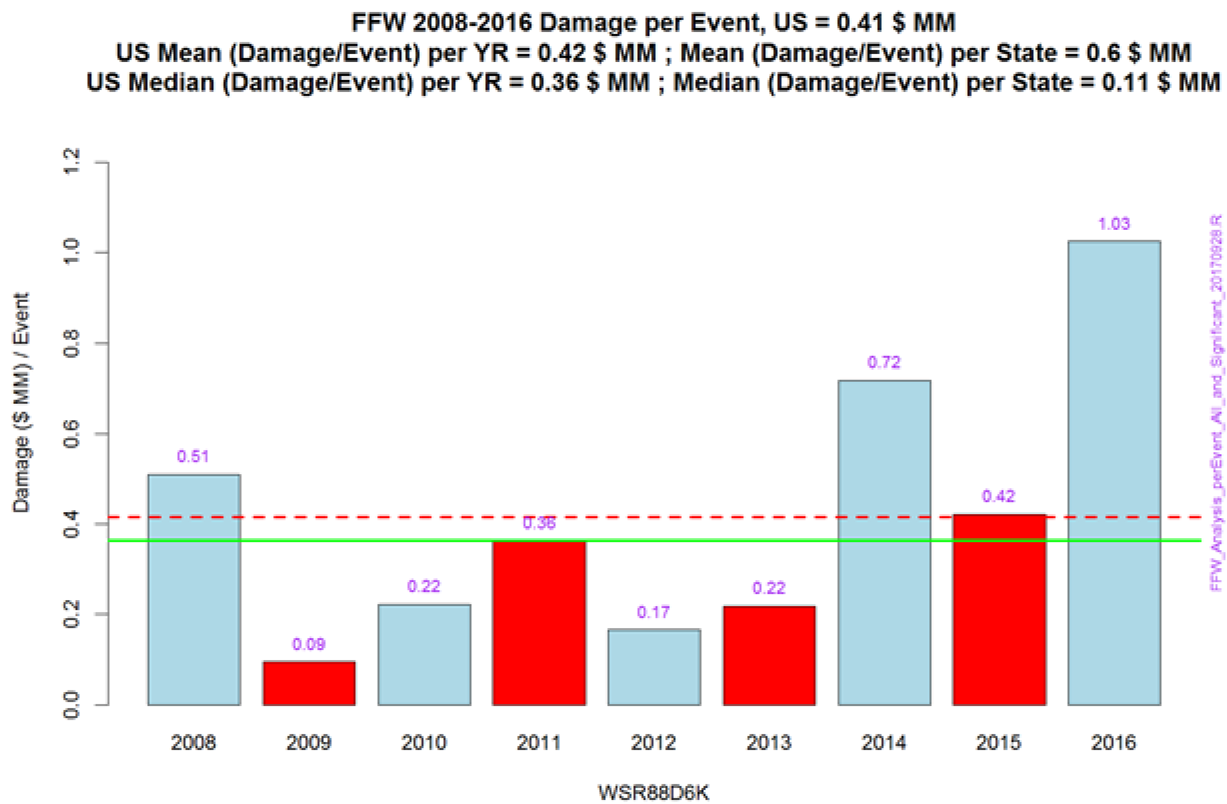


Figure E.25 – Damages per flash flood event by year from 2008 to 2016. 2016 recorded much above average damages per event. Over this time period, flash flood events each averaged just over $410,000 in damages.

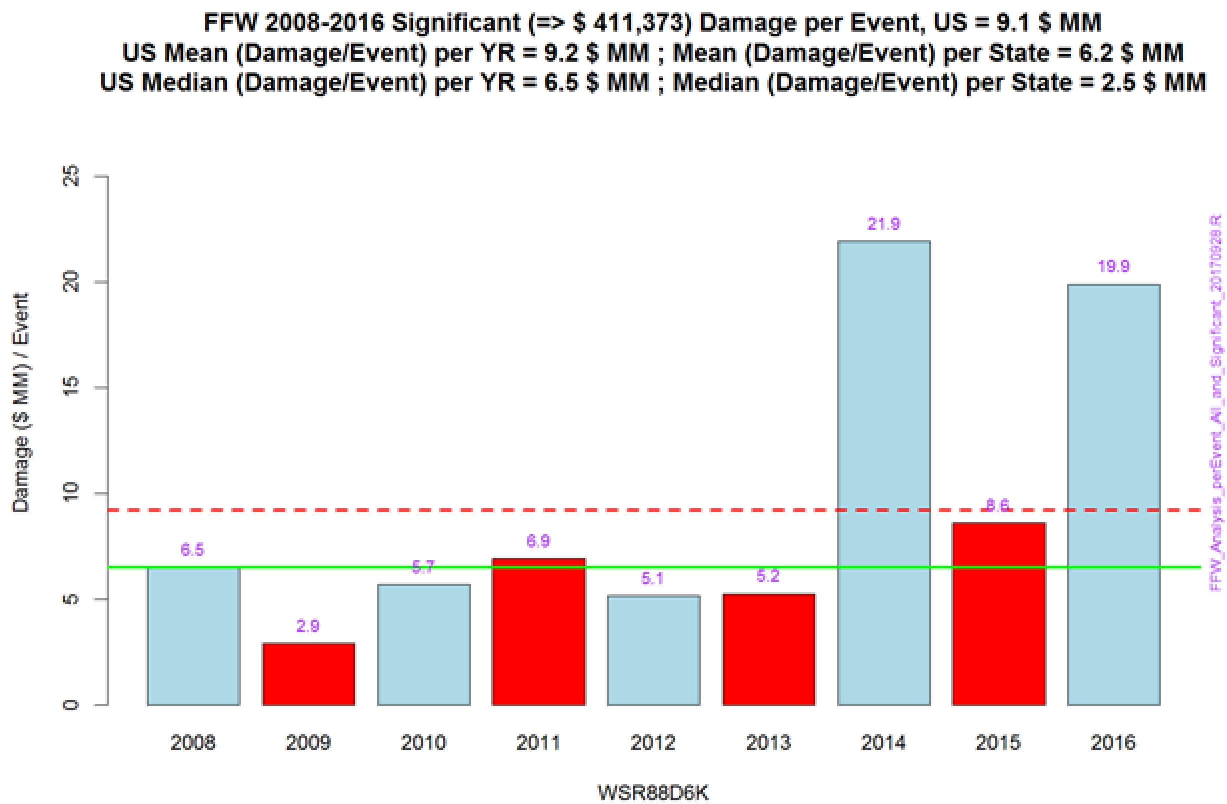


Figure E.26 – Significant damages per flash flood event by year from 2008 to 2016. Significant damages were defined as damages greater than the mean per event for the total time period ($411,373 per event). Significant damage events are noticeably greater in value than the overall average eight-year average, coming in at $9,100,000 per significant damage event.

Trends in Unwarned Flash Flood Events, Fatalities, Injuries, and Damages

From 2008 to 2016, there were 4308 unwarned flash flood events, and, associated with these unwarned events there, were 122 fatalities, 73 injuries, and nearly 3.4 billion dollars in combined property and crop damages. This indicated that less than 13% of all flash flood events are unwarned. Fatality and injury statistics roughly equates to 28 fatalities per thousand unwarned events and 17 injuries per thousand unwarned events. While this event sample size is much smaller, on a per event basis, this is slightly higher than the rate of fatalities and injuries per all events. Additional analysis is needed to determine if this difference is statistically significant. While the number of unwarned events per year shows a fairly similar trend to all flash flood events by year (Figure E.27), unlike total fatalities and injuries, unwarned fatalities shown in Figure E.28 and unwarned injuries shown in Figure E.29 are not dominated by a single above-average year. Among all flash flood-related damages (Figure E.30), the dataset is dominated by a single event in 2014 with over a billion dollars in damages. Though this event dominates monetarily, significant damage events with above average losses occur every year, on average 13 times a year as shown in Figure E.31.

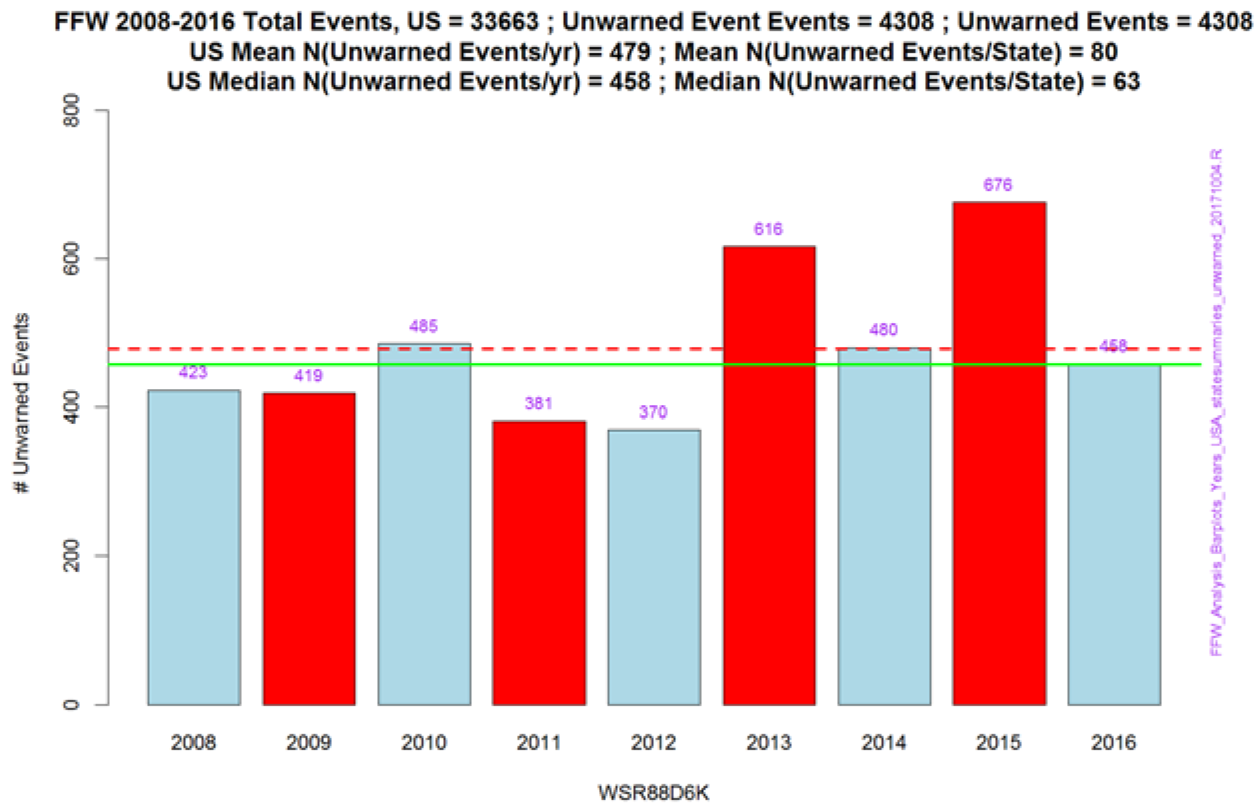


Figure E.27 – Unwarned flash flood events per year from 2008 to 2016. Both 2013 and 2015 recorded above average number of total as well as unwarned events. Year 2012 had the least number of flash flood events and similarly shows the lowest number of unwarned events. There were 4308 unwarned events out of 3363 with a mean (red line) of 479 unwarned per year and median (green line) of 458. Only two years exceed the mean.

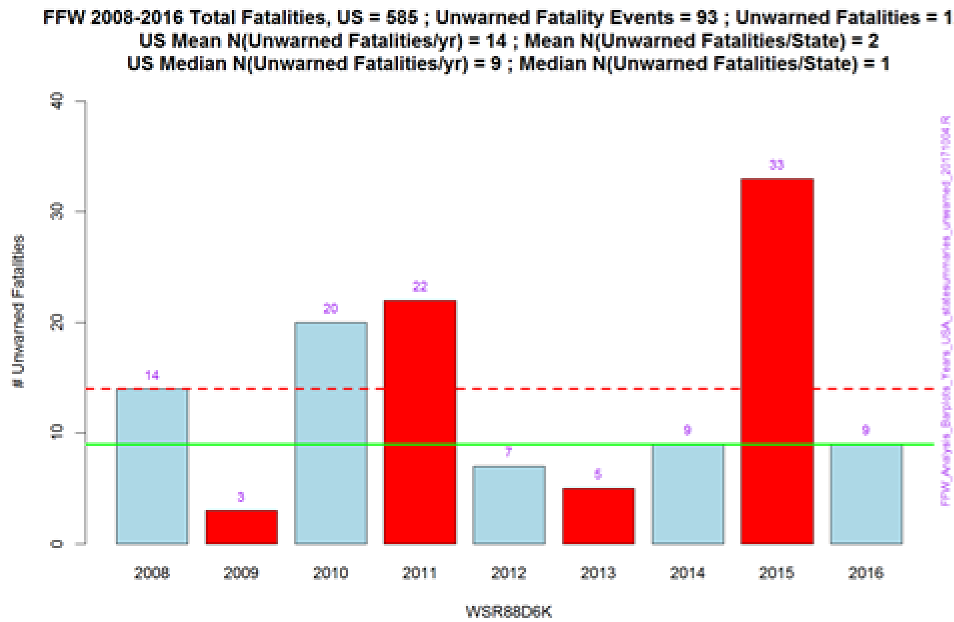


Figure E.28– Fatalities associated with unwarned flash floods per year from 2008 to 2016. Although a few years show much above average numbers of fatalities associated with unwarned events, these are not clustered in single events.

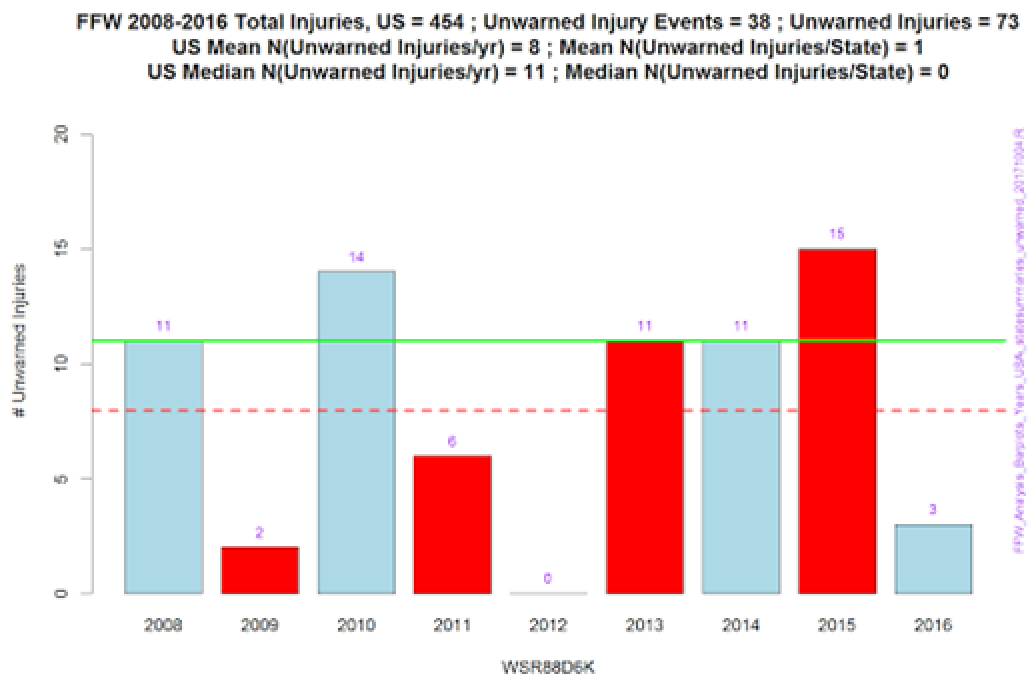


Figure E.29 – Injuries associated with unwarned flash floods per year from 2008 to 2016. There is large variability among injuries recorded in associated with unwarned event per year.

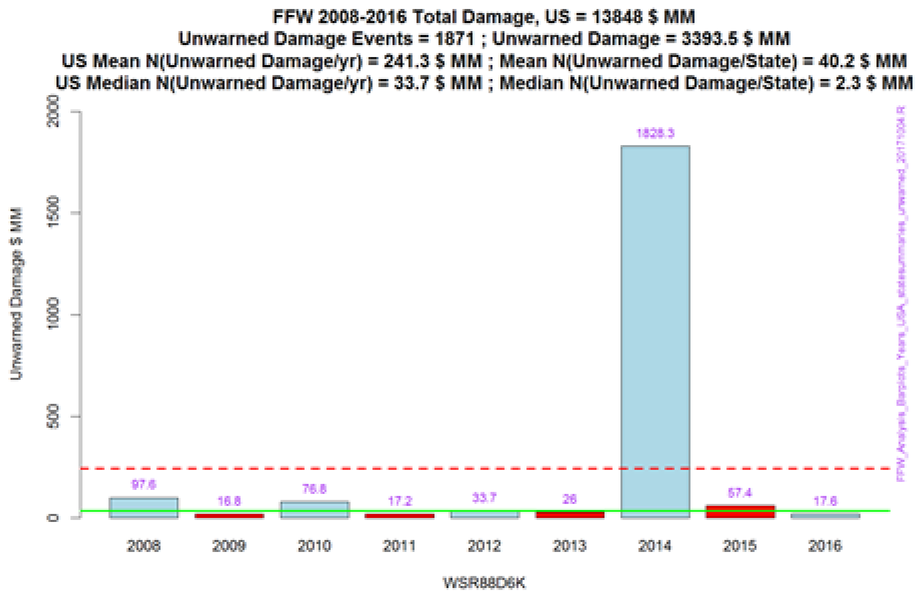


Figure E.30 – Damages associated with unwarned flash floods per year from 2008 to 2016. A single event in Michigan in 2014 with over a billion dollars in damages dominates these statistics.

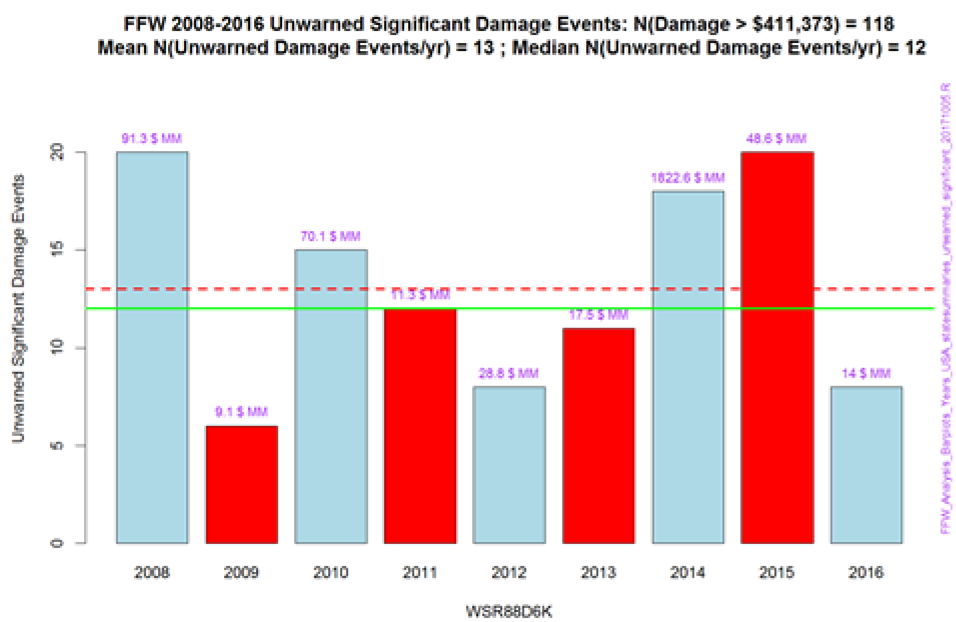


Figure E.31 – Significant damage (> $411,373) events associated with 118 unwarned flash floods per year from 2008 to 2016. Though a single event in Michigan in 2014 with over a billion dollars in damages dominates damages statistics indicated by the purple text above each bar, events with damages much above average have occurred on average 13 times a year during the time period analyzed.

Flash Flood Events, Fatalities, Injuries, and Damages and Relationship to Population and Radar Coverage: All Events and Unwarned Events

The relationship between events, fatalities, injuries and damages by state population as recorded in the latest Census released in 2011 was also explored. Increased population might be expected to be positively associated with fatalities, injuries, and damages recorded by state from flash flood events due to increased exposure of lives and property, but interestingly, flash flood events themselves also show some positive correlation with state population (Figure E.32). Because the most populous states (CA, TX, FL, NY) enjoy 60% or greater NEXRAD area coverage, there is a statistically significant (better than 95% significance level) upward linear regression whether either of the two most populous states (CA and TX) are removed from the regression. However, the least populated states have the lowest coverage below about 40%, as seen in Figure E.33 and the lowest coverage trend. Additionally, while there is a positive relationship between fatalities and state population (Figure E.34), there is little to no correlation between injuries (Figure E.35) and state population and generally very little relationship between damages and state population (Figure E.36). Further analysis is required to fully explain this trend.

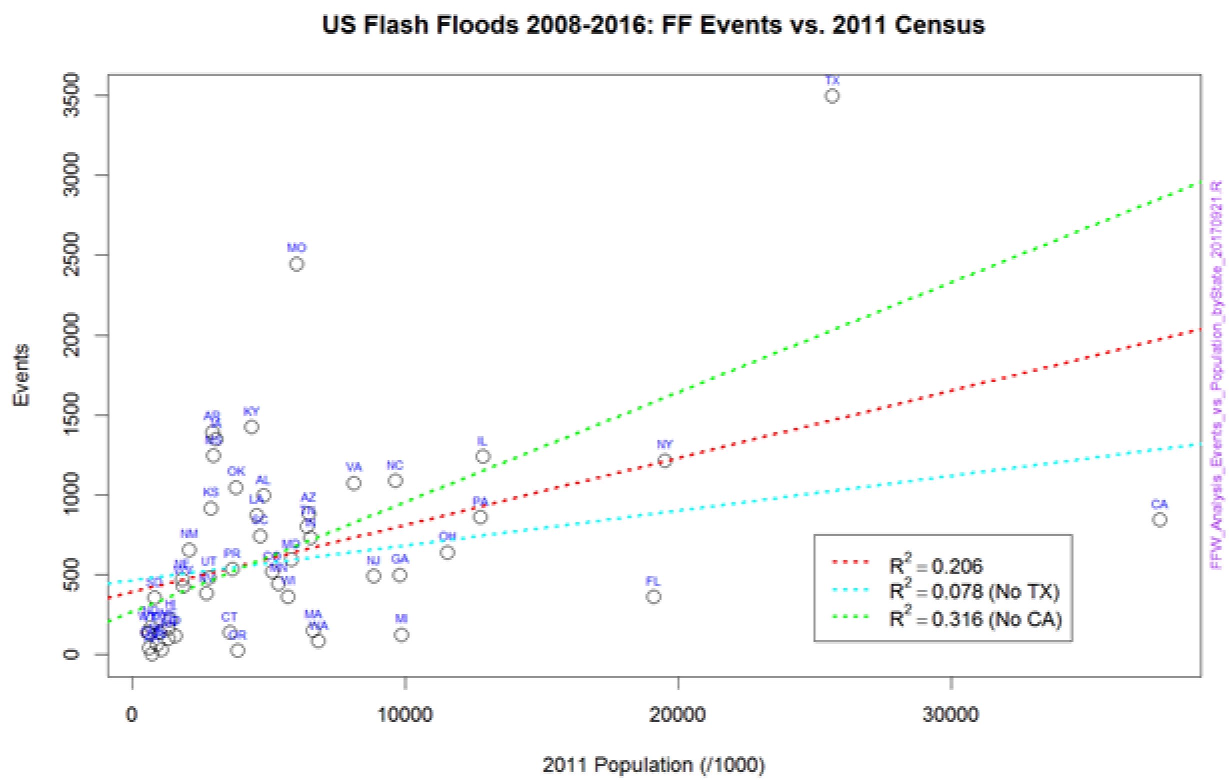


Figure E.32 – Flash flood events per state from 2008 to 2016 by state population from 2011 Census. The strength of this correlation decreases when Texas (most flash flood events, second most populous state) is not included in the analysis. The relationship increases when California (fewer flash flood events, most populous state) is excluded from the analysis and is a test of the sensitivity to population. The fit to all the data is statistically significant at better than the 99% level.

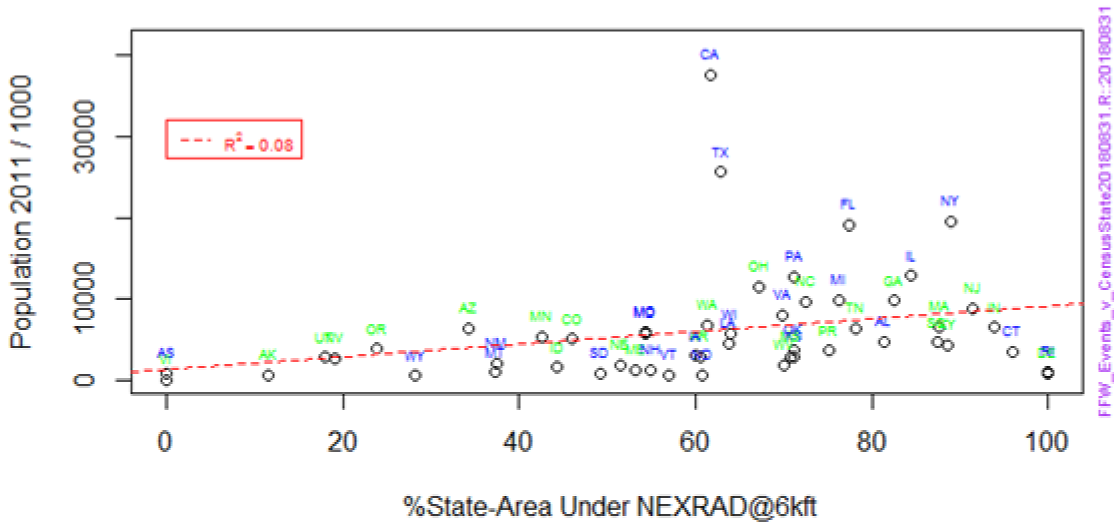


Figure E.33 – State populations from 2011 Census (in thousands) as a function of the percent state area coverage under the NEXRAD beam at 6,000 ft AGL. The least populated states generally have < 40% NEXRAD coverage. The linear fit is statistically significant (red dotted line) at better than the 95% level (p = 0.04).

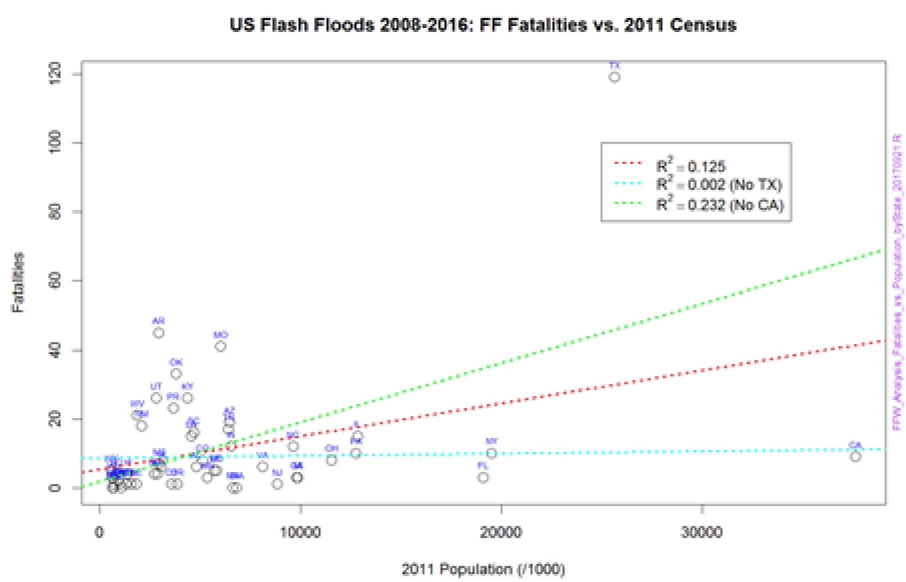


Figure E.34 – Flash flood fatalities per state from 2008 to 2016 by state population from 2011 Census. The strength of this correlation decreases when Texas (most flash flood fatalities, second most populous state) is not included in the analysis. The relationship increases when California (fewer flash flood fatalities, most populous state) is excluded from the analysis.

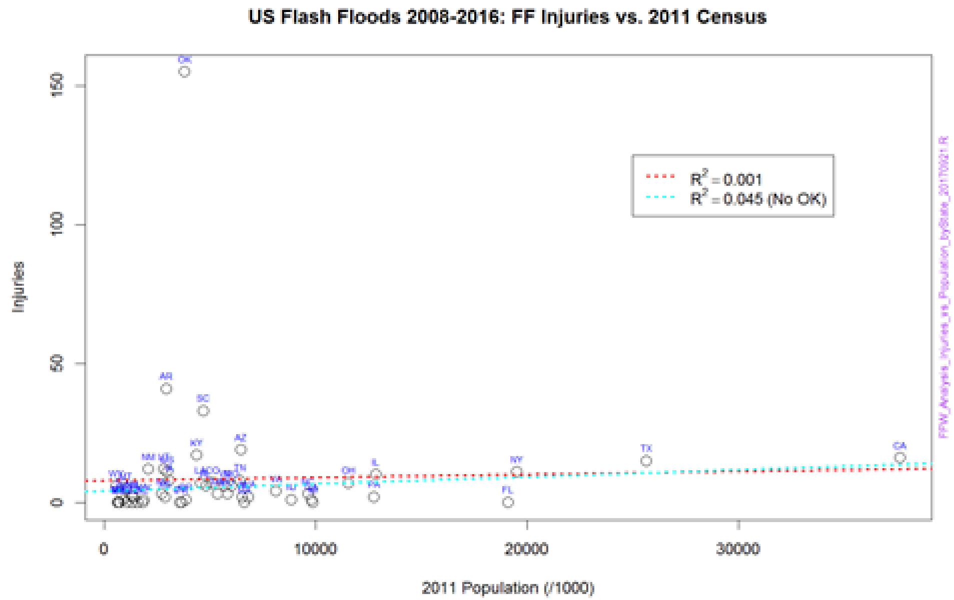


Figure E.35 – Flash flood injuries per state from 2008 to 2016 by state population from 2011 Census. There is little relationship between flash flood injuries and state populations, even with Oklahoma excluded as an outlier.

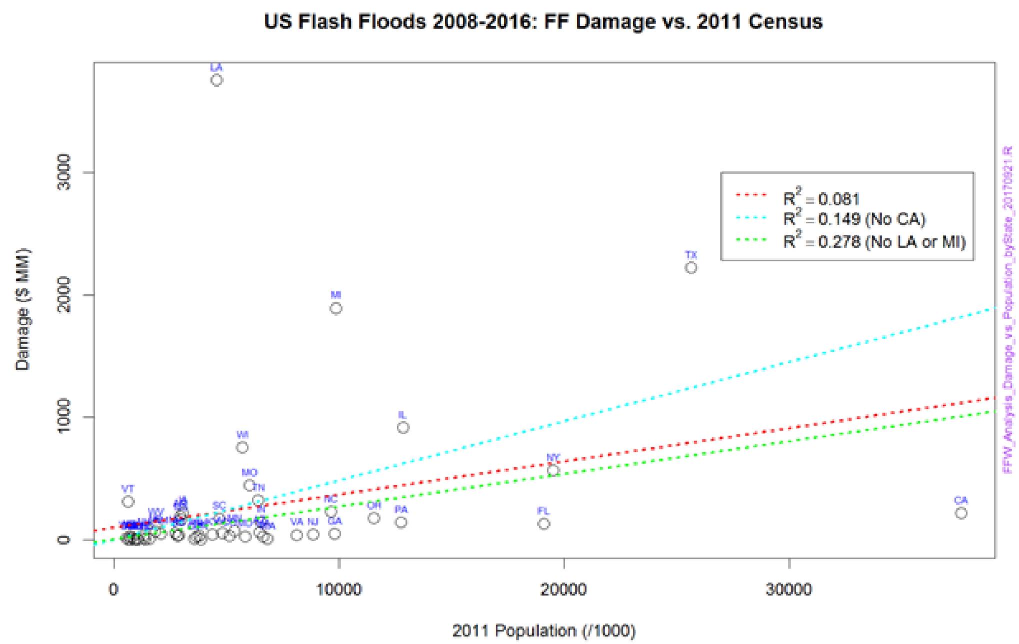


Figure E.36 – Flash flood damages per state from 2008 to 2016 by state population from 2011 Census. There is not a strong correlation between damage amounts and state population. The relationship increases somewhat by removing either California or the pair of Louisiana and Michigan as outlier.

Events, Fatalities, Injuries and Damages by Percent State Covered by Radar

The relationship between events, fatalities, injuries and damages by percent of state covered by radar as previously defined was calculated. There is little relationship between events (Figure E.37), fatalities (Figure E.38), injuries (Figure E.39), and damages (Figure E.40), recorded by state as a function of state radar coverage.

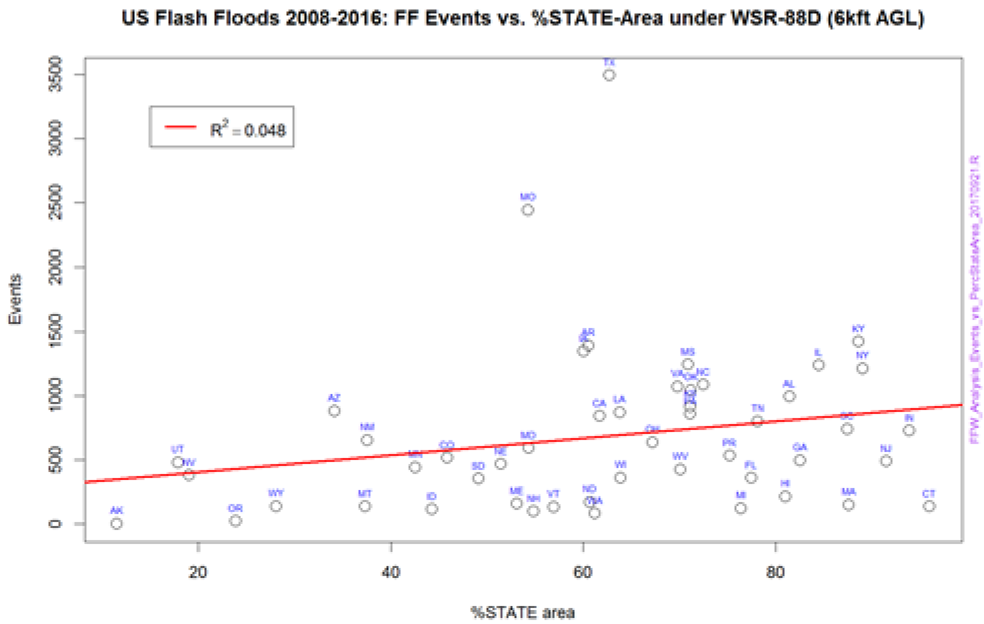


Figure E.37 - Flash flood events per state from 2008 to 2016 by percent state covered by radar. There is little relationship among events and increasing state radar coverage.

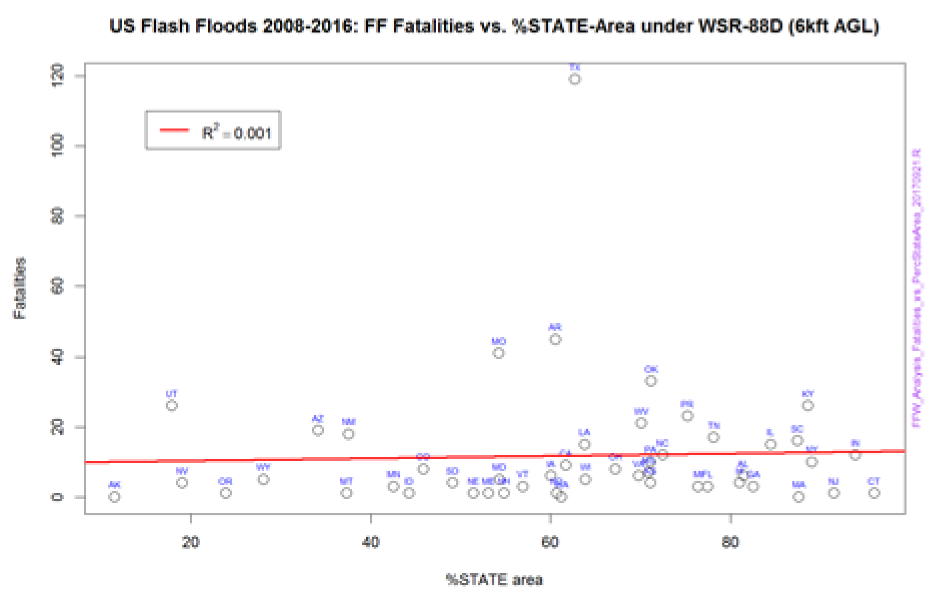


Figure E.38 - Flash flood fatalities per state from 2008 to 2016 by percent state covered by radar. There is little relationship among fatalities and increasing state radar coverage.

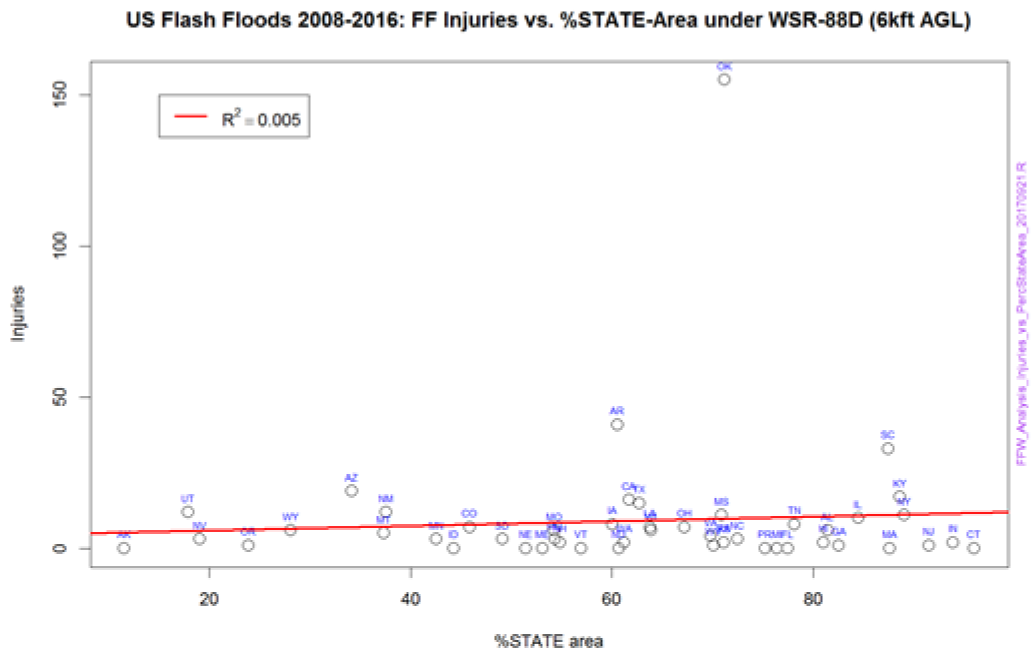


Figure E.39 - Flash flood injuries per state from 2008 to 2016 by percent state covered by radar. There is little relationship among injuries and increasing state radar coverage.

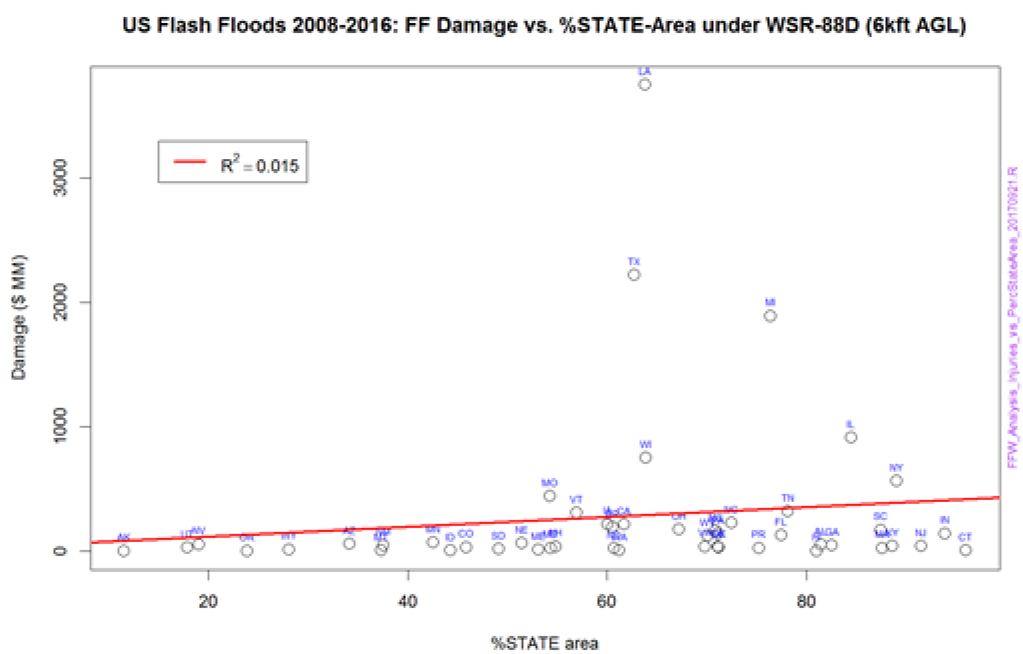


Figure E.40 - Flash flood damages per state from 2008 to 2016 by percent state covered by radar. There is little relationship among damages and increasing state radar coverage.

Fatalities, injuries, damages and significant damages were also calculated on a per event basis. The impacts per event for all events as well as for unwarned events were then compared to percent of state covered by radar. There is again little relationship between fatalities per event (Figure E.41), fatalities per unwarned event (Figure E.42), injuries per event (Figure E.43), injuries per unwarned event (Figure E.46), damages per event (Figure E.47), damages per unwarned event (Figure E.50), significant damages per event (Figure E.53), and significant unwarned damages per event (Figure E.54), recorded by state as a function of state radar coverage.

A ratio of events for which a fatality, injury, or damage was recorded as a proportion of total events was also calculated by state. When compared to the percent area covered by radar per state, there is little correlation between fatalities (Figures E.43 and E.44) or significant damages (Figures E. 55 and E.56) among ratios of impactful events to all events as a function of state radar coverage for both warned and unwarned impacts. There is also little correlation between the ratio of damaging events as a ratio of total events and percent state covered by radar (Figure E.51). However, analysis shows that increasing state percent radar coverage is rather negatively correlated with a state's unwarned damaging events as a ratio of total events (Figure E.52). While the number of injuries is a small sample size to compare, there is also a slight negative correlation between increasing state percent radar coverage and injurious flash flood events as a ratio of total events (Figure E.47) as well as unwarned injurious events as a ratio of total events (Figure E.48).

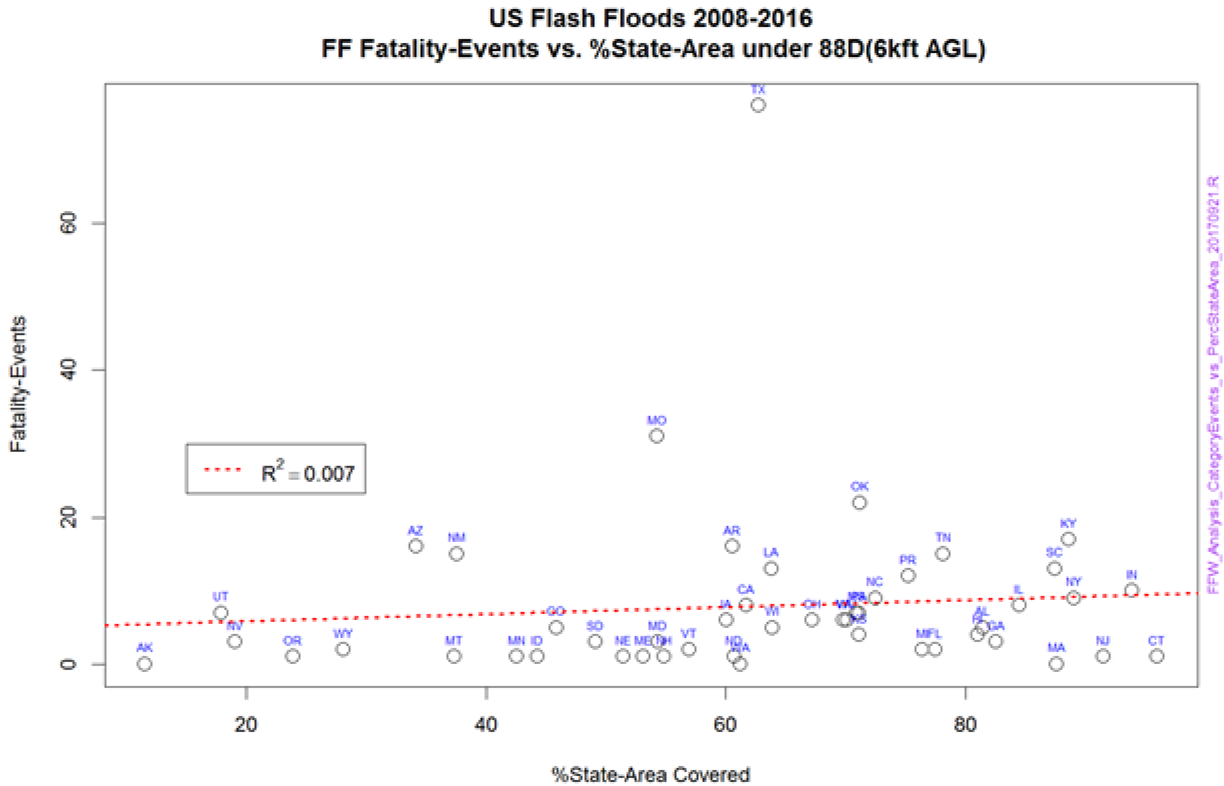


Figure E.41 - Flash flood fatalities per event per state from 2008 to 2016 by percent state covered by radar. There is little to no relationship between a state's flash flood fatality per event rate and increasing state percentage radar coverage.

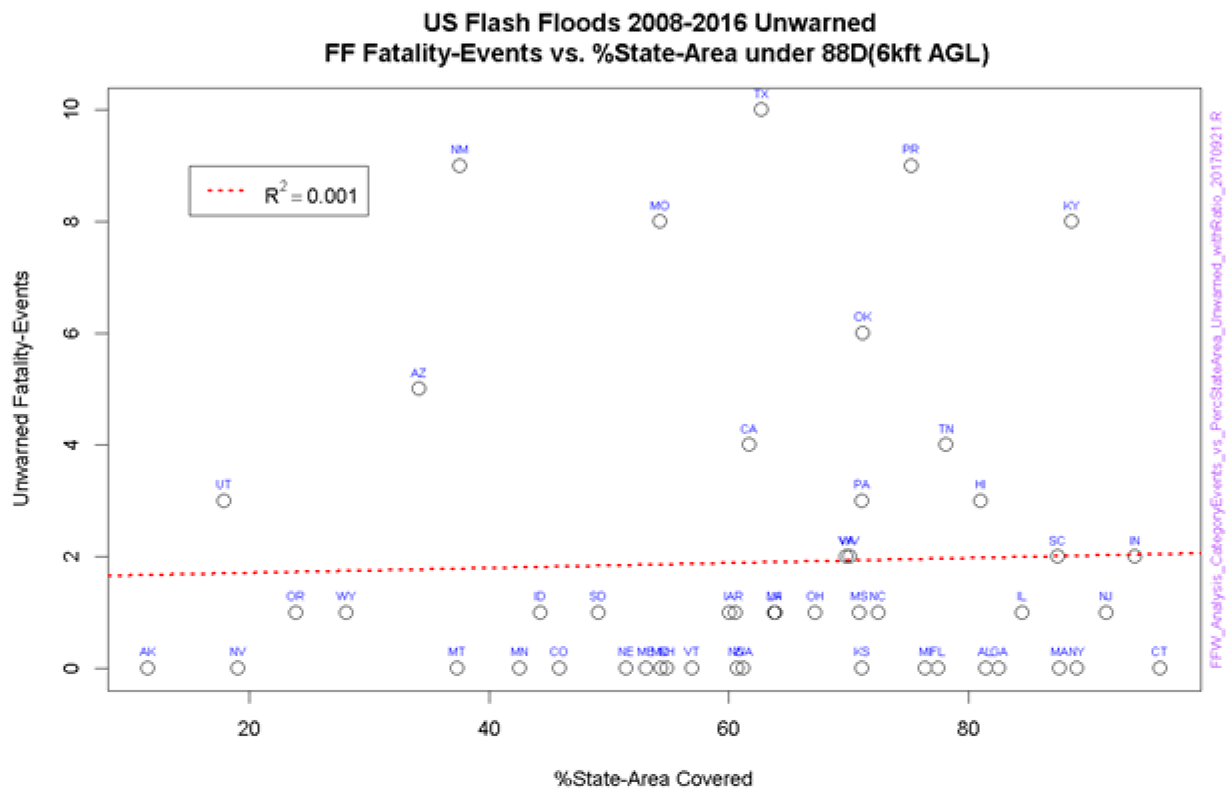


Figure E.42 - Unwarned flash flood fatalities per event per state from 2008 to 2016 by percent state covered by radar. There is little to no relationship between a state's unwarned flash flood fatality per event rate and increasing state percentage radar coverage.

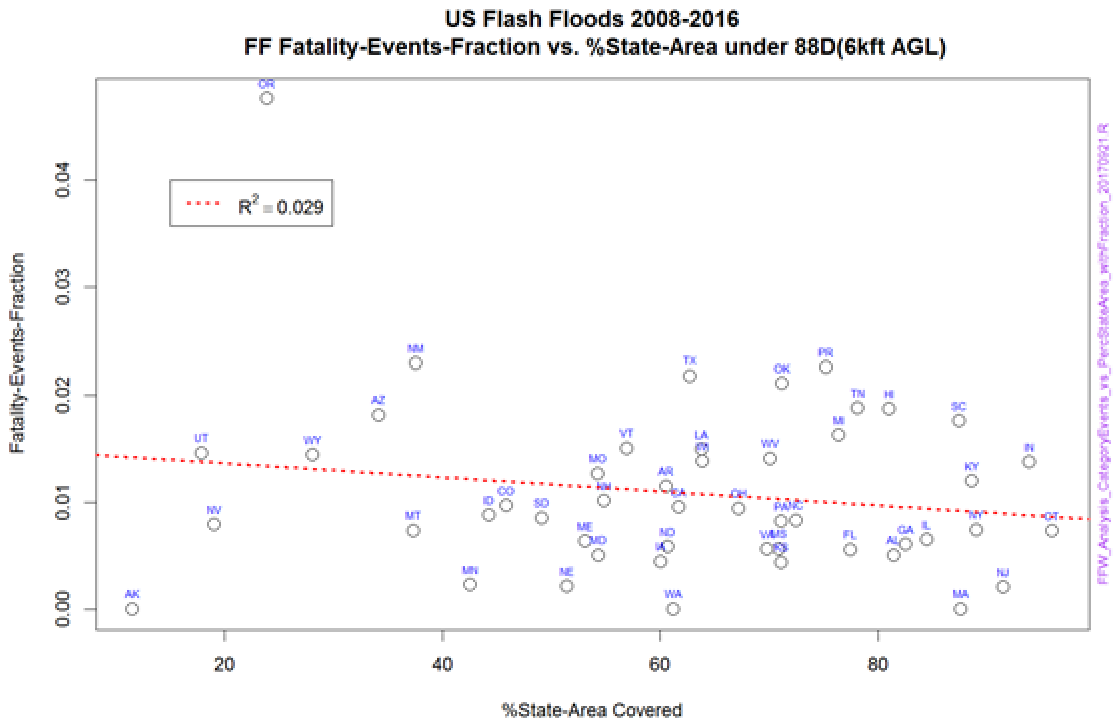


Figure E.43 - Fatal events as a ratio of total events by state from 2008 to 2016 by percent state covered by radar. There is little relationship between a state's ratio of fatal flash flood events as a ratio of total events and increasing state percentage radar coverage.

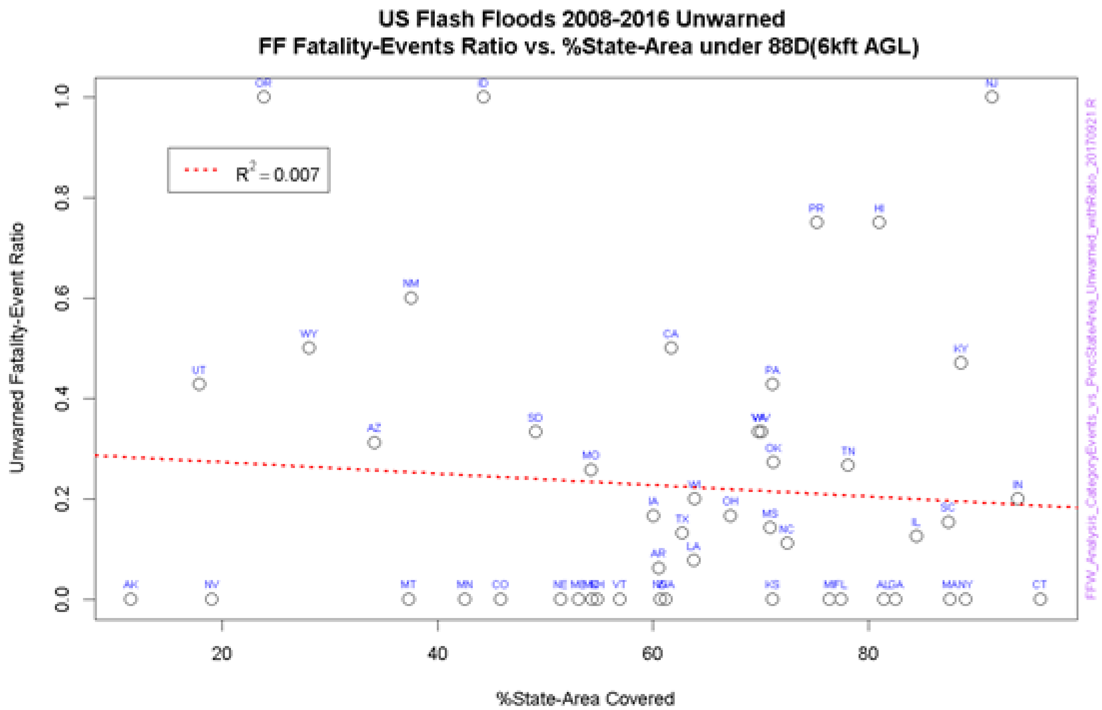


Figure E.44 - Unwarned fatal events as a ratio of total events by state from 2008 to 2016 by percent state covered by radar. There is little to no relationship between a state's ratio of unwarned fatal events to total events by state and increasing state percentage radar coverage.

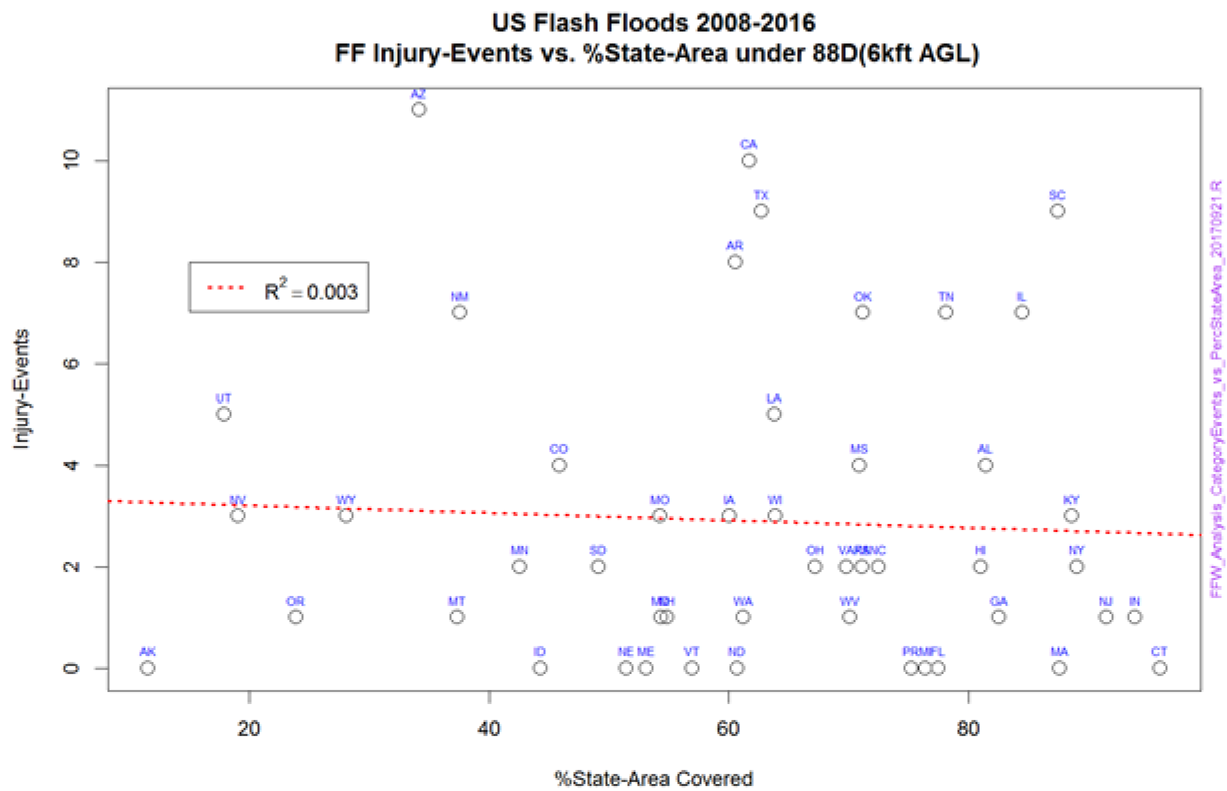


Figure E.45 - Flash flood injuries per event per state from 2008 to 2016 by percent state covered by radar. There is little to no relationship between a state's injury per event rate and increasing state percentage radar coverage.

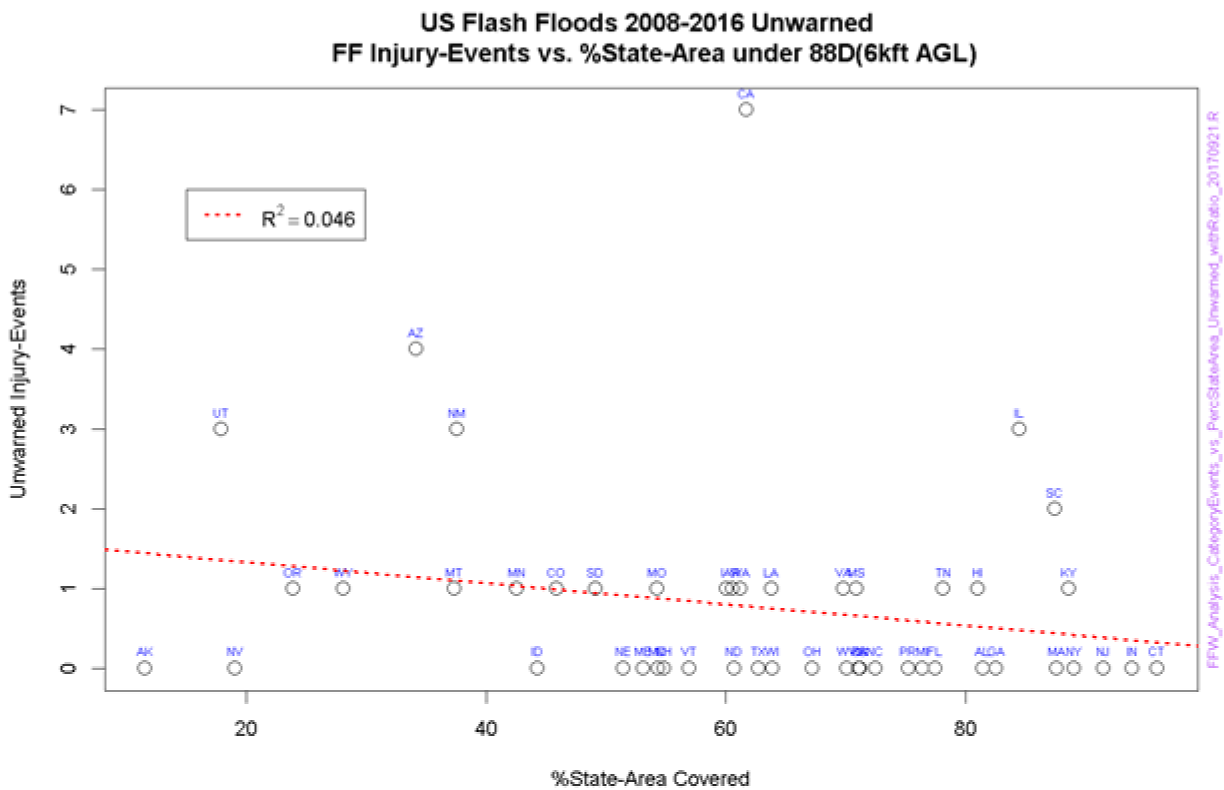


Figure E.46 - Unwarned flash flood injuries per event per state from 2008 to 2016 by percent state covered by radar. There is little relationship between a state's unwarned flash flood injuries per events and increasing state percentage radar coverage.

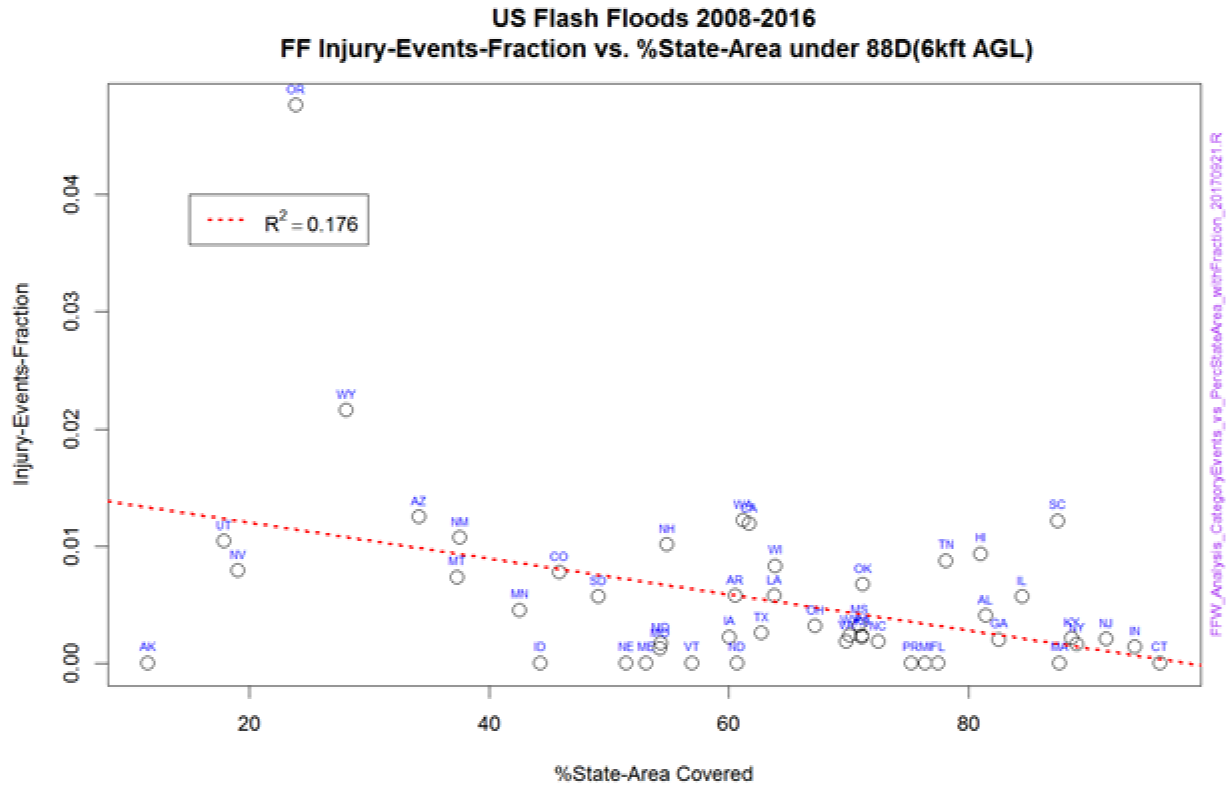


Figure E.47 - Injurious events as a ratio of total events by state from 2008 to 2016 by percent state covered by radar. There is some relationship between a state's ratio of injurious flash flood events as a ratio of total events and increasing state percentage radar coverage.

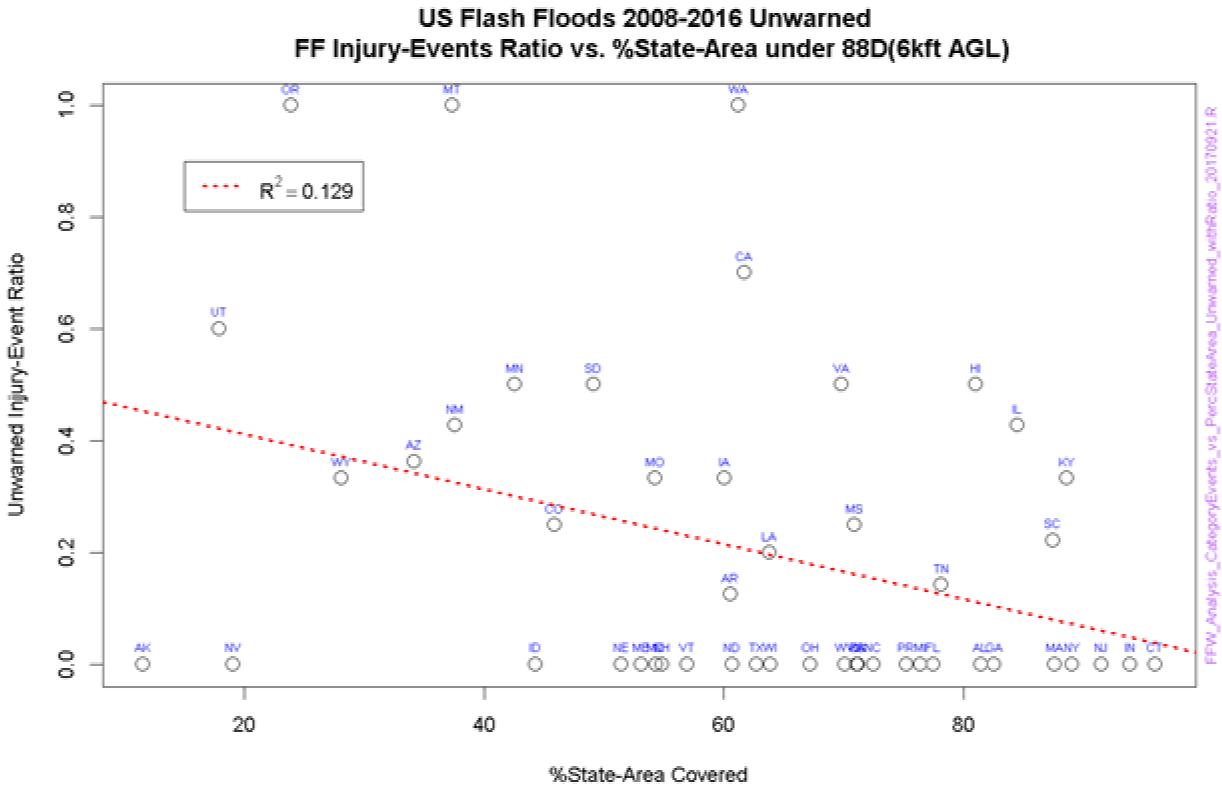


Figure E.48 - Unwarned injurious events as a ratio of total events by state from 2008 to 2016 by percent state covered by radar. The percentage of state covered by radar is negatively correlated to the ratio of unwarned injuries per event.

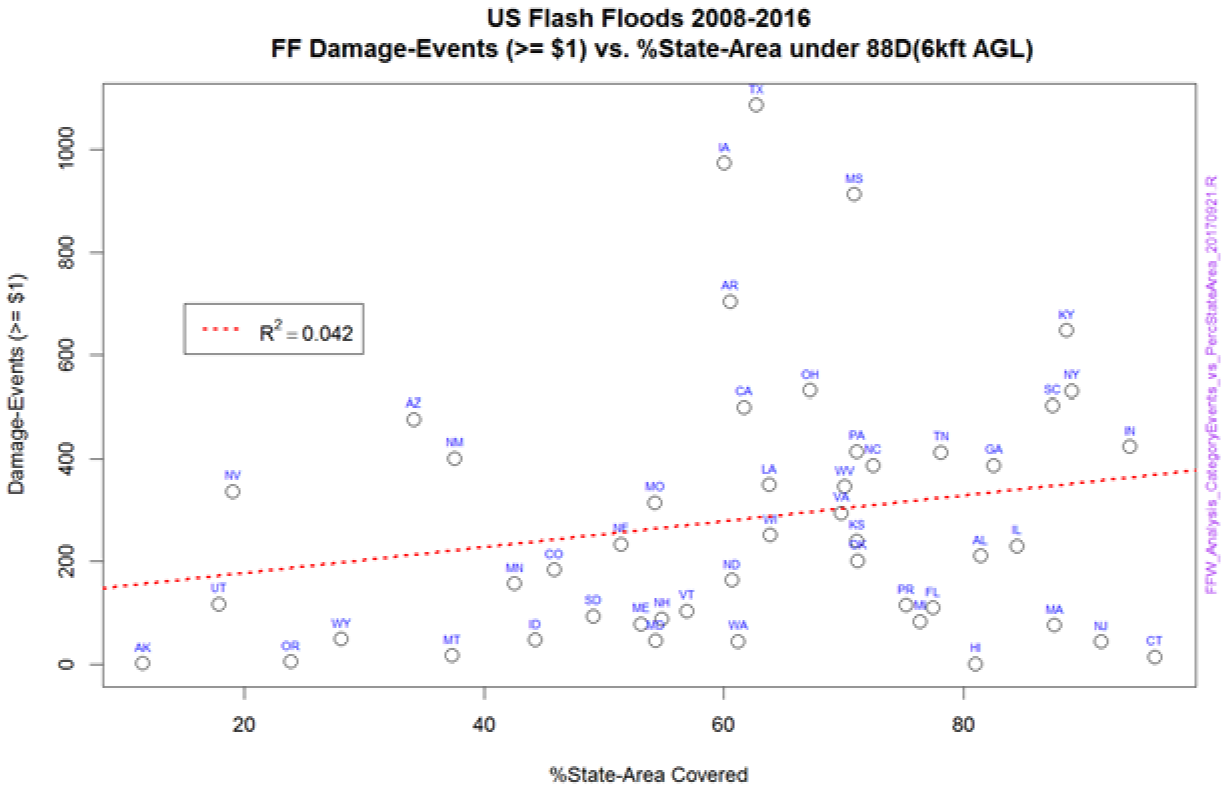


Figure E.49 - Flash flood damages per event per state from 2008 to 2016 by percent state covered by radar. There is little relationship between a state's flash flood damages per events and increasing state percentage radar coverage.

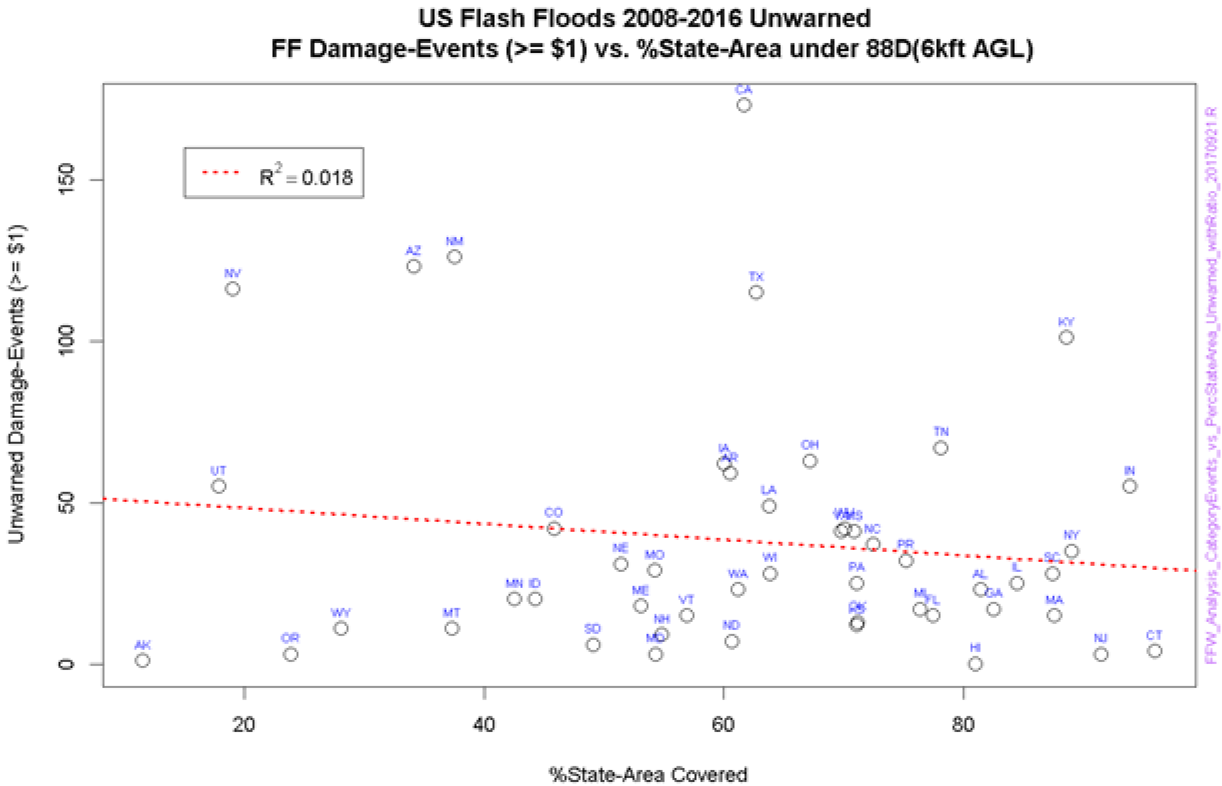


Figure E.50 - Unwarned flash flood damages per event per state from 2008 to 2016 by percent state covered by radar. There is little relationship between a state's unwarned flash flood damages per event and increasing state percentage radar coverage.

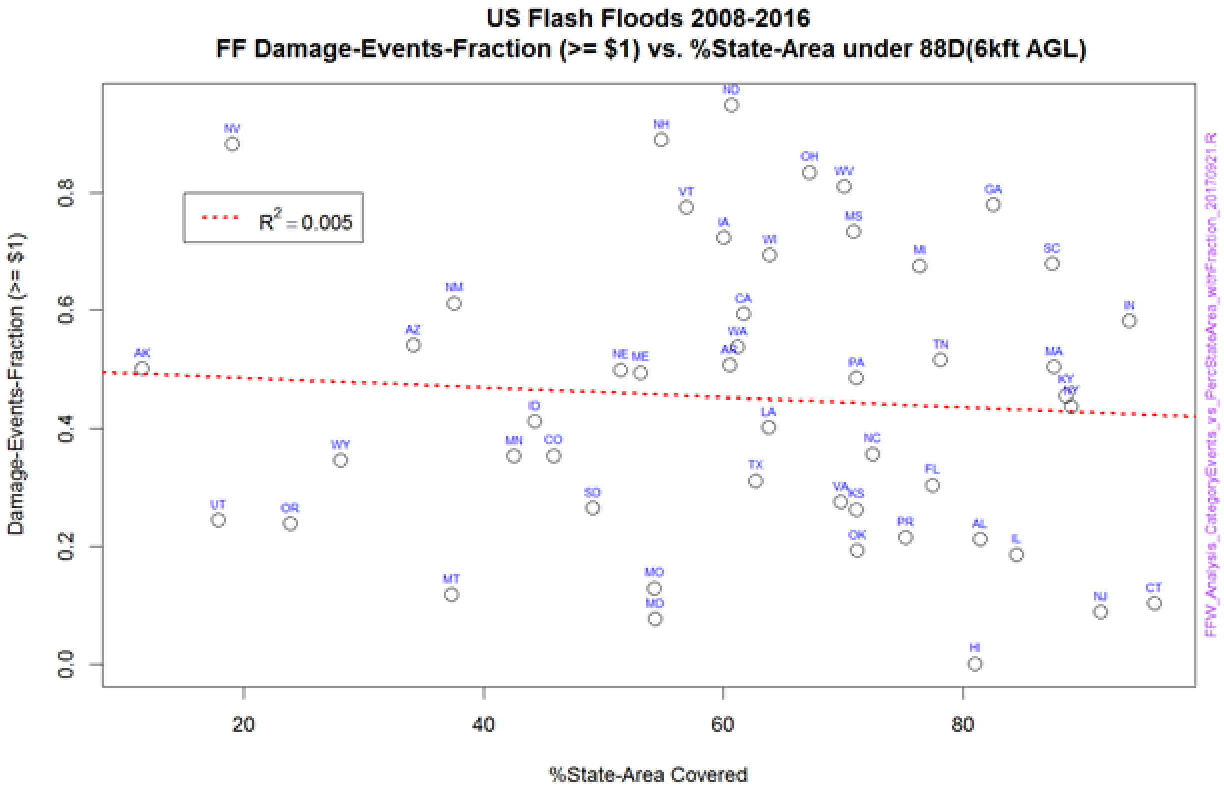


Figure E.51 - Unwarned damaging events as a ratio of total events by state from 2008 to 2016 by percent state covered by radar. Increasing state percent radar coverage is positively correlated with a state's unwarned damaging events as a ratio of total events.

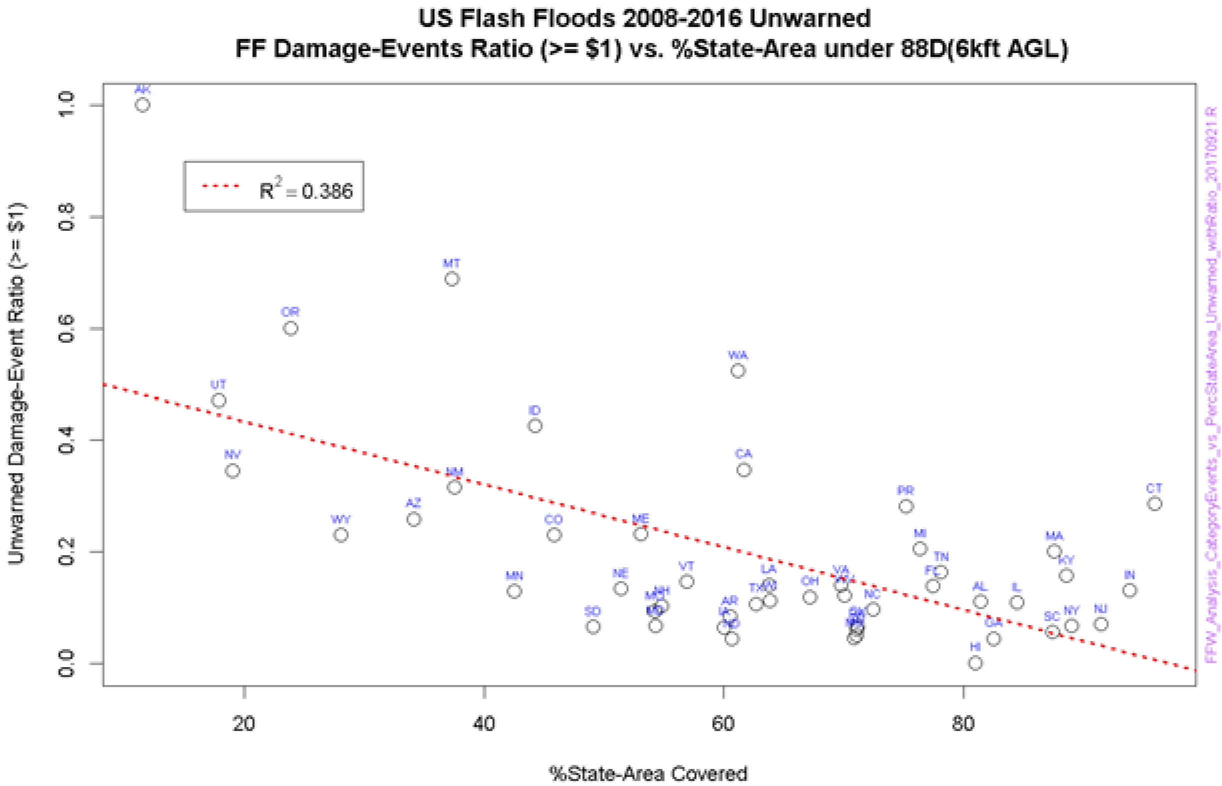


Figure E.52 - Unwarned damaging events as a ratio of total events by state from 2008 to 2016 by percent state covered by radar. Increasing state percent radar coverage is positively correlated with a state's unwarned damaging events as a ratio of total events.

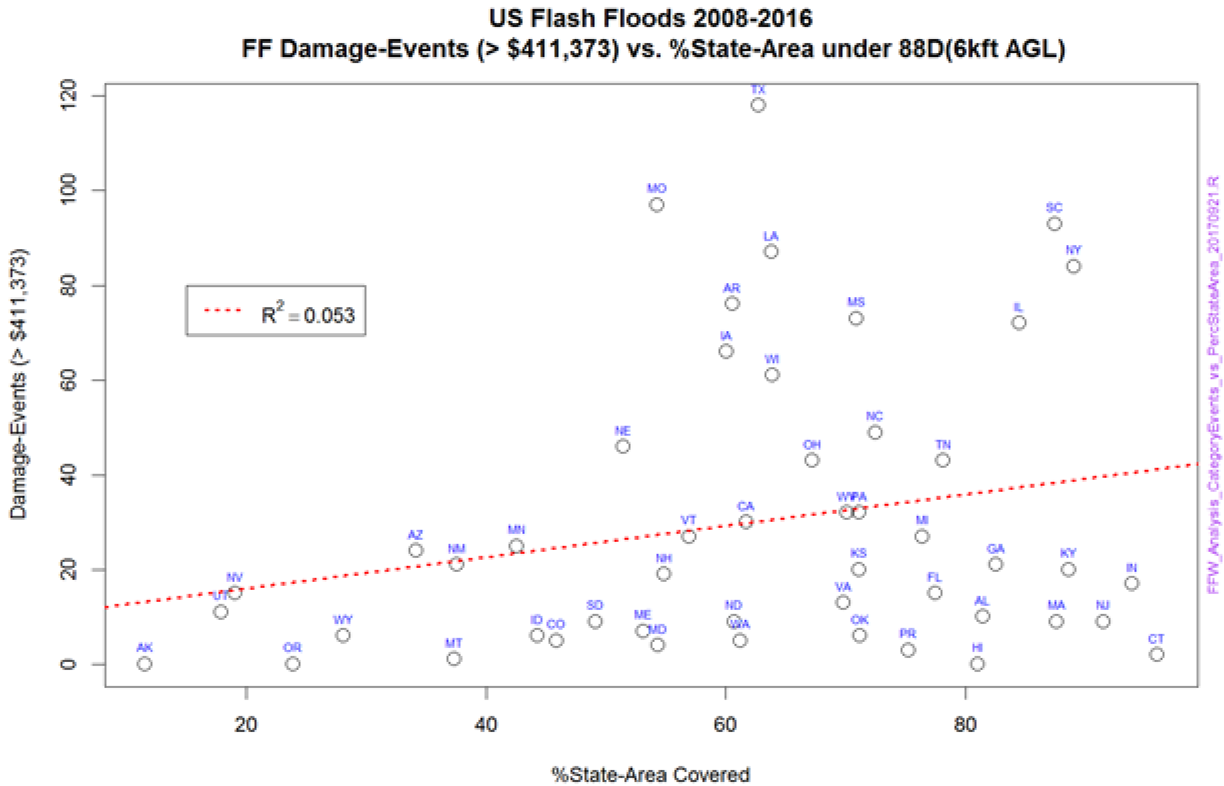


Figure E.53 - Flash flood significant damages per event per state from 2008 to 2016 by percent state covered by radar. There is little relationship between a state's significant flash flood damages per event and increasing percent state area covered by radar.

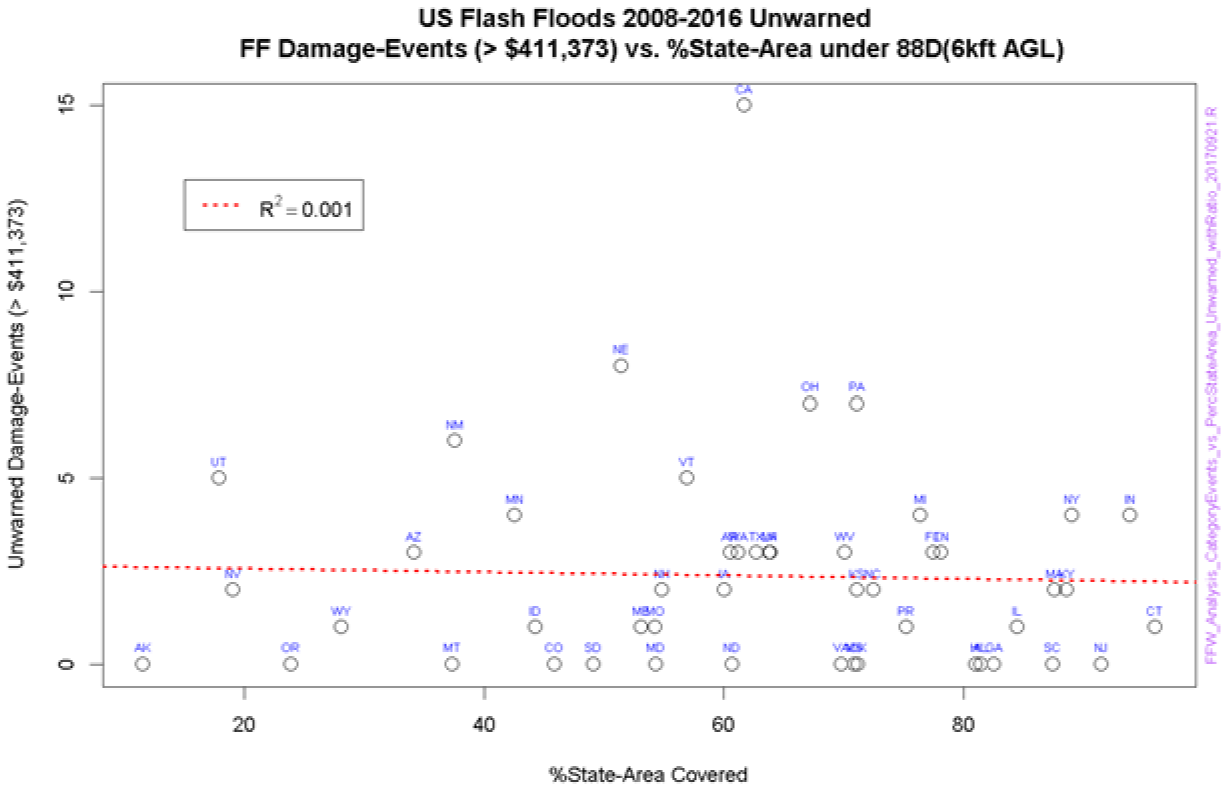


Figure E.54 - Unwarned significant flash flood damages per event per state from 2008 to 2016 by percent state covered by radar. There is little to no relationship between a state's unwarned significant flash flood damages per event and increasing percent state area covered by radar.

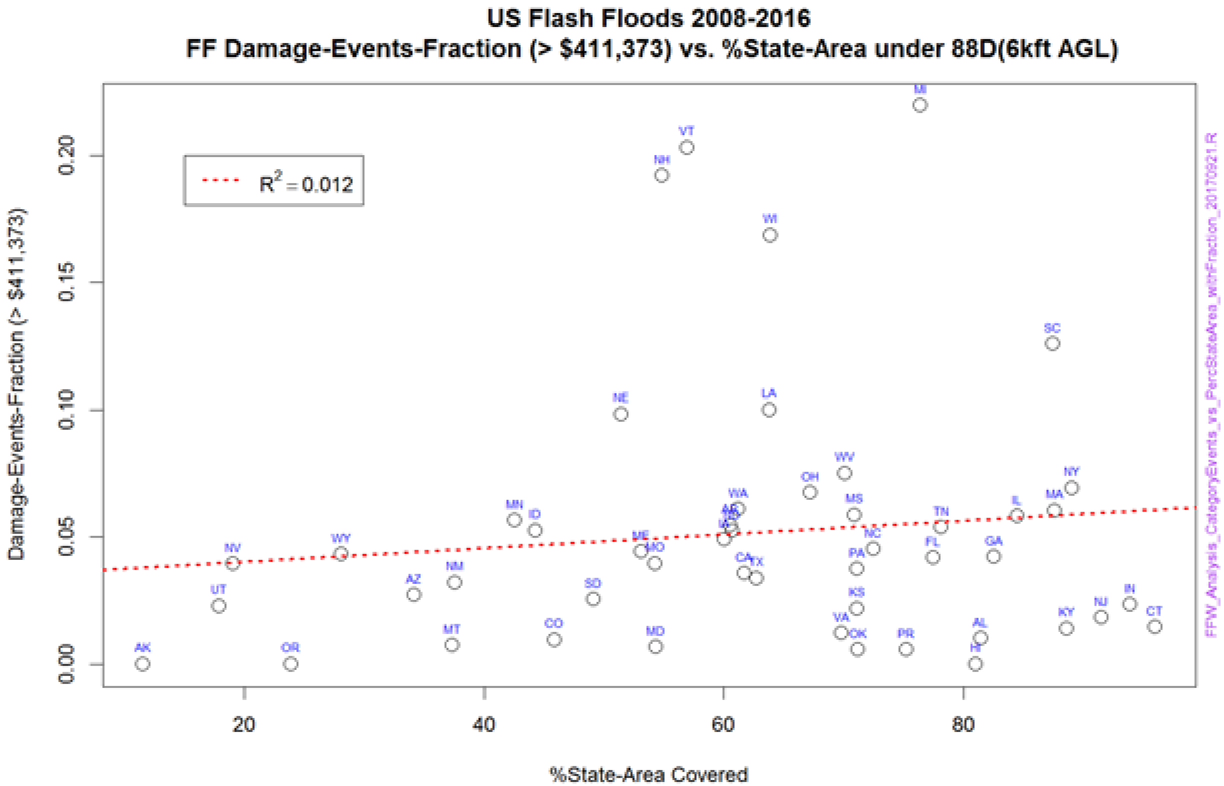


Figure E.55 - Significantly damaging events as a ratio of total events by state from 2008 to 2016 by percent state covered by radar. There is little relationship between a state's ratio of significantly damaging flash flood events as a ratio of total events and increasing state percentage radar coverage.

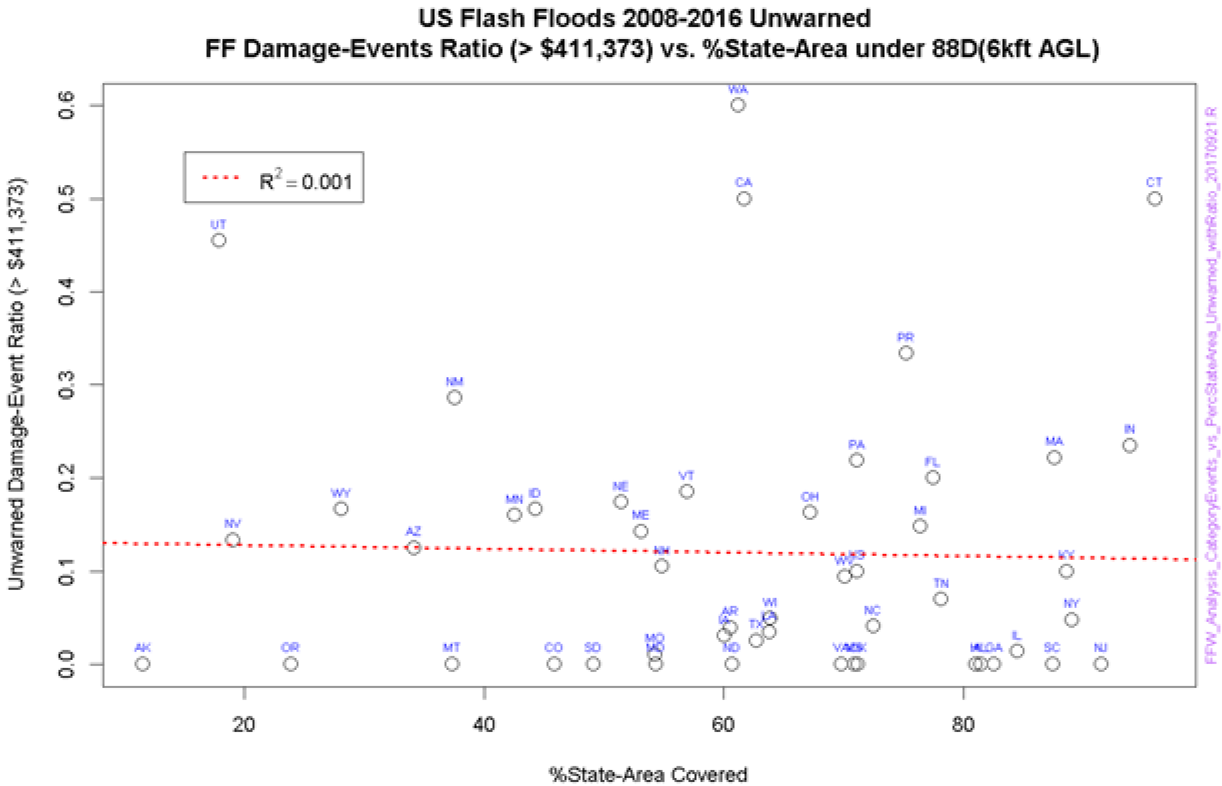


Figure E.56 - Unwarned significantly damaging events as a ratio of total events by state from 2008 to 2016 by percent state covered by radar. There is little to no relationship between unwarned significantly damaging events as a ratio of total event and increasing percent state area covered by radar.

Events, Fatalities, Injuries and Damages by Percent WFO Covered by Radar

The relationship was calculated between events, fatalities, injuries and damages by percent of WFO covered by radar as previously defined. There is little to no relationship between events (Figure E.57), fatalities (Figure E.58), injuries (Figure E.59), and damages (Figure E.60), recorded by WFO as a function of state radar coverage. Fatalities, injuries, damages and significant damages were also analyzed on a per event basis by WFO. A ratio of events for which a fatality, injury, damage, or significant damage was recorded as a proportion of total events was also calculated by WFO. This analysis was also completed for unwarned events. When compared to the percent area covered by radar per WFO, there is little to no correlation between any of these impacts on a per event basis or among ratios of impactful events to all events as a function of WFO radar coverage.

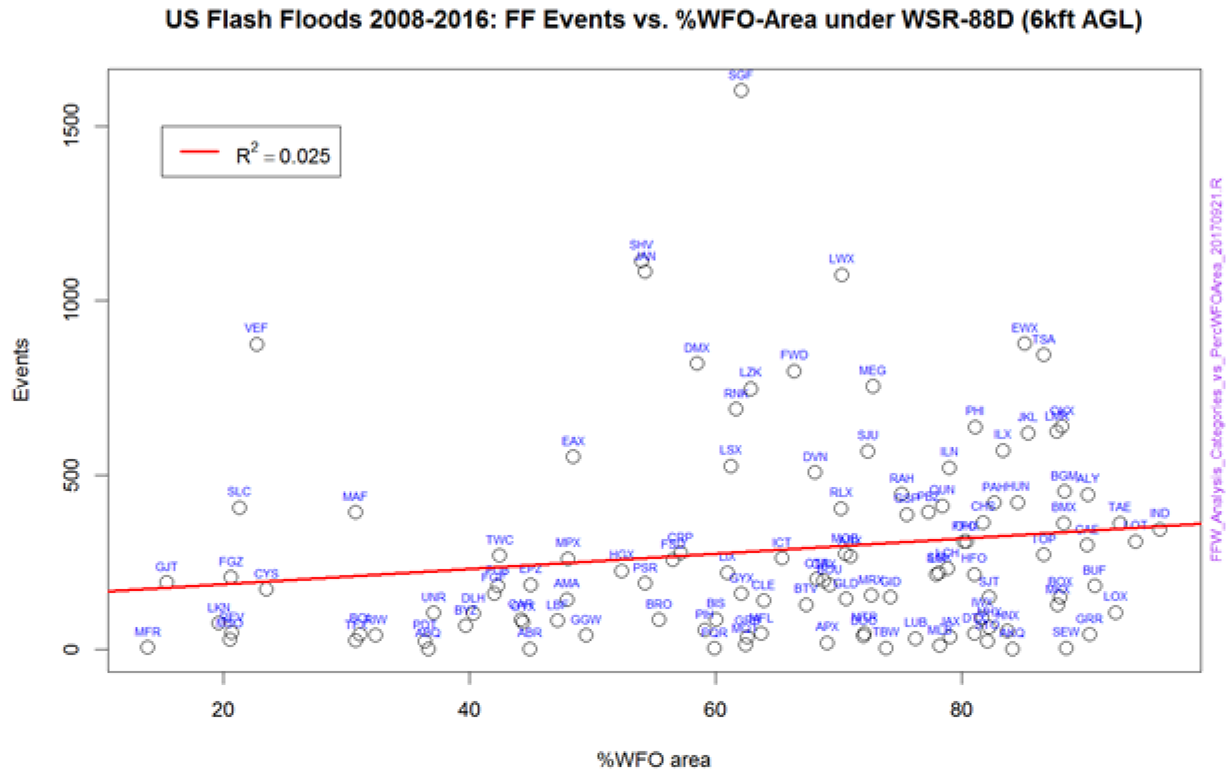


Figure E.57- Flash flood events per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between flash flood events and increasing percent WFO area covered by radar.

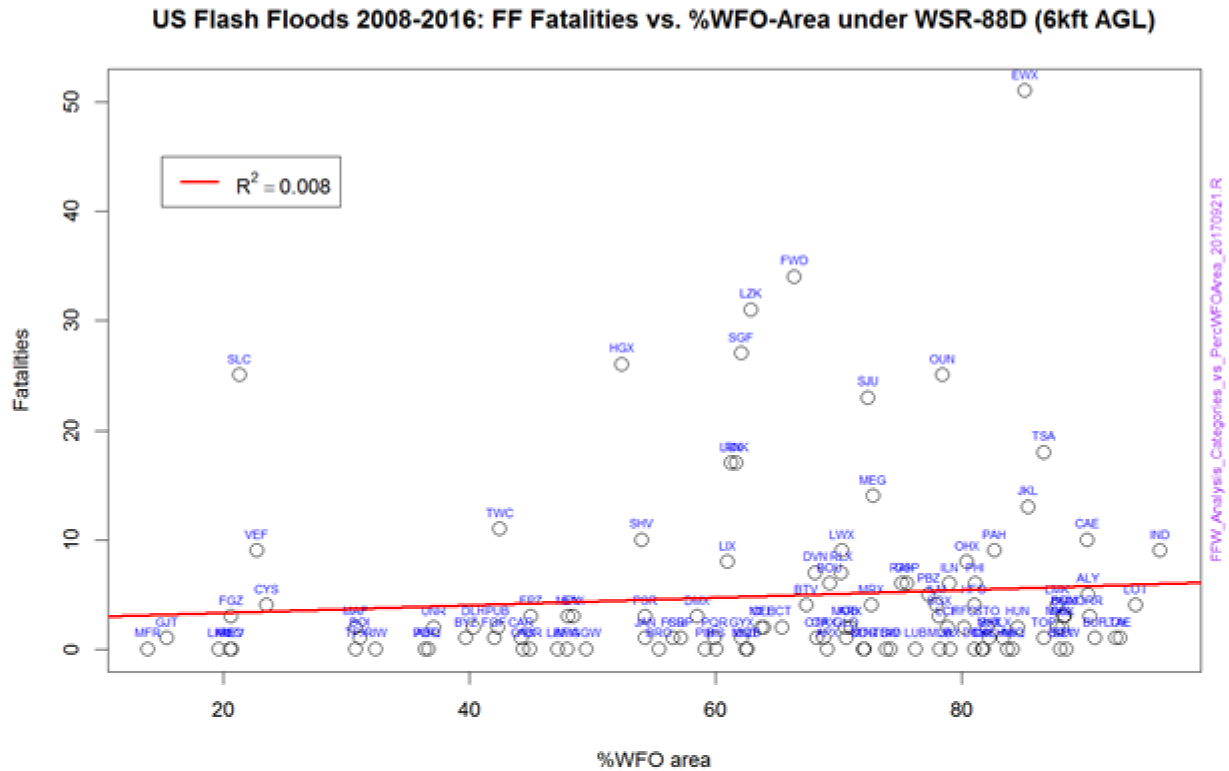


Figure E.58 - Flash flood fatalities per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between flash flood fatalities and increasing percent WFO area covered by radar.

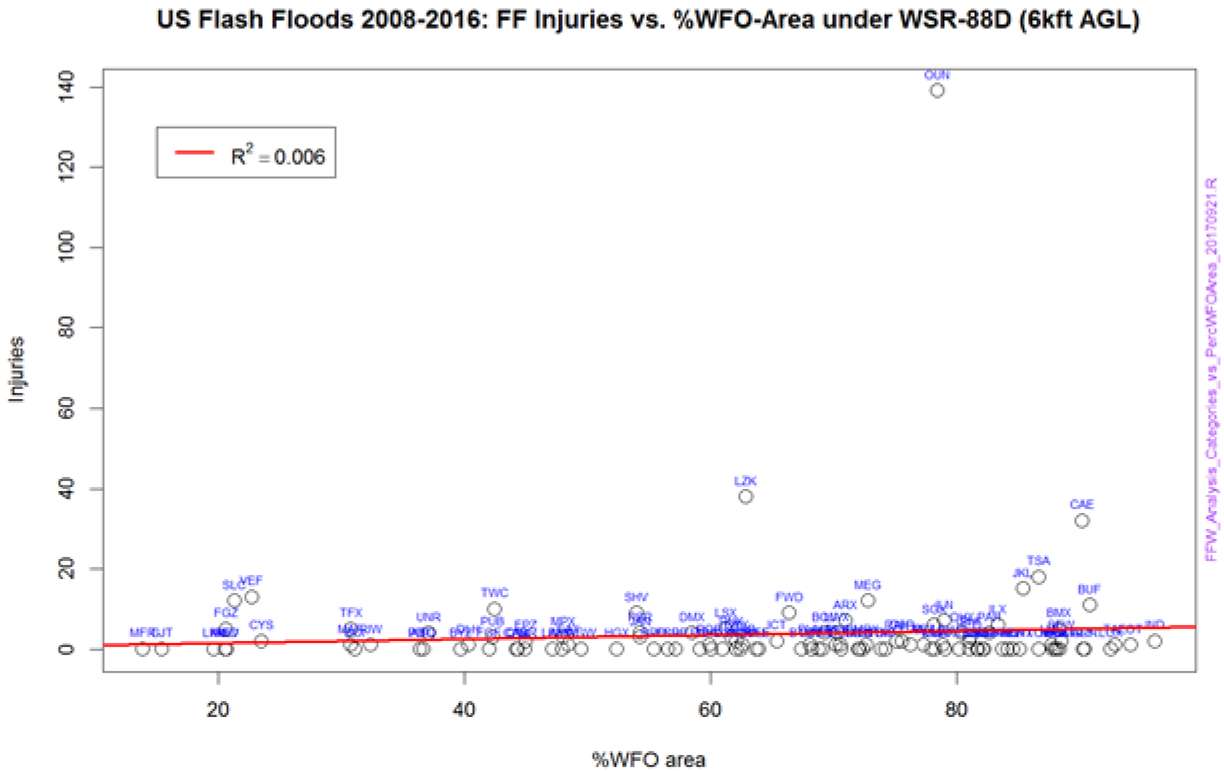


Figure E.59 - Flash flood injuries per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between flash flood injuries and increasing percent WFO area covered by radar.

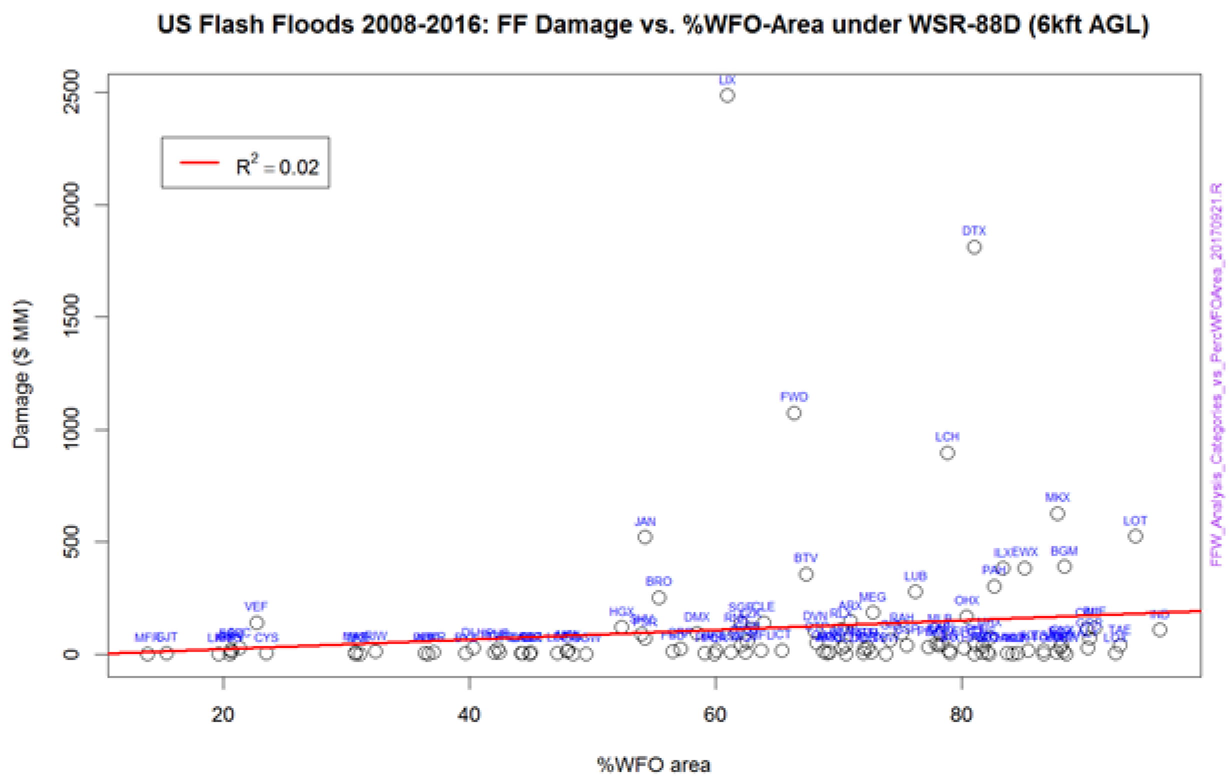


Figure E.60 - Flash flood damages per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between flash flood damages and increasing percent WFO area covered by radar.

Fatalities, injuries, damages and significant damages were also analyzed on a per event basis by WFO. A ratio of events for which a fatality, injury, damage, or significant damage was recorded as a proportion of total events was also calculated by WFO. This analysis was also completed for unwarned events. When compared to the percent area covered by radar per WFO, there is little to no correlation between any of these impacts on a per event basis or among ratios of impactful events to all events as a function of WFO radar coverage. These correlations are depicted in Figures E.61 through E.76.

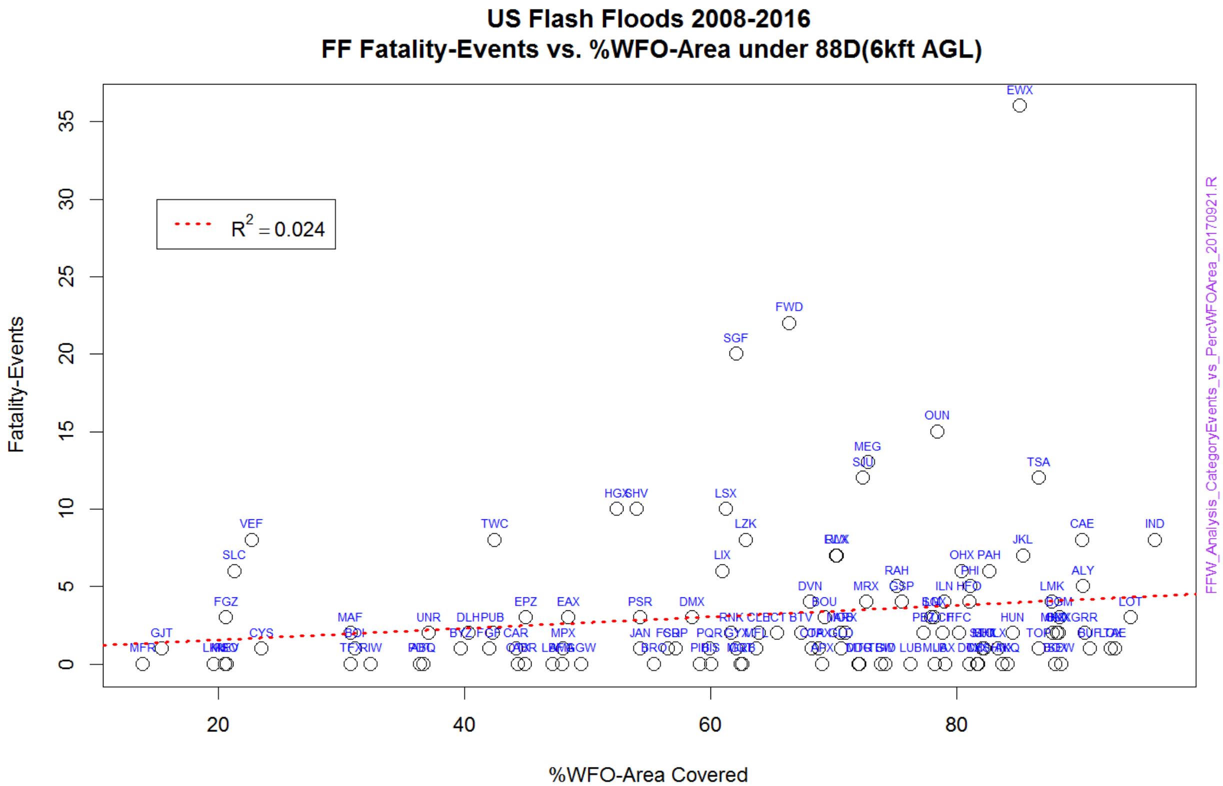


Figure E.61 - Flash flood fatalities per event per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between flash flood fatalities per event and increasing percent WFO area covered by radar.

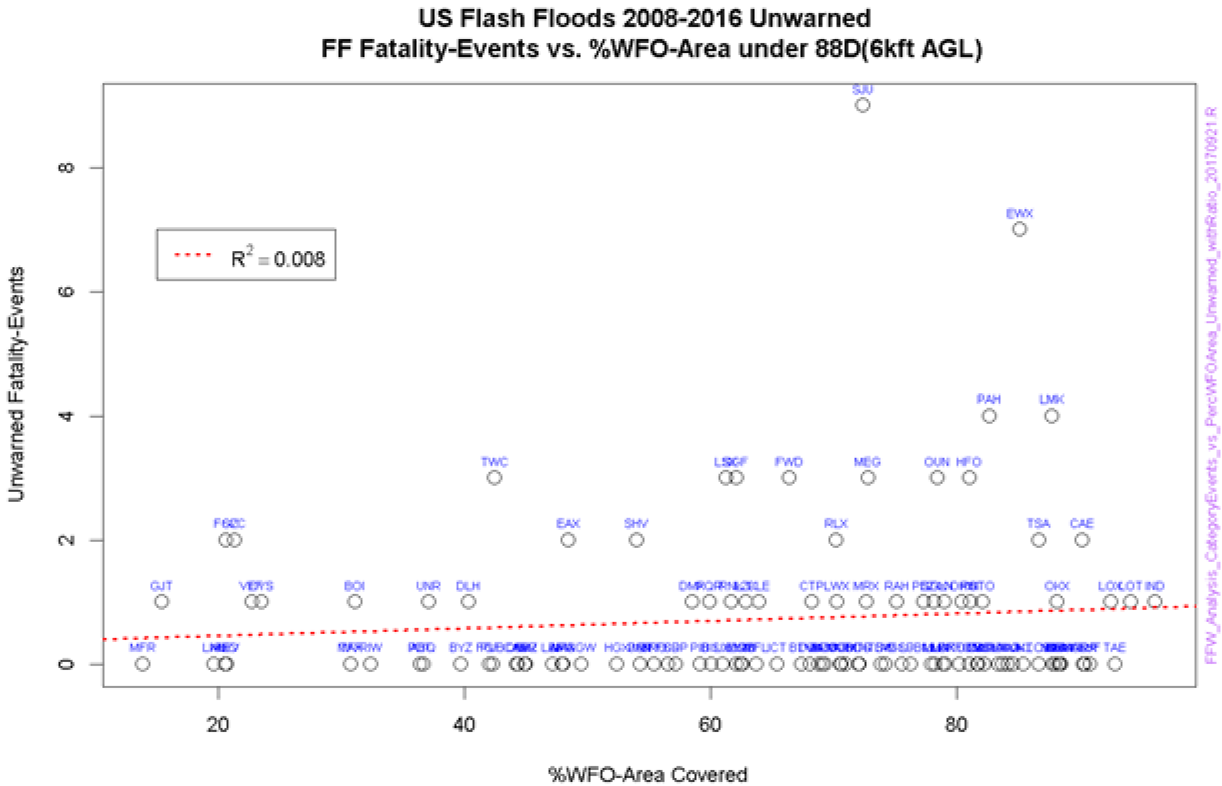


Figure E.62 - Unwarned flash flood fatalities per event per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between unwarned flash flood fatalities per event and increasing percent WFO area covered by radar.

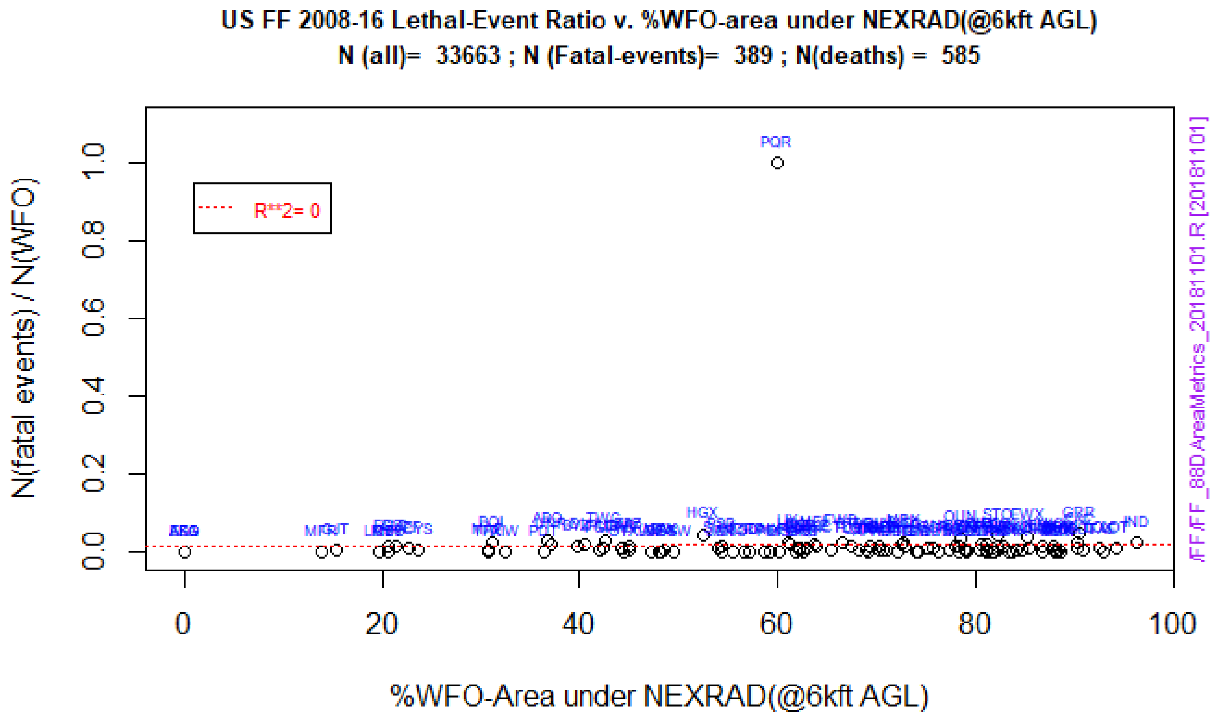


Figure E.63- Fatal events as a ratio of total events per WFO for 2008-2016 by percent WFO-area covered by NEXRAD's beam under 6 kft AGL. There is no relationship between fatal events as a ratio of total events and increasing percent WFO area covered by radar as the fit is not statistically significant.

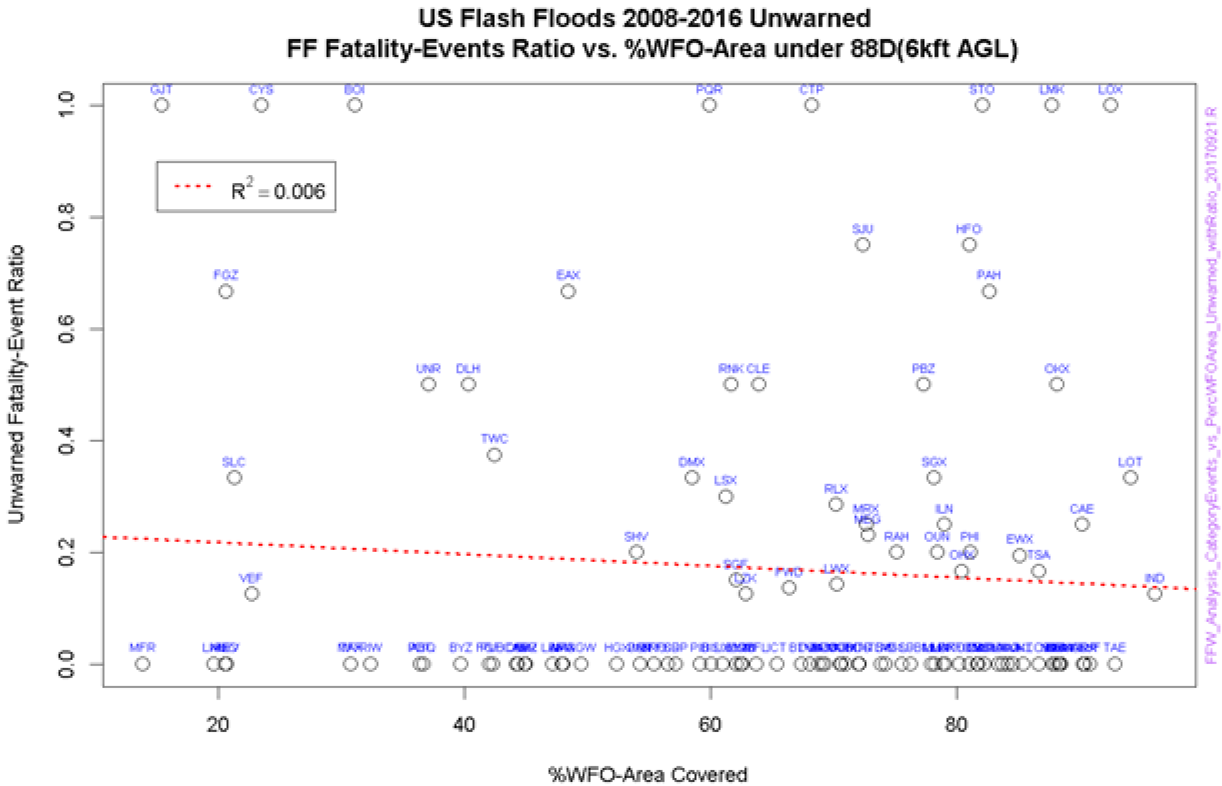


Figure E.64 - Unwarned fatal events as a ratio of total events per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between unwarned fatal events as a ratio of total events and radar coverage as the linear fit is not statistically significant.

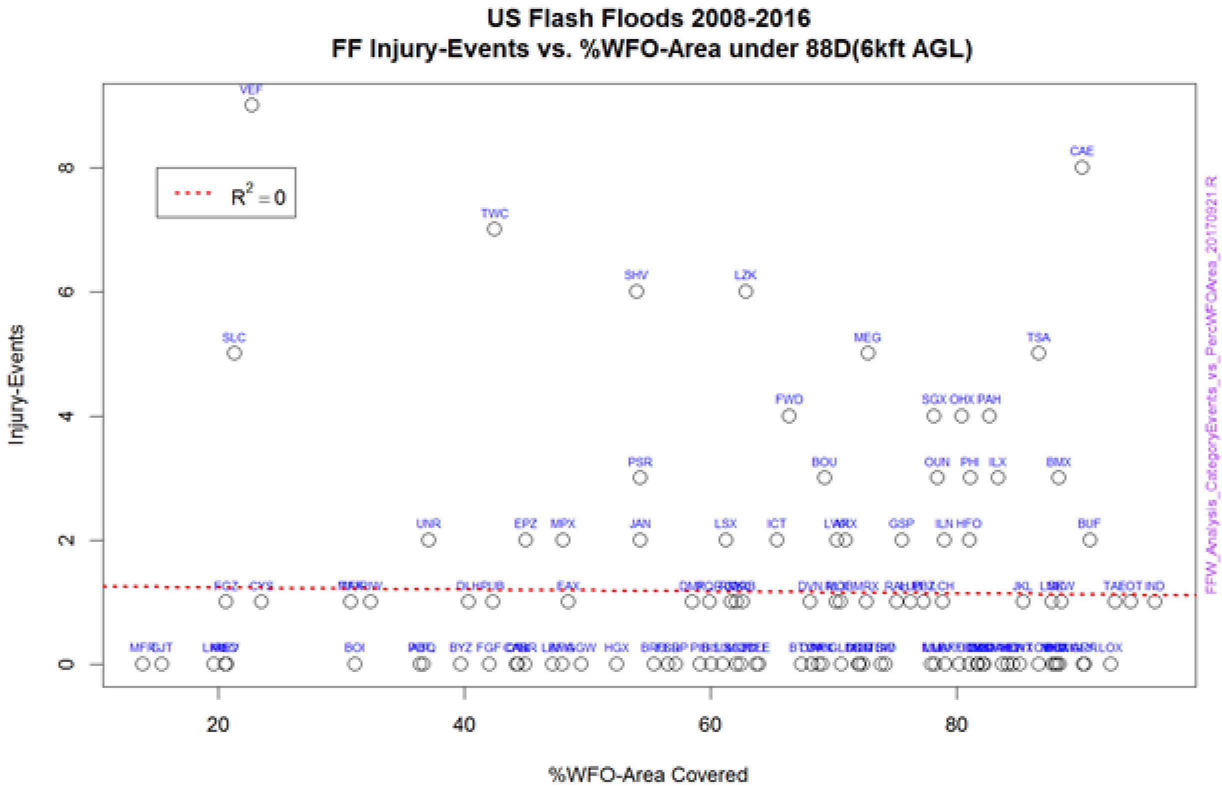


Figure E.65 - Flash flood injuries per event per WFO from 2008 to 2016 by percent WFO covered by radar. There is no relationship between flash flood injuries per event and increasing percent WFO area covered by radar. The staggered nature of this plot makes clear the drawbacks of a limited dataset.

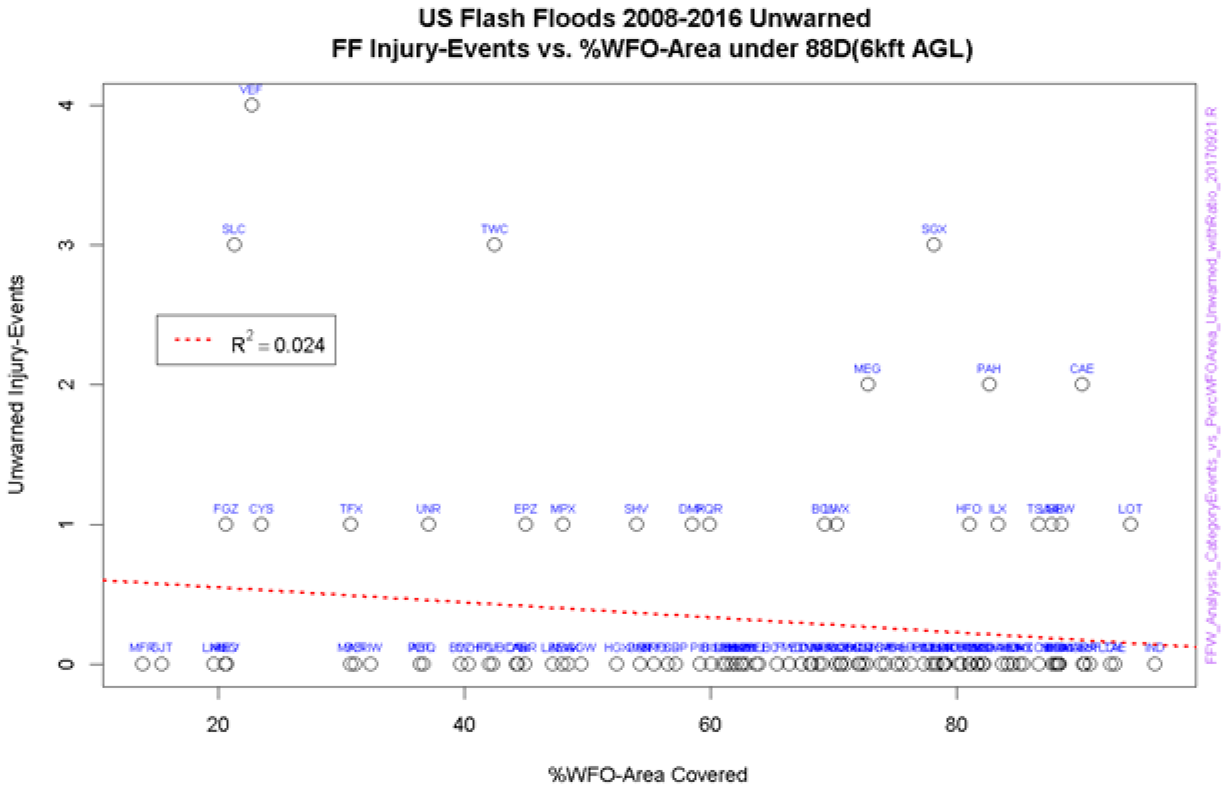


Figure E.66 - Unwarned flash flood injuries per event per WFO from 2008 to 2016 by percent WFO covered by radar. There is no relationship between unwarned flash flood injuries per event and increasing percent WFO area covered by radar. The staggered nature of this plot makes clear the drawbacks of a limited dataset.

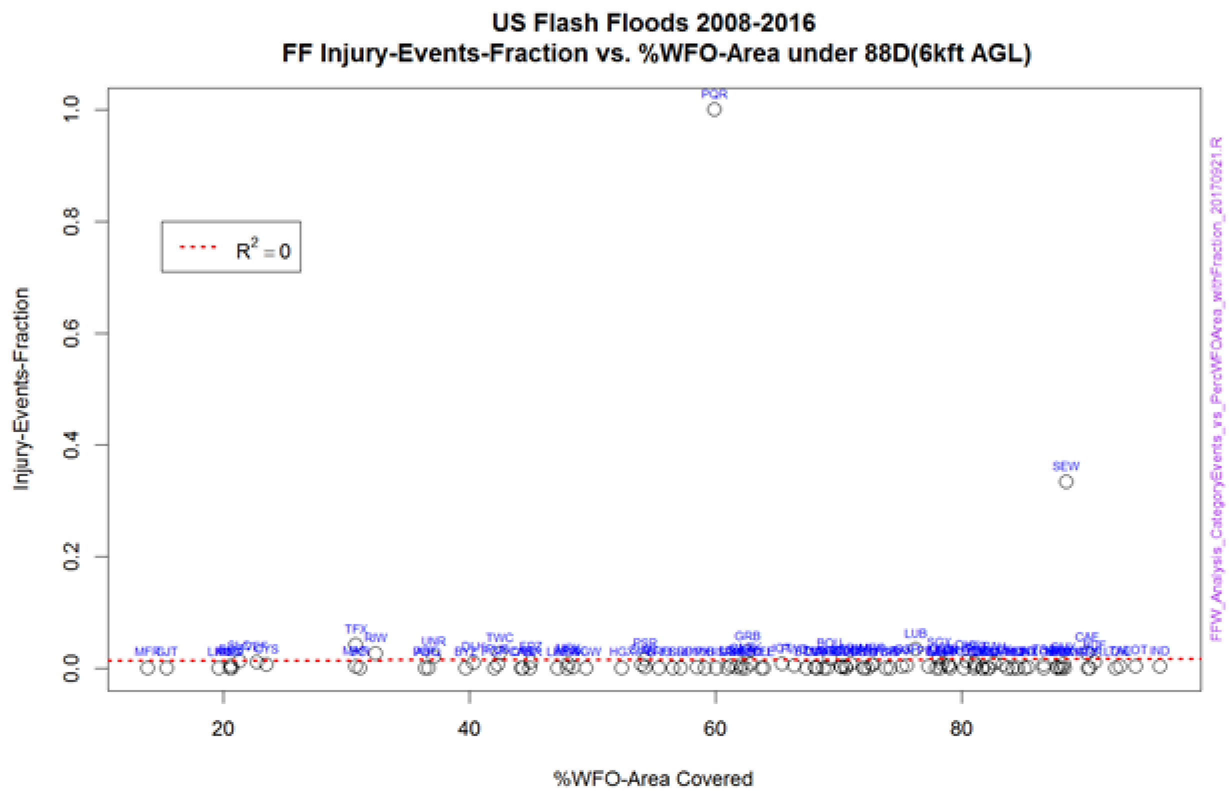


Figure E.67 - Injurious events as a ratio of total events per WFO from 2008 to 2016 by percent WFO covered by radar. There is no relationship between injurious events as a ratio of total events and increasing percent WFO area covered by radar.

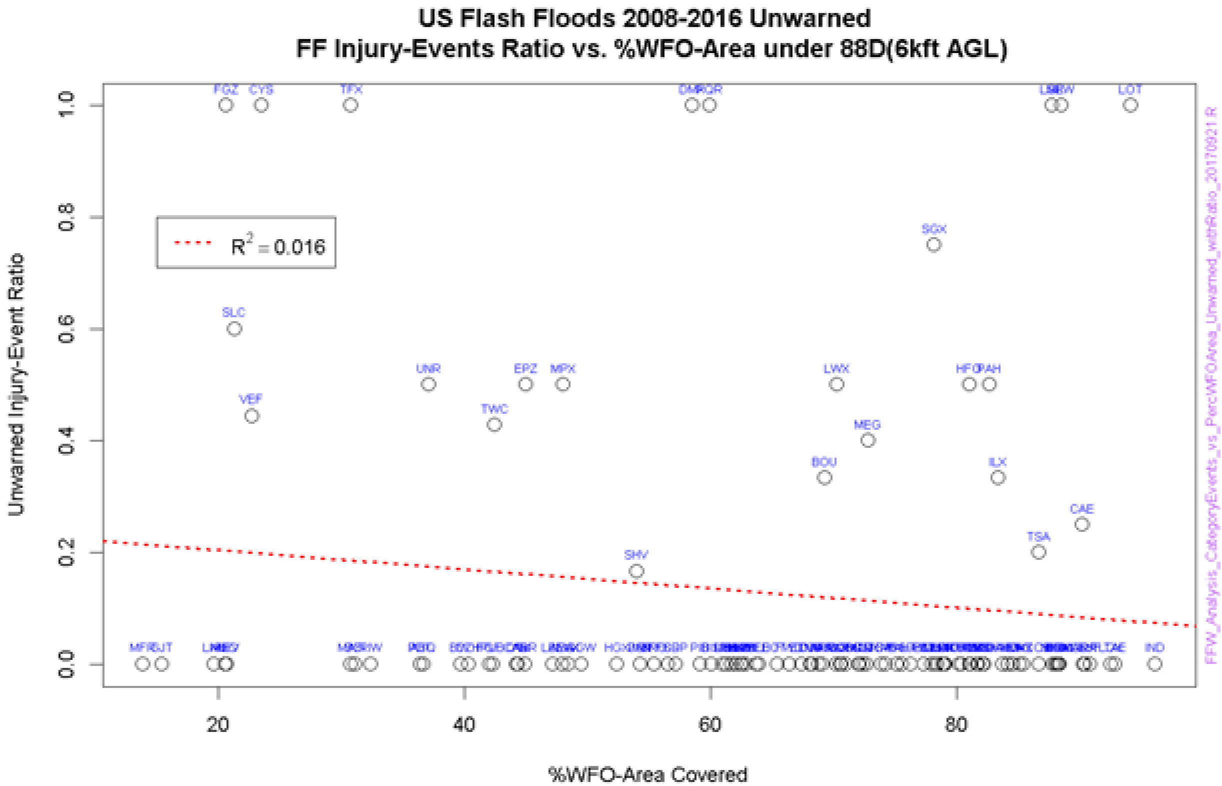


Figure E.68 - Unwarned injurious events as a ratio of total events per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between unwarned injurious events as a ratio of total events and increasing percent WFO area covered by radar.

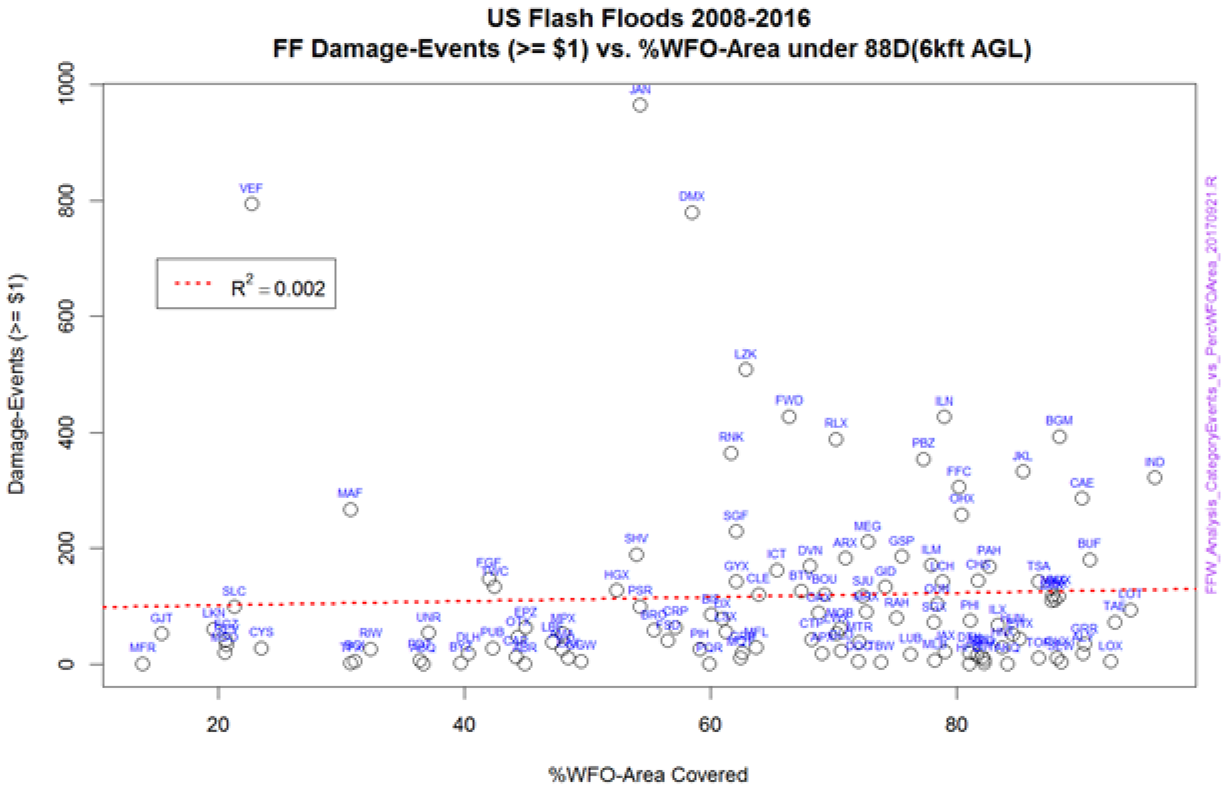


Figure E.69 - Flash flood damages per event per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between flash flood damages per event and increasing percent WFO area covered by radar.

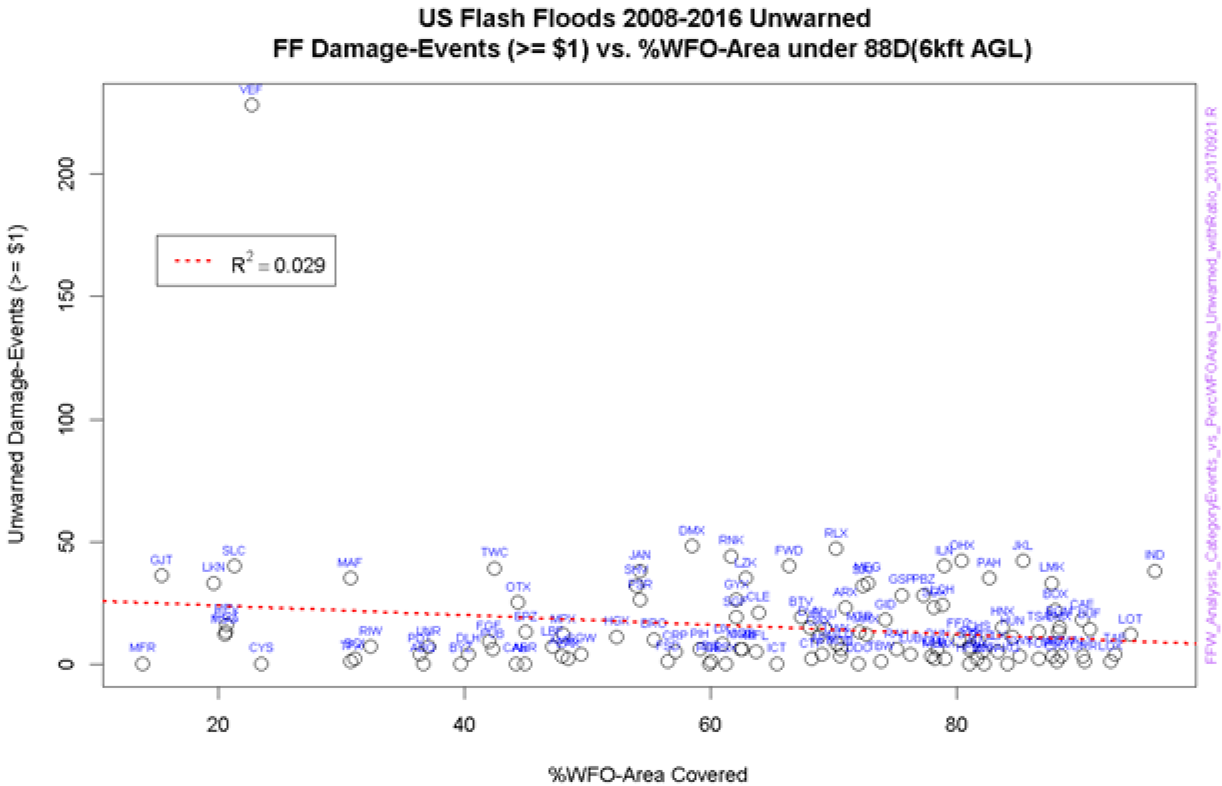


Figure E.70 - Unwarned flash flood damages per event per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between unwarned flash flood damages per event and increasing percent WFO area covered by radar.

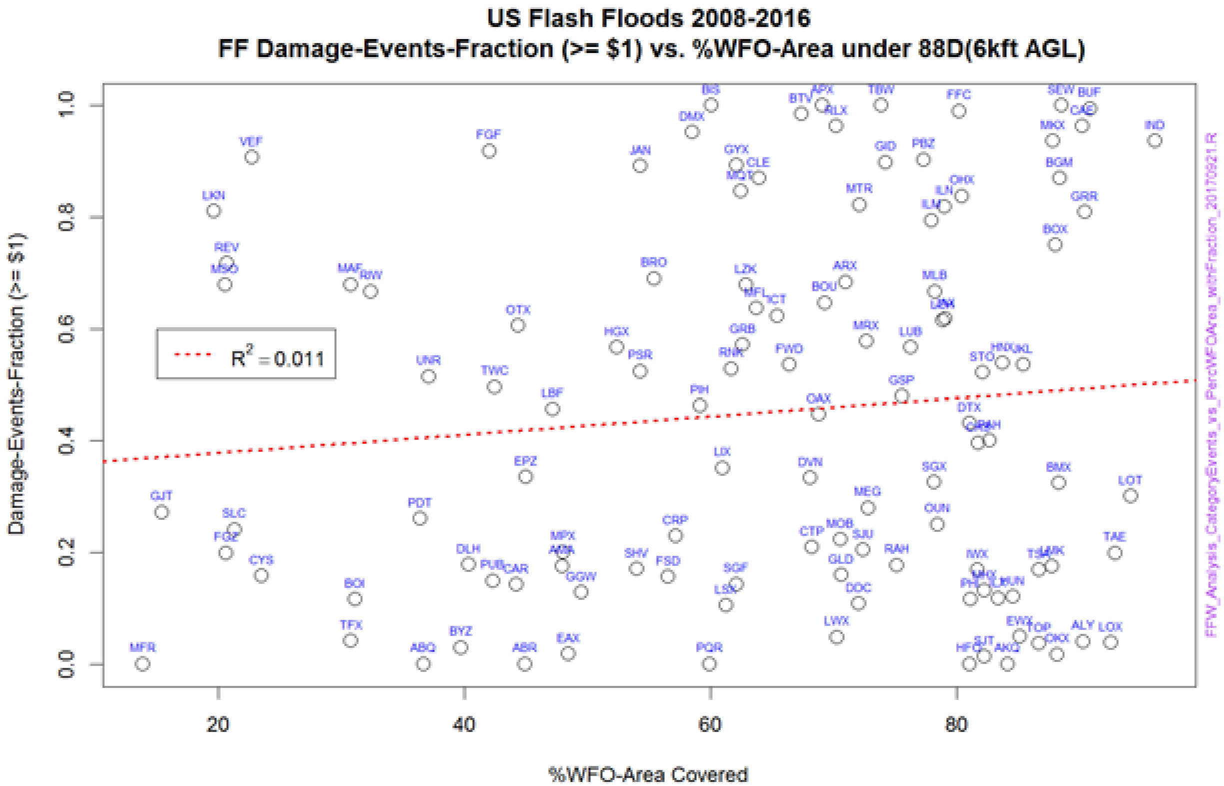


Figure E.71 - Damaging events as a ratio of total events per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between damaging events as a ratio of total events and increasing percent WFO area covered by radar.

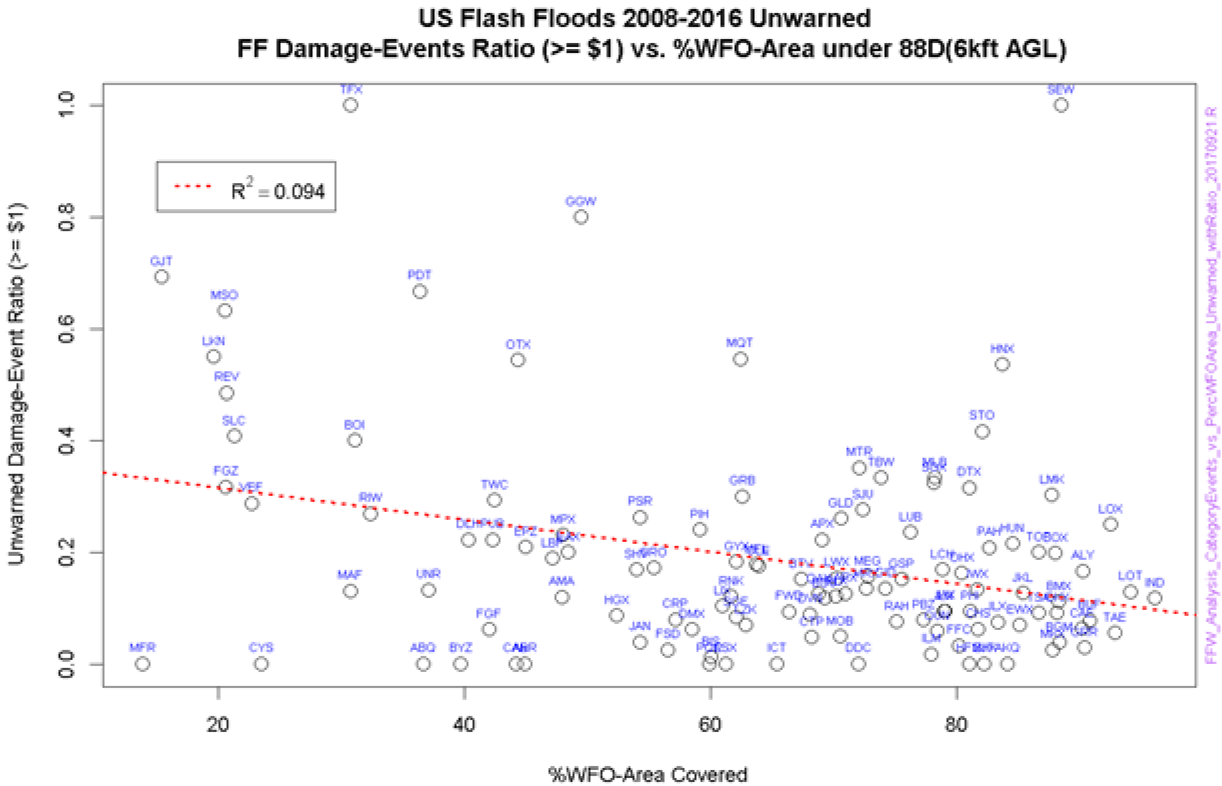


Figure E.72 - Unwarned damaging events as a ratio of total events per WFO from 2008 to 2016 by percent WFO covered by radar. There is little relationship between unwarned damaging events as a ratio of total events and increasing percent WFO area covered by radar.

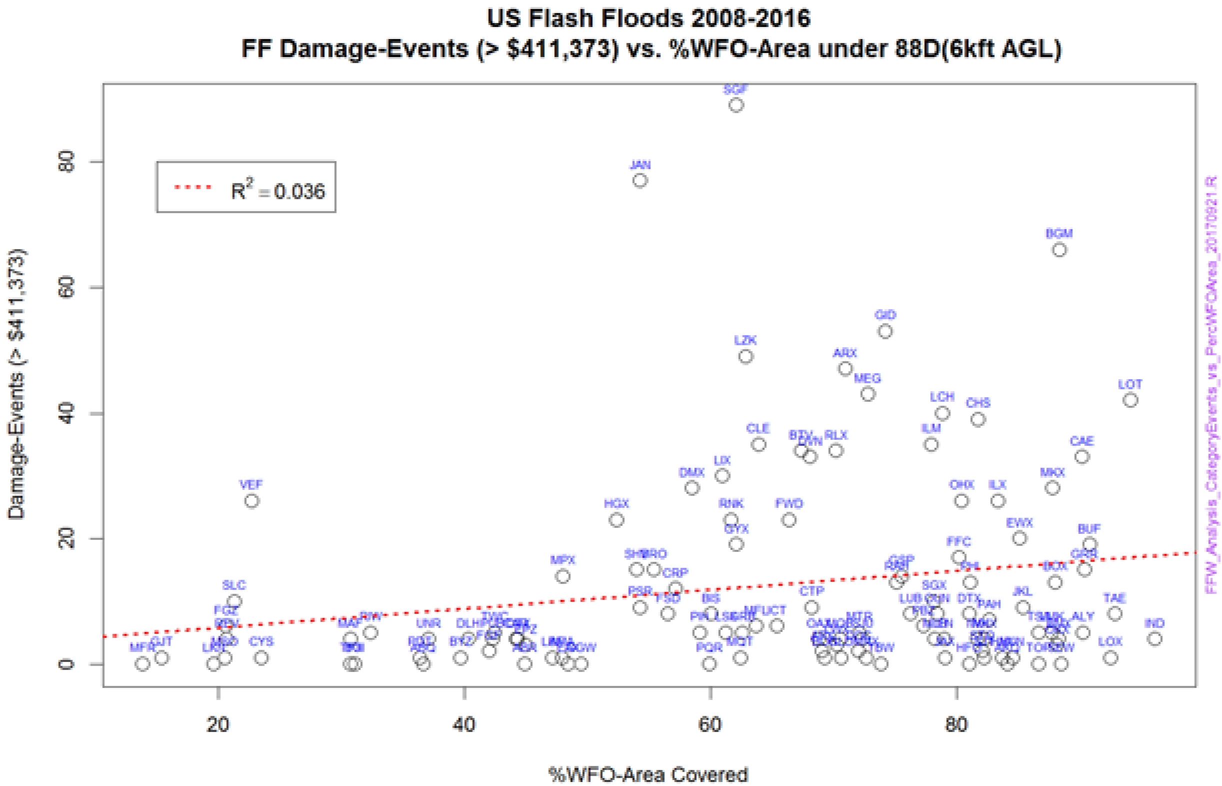


Figure E.73 - Flash flood significant damages per event per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between significant flash flood damages per event and increasing percent WFO area covered by radar.

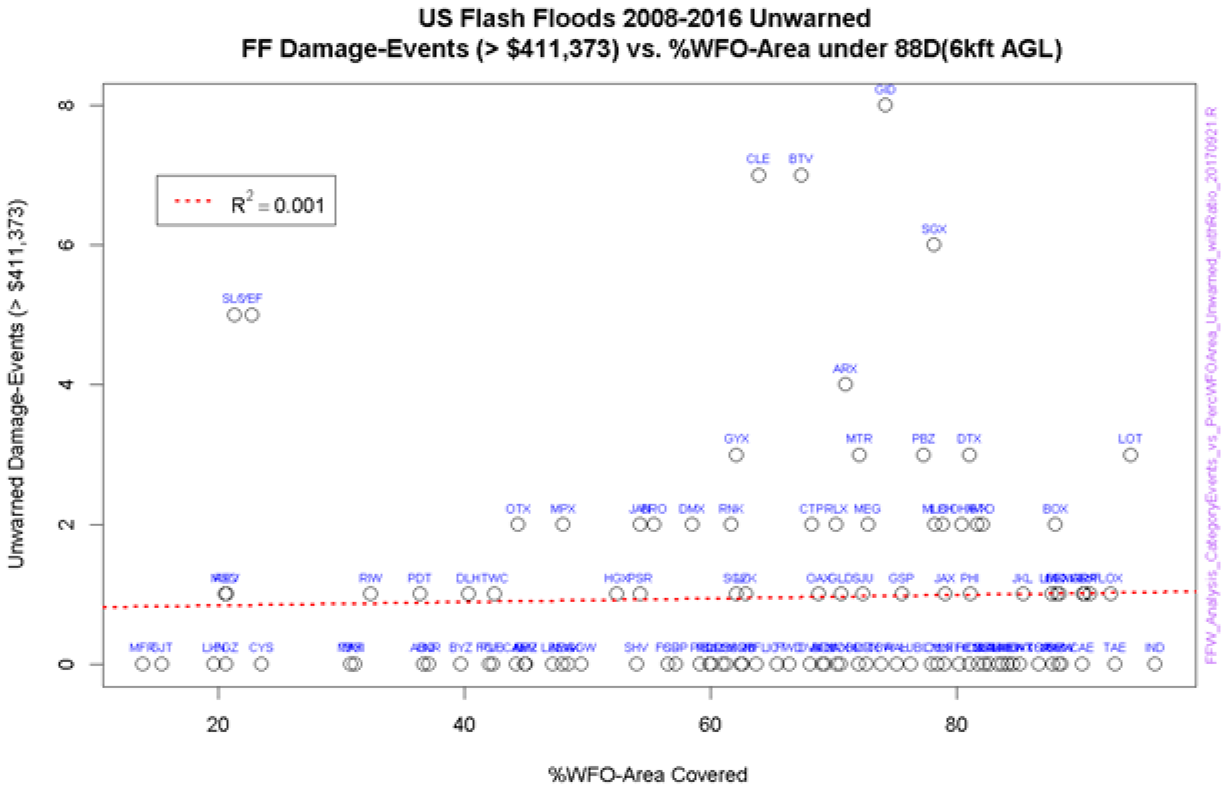


Figure E.74 - Unwarned significant flash flood damages per event per WFO from 2008 to 2016 by percent WFO covered by radar. There is little to no relationship between unwarned significant flash flood damages per event and increasing percent WFO area covered by radar. The staggered nature of this plot makes clear the drawbacks of a limited dataset

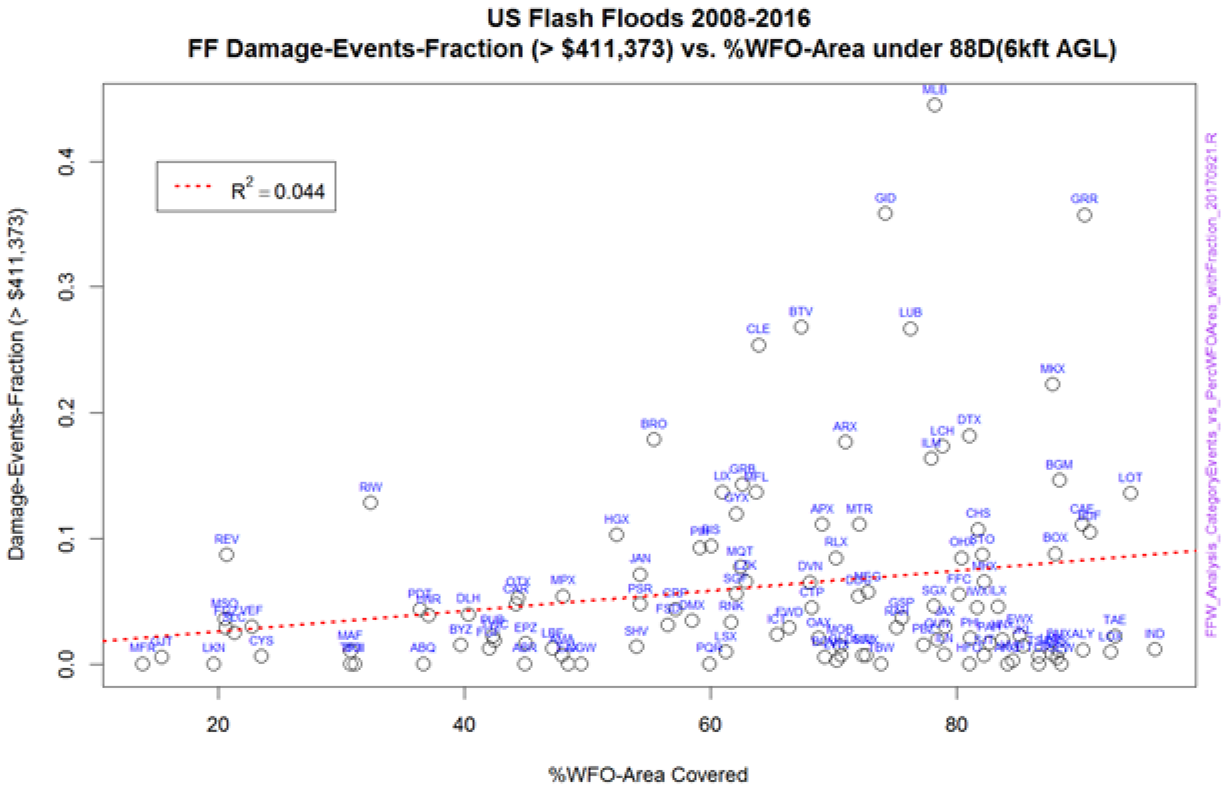


Figure E.75 - Significantly damaging events as a ratio of total events per WFO from 2008 to 2016 by percent WFO covered by radar. There is little relationship between significantly damaging events as a ratio of total events and increasing percent WFO area covered by radar.

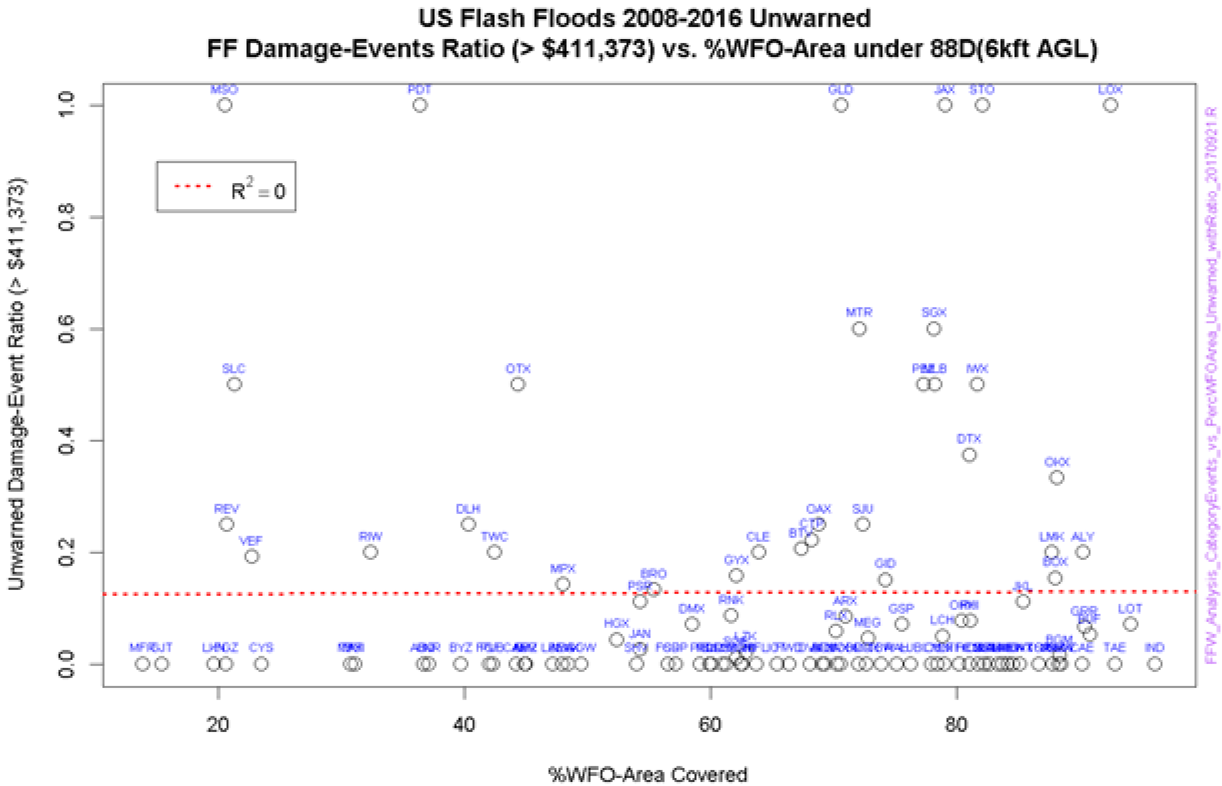


Figure E.76 - Unwarned significantly damaging events as a ratio of total events per WFO from 2008 to 2016 by percent WFO covered by radar. There is no relationship between unwarned significantly damaging events as a ratio of total events and increasing percent WFO area covered by radar.

Statistical Significance of Normalized Unwarned Events, Fatalities, Injuries by Percent WFO Covered by Radar

There were 4295 unwarned flash flood events in 2008-2016, amounting to 12.8% of the total, therefore, the majority of events were warned (including non-zero PEWs discussed earlier). Linear fit is made to the ratio of unwarned events normalized by the number of events per WFO, shown in Figure E.77, and which is statistically significant negative slope, though a large scatter is observed.

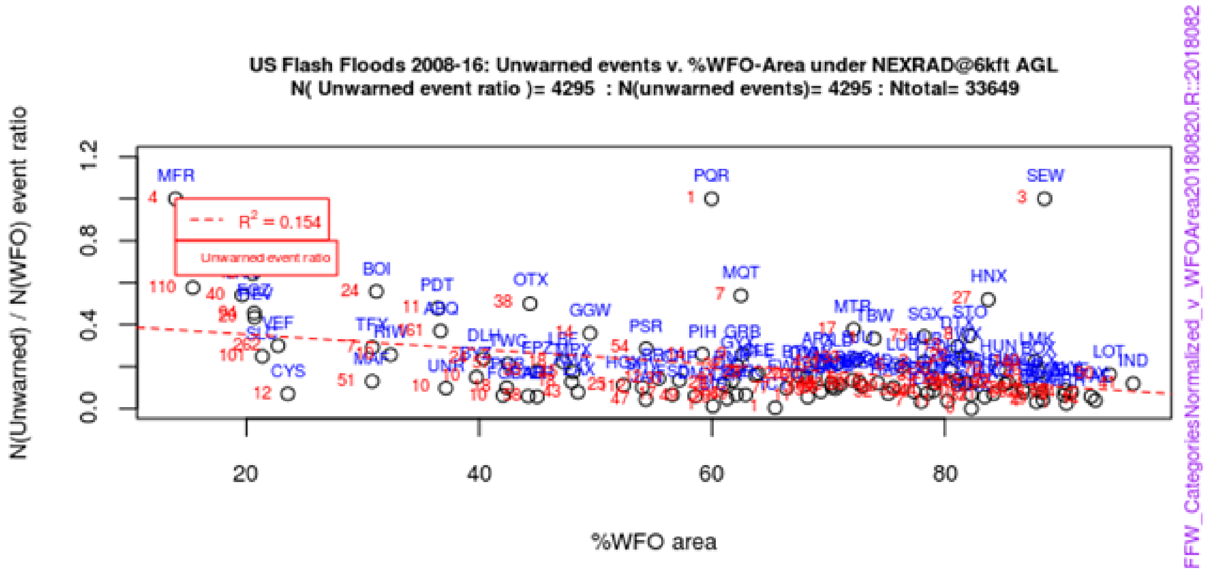


Figure E.77 - Relationship between the ratio of unwarned events normalized by the number of events per WFO and percentage of WFO area covered. While there is considerable scatter, the negative slope is statistically significant.

The ratio of 389 fatal events to all events per WFO (totaling 33649 since a few WFOs, such as American Samoa, having no NEXRAD coverage or not geospatially sorted were removed) is essentially insensitive to radar coverage with a slope statistically indistinguishable from zero, as seen in Figure E.78. This fit serves to provide context to the fit to the 93 unwarned fatal event ratios (with respect to fatal events per WFO), shown in Figure E.79.

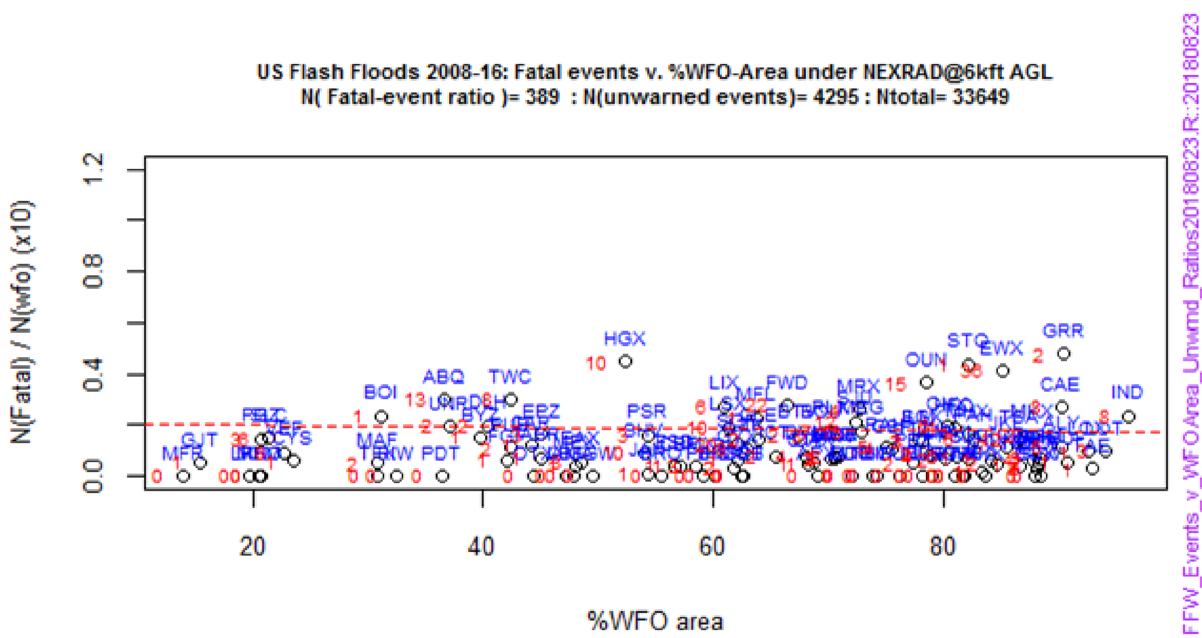


Figure E.78 - Relationship between the ratio of number of fatal events normalized by ten times the total number of events by WFO and percentage of WFO area covered by radar.

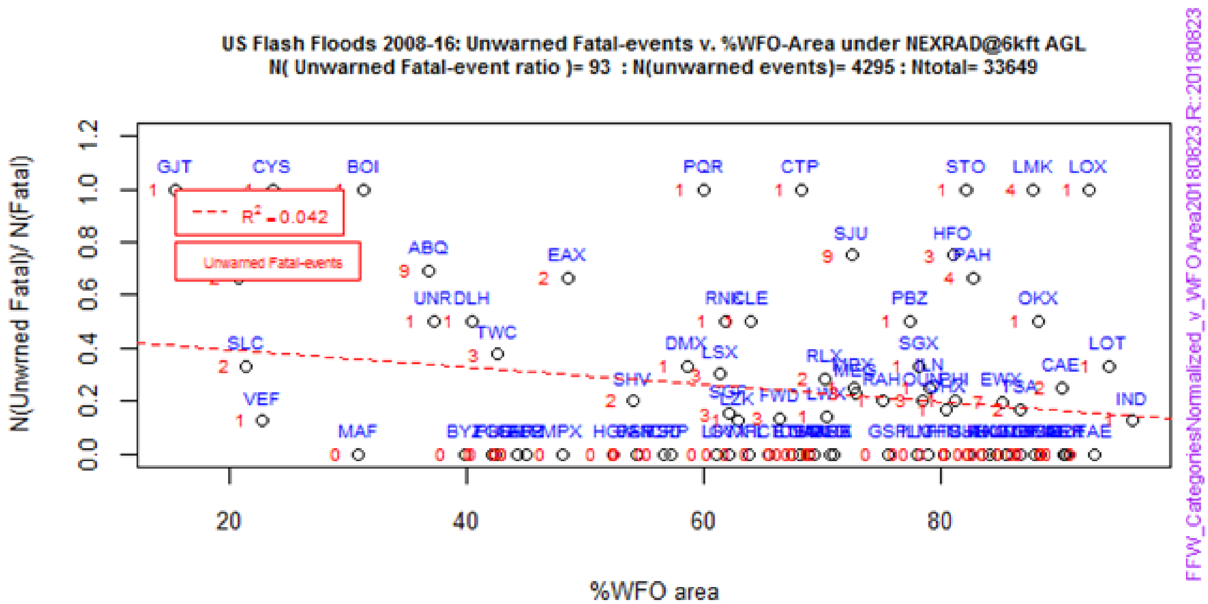


Figure E.79 - Relationship between the ratio of number of unwarned fatal events normalized by the number of fatal events by WFO as compared to percentage of WFO area covered by radar.

There are 143 injury-events and 454 injuries in 2008-2016. As with the fatal-events ratios, the ratios of injury-related to flash flood events per WFO have essentially no variation with WFO-area radar coverage. In terms of absolute injuries, there is a slight increase with more coverage, just like with fatalities and likely for the same reasons related to population. There are fewer outliers in the absolute injuries versus coverage distribution (Figure E.59) but one WFO stands far from the rest at 140 injuries. This large outlier helps explain the distinct pattern the in the inside/outside ratios (Fig. E.3). There are 38 unwarned injury-related events or less than 1% of all unwarned events. A regression to the distribution of injurious event ratios (Figure E.80) and unwarned event ratios versus coverage (Figure E.81) yields a statistically insignificant negative slope. The fit including the zero ratios results in a nearly tripled slope compared to the fit without the zero ratios (Table E.1), however, neither slope is statistically significant better than 95% so the null hypothesis (zero slope) cannot be ruled out. As with the fatal ratios, the linear model is probably the best case scenario that can be argued for the variation of injury-events with coverage. Injury events can be regarded as the less extreme case of fatal events. There were only 50 events causing both at least one fatality and one injury, and their distribution shows no linear variation with coverage.

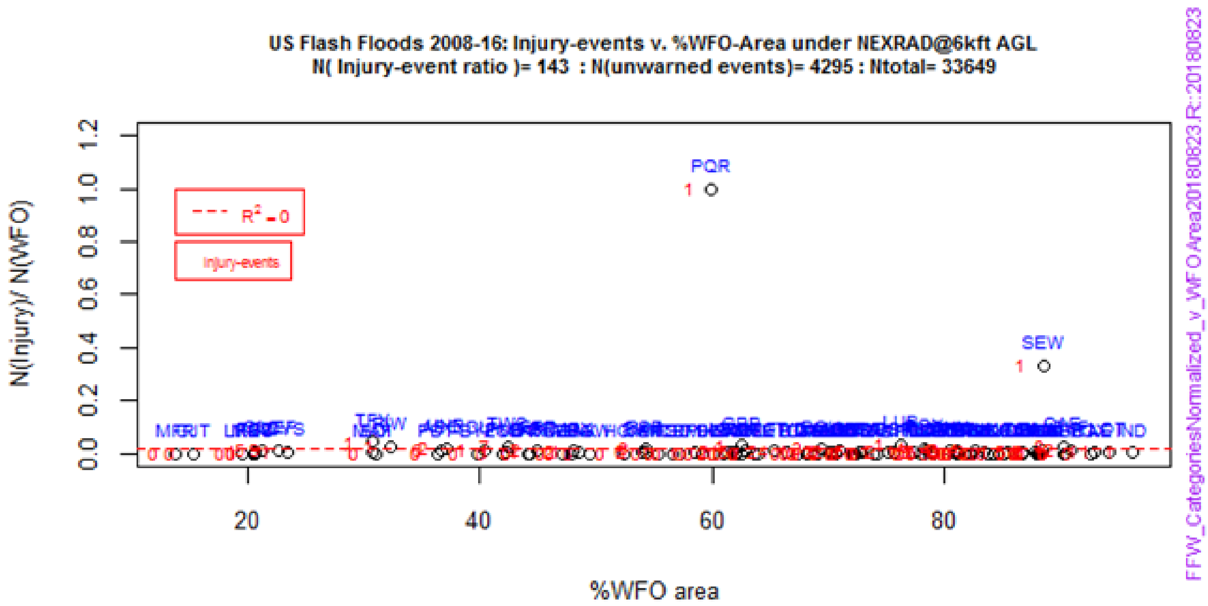


Figure E.80- Relationship between the ratio of number of injurious events normalized by the total number of events by WFO and percentage of WFO area covered by radar.

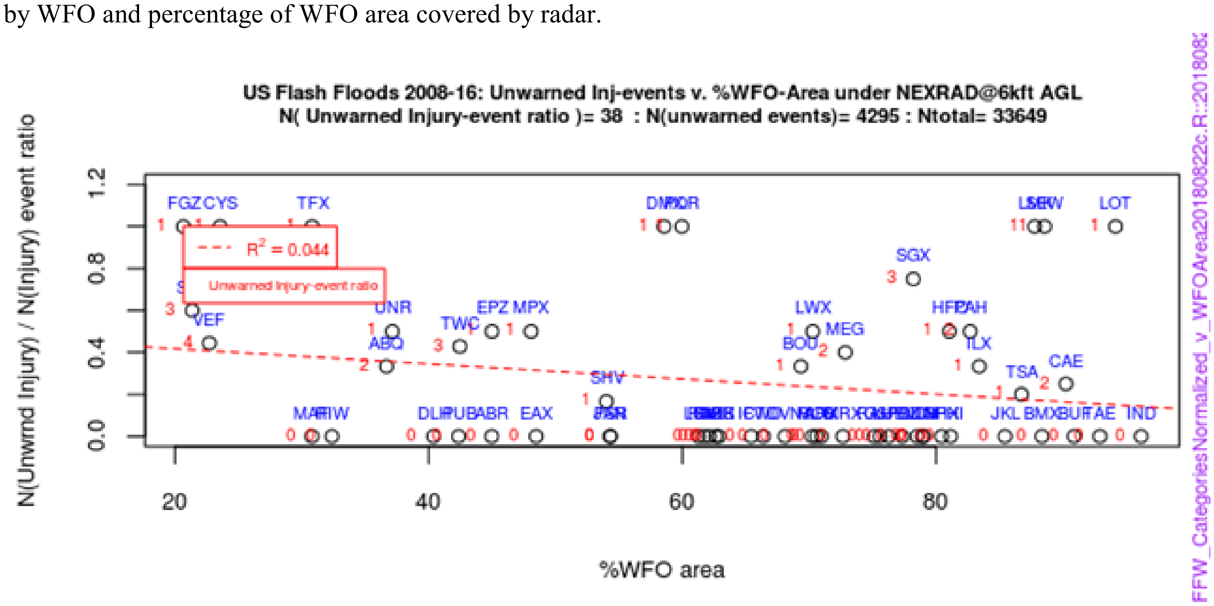


Figure E.81 - Relationship between the ratio of number of unwarned injurious events (UWIE) normalized by the number of injurious events by WFO as compared to percentage of WFO area covered by radar.

Table E.1 and Table E.2 below summarize the statistical significance and slopes of the fits for Figures E.77 to E.81. Table E.1 considers all of the ratios, while Table E.2 only considers those which are non-zero. Rows in red are those which have statistically significant linear fits. Table E.3 summarizes the number of flash flood events and those events which caused injuries, deaths, or damages by their warned status and location inside, outside, or crossing radar coverage at

6,000 ft AGL.

Table E.1. - Linear fit parameters. Statistically significant linear fits are in red. SE = standard error. Rows in red denote statistically significant linear fits.

parameter	Slope/%area	SlopeSE/%area	p-value	R^2	Fstat
N(Unwarned) / N(WFO) event ratio	-3.57e-03	7.83e-04	0	0.154	2.08e+01
N(Injury)/ N(WFO)	1.51e-05	4.35e-04	0.972	0	1.21e-03
N(Unwarned Injury) / N(Injury) event ratio	-3.61e-03	2.24e-03	0.112	0.044	2.61e+00
N(Fatal) / N(WFO) (x10)	-3.33e-04	4.13e-03	0.936	0	6.48e-03
N(Unwarned Fatal)/ N(Fatal)	-3.30e-03	1.72e-03	0.058	0.042	3.69e+00
N(Damage) / N(WFO) event ratio	1.20e-03	1.43e-03	0.404	0.006	7.03e-01
N(Unwarned Dmg) / N(Dmg)	-3.44e-03	8.36e-04	0	0.132	1.69e+01
N(Significant-Damage) / N(Damage)	1.83e-03	6.55e-04	0.006	0.066	7.78e+00
N(Unwarned Sig-Dmg)/ N(Sig-Dmg)	-6.64e-04	1.28e-03	0.604	0.003	2.71e-01

Table E.2 - Linear fit parameters for fit to non-zero ratios. Rows in red denote statistically significant linear fits.

parameter	Slope/%area	SlopeSE/%area	p-value	R^2	Fstat
N(Unwarned) / N(WFO) event ratio	-3.52e-03	7.83e-04	0	0.151	2.08e+01
N(Injury)/ N(WFO)					
N(Unwarned Injury) events	-9.24e-03	7.02e-03	0.201	0.07	1.73
N(Unwarned Injury) / N(Injury) event ratio	-1.26e-03	2.48e-03	0.615	0.011	0.26
N(Unwarned Fatal) events	2.76e-03	1.33e-02	0.837	0.001	4.27e-02
N(Unwarnd Fatal) / N(Fatal)	-3.26e-03	2.07e-03	0.123	0.056	2.48
N(Damage) / N(WFO) event ratio					

N(Unwarned Dmg) / N(Damage) events	-3.88e-03	8.49e-04	0	0.17	20.9
N(Unwarned Damage) events	-3.21e-01	1.22e-01	0.01	0.064	0.7
N(Unwarned Sig-Dmg (> $411373)) events	-1.03e-02	1.23e-02	0.407	0.014	0.26
N(Unwarned Sig-Dmg)/ N(Sig-Dmg)	-1.37e-03	2.07e-03	0.51	0.009	44.1

Table E.3 - Flash flood warned, unwarned, and crossed (partially in/out) events for 2008-2016 and events causing direct and indirect fatalities, injuries or significant damage (greater than the mean of damage per event of $411,373). Total damage includes crops and property.

Status	Total # of FF Events	# of FF Events causing Injuries*	# of FF Events causing Deaths**	# of FF Events causing total Damage > $411,373***
Warned - Inside	21956	84	231	980
Warned - Outside	5229	14	41	183
Warned - Crosses	2170	7	24	191
Unwarned - Inside	2933	16	65	83
Unwarned - Outside	1130	20	22	27
Unwarned - Crosses	245	2	6	8
Total	33663	143	389	1472

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Appendix F – NWS Flash Flood Warning Operational Warning and Forecast Process, and Observational Sources Besides Radar

[WRITERS - AFS/Mullusky, Abshire, NSSL/Howard, Martinaitis]

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) provides climate, water, weather, ocean, aviation, and space weather warnings and forecasts for the United States, its territories, adjacent waters, and ocean areas to help protect life and property and enhance the national economy. These services are provided through 122 Weather Forecast Offices (WFO), 13 River Forecast Centers (RFC), the National Centers for Environmental Prediction (NCEP), and the Office of Water Prediction (OWP). These offices collect data, prepare local warnings and forecasts, and disseminate information to the public, both nationally and internationally, through NOAA Weather Radio (NWR), satellite-based telecommunication systems, radiofacsimile, the media, and the internet. NWS forecasters issue short-duration watches and warnings for severe weather, such as tornadoes and severe thunderstorms, as well as long-duration forecasts, watches, warnings and advisories for hazardous winter weather conditions, high wind events, dense fog, river levels, flooding and extreme temperatures.

The NWS uses surveillance technologies including a national network of Doppler weather radars; satellites operated by NOAA's National Environmental Satellite, Data, and Information Service (NESDIS); aircraft observations; data buoys for marine observations and tsunami detection; surface weather observing systems at airports; and weather balloons to obtain vertical measurements of the atmosphere. Some observations are obtained through the Cooperative Observer Program (COOP), a nationwide network of volunteer-operated weather observing sites. Many other observations are contributed through arrangements with publicly and privately operated networks (primarily via the National Mesonet Program, see Appendix L). Observations feed sophisticated environmental prediction models running on high performance supercomputers, which provide weather, water, climate, ocean, aviation, and space weather forecast guidance that is available to users. The NWS' highly trained and skilled workforce uses powerful workstations to analyze these data to issue forecasts and warnings around the clock. A high-speed communications hub allows for the efficient exchange of these data and products among NWS components, partners, and other users. NWS integrated dissemination infrastructure includes NWR and satellite broadcasts, while the internet rapidly distributes this information.

The NWS creates forecasts in digital formats and makes them readily available. Forecasters use their expertise to maintain an up-to-date digital forecast database of weather elements. This information is stored in the National Digital Forecast Database (NDFD). Output from the NDFD is publicly available in the form of web graphics on the Internet and in several other digital formats. Outreach, education, and feedback are also critical elements in effective public response and improvements to NWS services.

Specifically, using hydrologic models, our RFC forecasters integrate information that includes terrain, slope, land use, and soil characteristics with observed and forecasted rainfall, soil moisture, current stream levels, and several other variables to produce short range (deterministic) through extended range (probabilistic) river streamflow and flood forecasts and (deterministic) flash flood guidance. Information from the RFCs and NCEP's Weather Prediction Center

(WPC) serves as the basis for local flood and flash flood warnings, watches, and advisories issued by the WFOs.

NWS WFOs (http://www.nws.noaa.gov/organization.php) assess and monitor the threat of flash and river flooding 24 hours a day 7 days a week to provide timely and accurate life-saving flood watches and warnings. Toward this end, WFOs integrate a spectrum of RFC, NCEP and National Water Center (NWC) guidance, Doppler weather radar (NEXRAD)-based precipitation estimates, hydrologic model output, and real-time telemetered precipitation and stream gauge observations to provide routine river forecast services and critical, event-based decision support services and products for flash and river flooding. In addition, WFOs work with dam operators and the emergency management community to provide timely warnings for floods that result from flood water releases and infrastructure failure, such as dam break and levee breaches. Moreover, WFOs routinely conduct local outreach and education to heighten public and partner awareness of flood risks and NWS hydrologic services.

From an operational flash flood warning perspective, NWS WFOs generally rely on the use of radar-based precipitation estimation and the use of a product called flash flood guidance (FFG). FFG depicts the estimated amount of rainfall needed within a certain period of time within a given area for small creeks and streams to overflow their banks. FFG is generally updated four times a day with more frequent updates as necessary during rainfall events and for changes in soil saturation. FFG is viewable within the Flash Flood Monitoring and Prediction (FFMP) software. This allows forecasters to compare radar-based QPE to FFG to determine if the amount of rainfall is exceeding FFG and by how much; however, the rainfall data used to compare against FFG is radar-based QPE.

The advent of new hydrologic modeling within NOAA and the NWS allows for more data to be available to NWS forecasters to assist in their forecast and warning decision making process. The National Water Model (NWM) provides short-term hydrologic forecasting using Multi-Radar Multi-Sensor (MRMS) QPE and model forecast precipitation to determine areas that might experience above normal river flows in the near future. The Flooded Locations and Simulated Hydrographs (FLASH) system uses MRMS QPE at an event-scale to provide information on where anomalous surface & river water flow is occurring and the potential rarity of QPE values. Both the NWM and FLASH became operational in the NWS in 2016. The current operational MRMS QPE ingested by the NWM and FLASH are radar-based; thus, their outputs are dependent upon radar coverage. More information regarding MRMS and its future updates for estimating rainfall can be found in Appendix M.

Appendix G – Impact of FAA TDWR Radars on Tornado and Flash Flood Warnings and Forecasting

This appendix lists key operational attributes of the FAA Terminal Doppler Weather Radar (TDWR). The specific impacts on tornado and flash flood warning performance are discussed in the corresponding appendices.

Characteristics	NWS Operational Value	Notes
• Reflectivity and Doppler data processed into products similar to WSR-88D data • Reflectivity range at lowest elevation: 230 km • Doppler range at lowest elevation: 90 km • Good temporal and spatial resolution • Subject to greater attenuation than WSR-88D due to shorter wavelength (C-band) • Radar operation and Volume Coverage Patterns controlled by FAA	• Extensive operational use from 45 TDWRs since 2008 • All TDWR data is processed into WSR-88D format and viewable on AWIPS • Low-elevation gap-filling • Low elevation angles (below 0.5 degrees) are highly valuable for detection of severe weather features (high winds, tornadoes)	Although highly valuable to NWS operations, TDWR data cannot be considered entirely equivalent to WSR-88D due to attenuation, range, clutter filtering, and other operating limitations.

Appendix H – Impact of FAA Non-TDWR Radars

System	Characteristics	NWS Impacts	Notes
FAA ASR-11 air traffic control radar Erie, PA	Coarse Reflectivity levels only No velocity data Short-range: 111 km Poor sensitivity	No usage beyond proof-of-concept demonstration	Useful only for identifying the presence or absence of moderate precipitation and limited convection. Radar is of no operational use as there are no requirements.
FAA long-range air traffic control radar ARSR-4 Makah, WA, Watford City, ND	Coarse Reflectivity levels only No velocity data Longer range: 460 km Poor sensitivity	No usage beyond proof-of-concept demonstration	Useful only for identifying the presence or absence of moderate precipitation and limited convection. Radar is of no operational use as there are no requirements.

Appendix I – Hazardous Weather Events Unwarned and Insufficiently Warned in Areas of Limited NEXRAD Coverage Resulting in Fatalities, Significant Injuries, Significant or Substantial Property Damage and Options to Improve Warning and Forecasts

This is covered in the TOR and FFW results in Appendices B – E, **Appendix J – NWS Western Region Tornado and Flash Flood Performance**

[**WRITERS**: STI/Daniel Meléndez]

1. NWS Western Region is comprised by the states of the states shown in Figure J.1. As such, it is comprised of varied and complex terrain having the tallest mountains within the continental US. Figure J.2 shows that in the region, fewer than 22% of events are either warned (12.8%) or partially warned (8.9%), with false alarm rates (FAR) above 78% in the period 2007-2017 (partial) since the storm-based polygonic verification was introduced, affording greater geographic specificity in the warnings and associated verification data.

2. In contrast, performance data for Southern and Eastern regions combined in Figure J.3 show lower unwarned tornado event rates averaging 27% (and about 10% partially-warned). FARs, however, are still relatively large at not less than 70% in a given year within the comparison period.

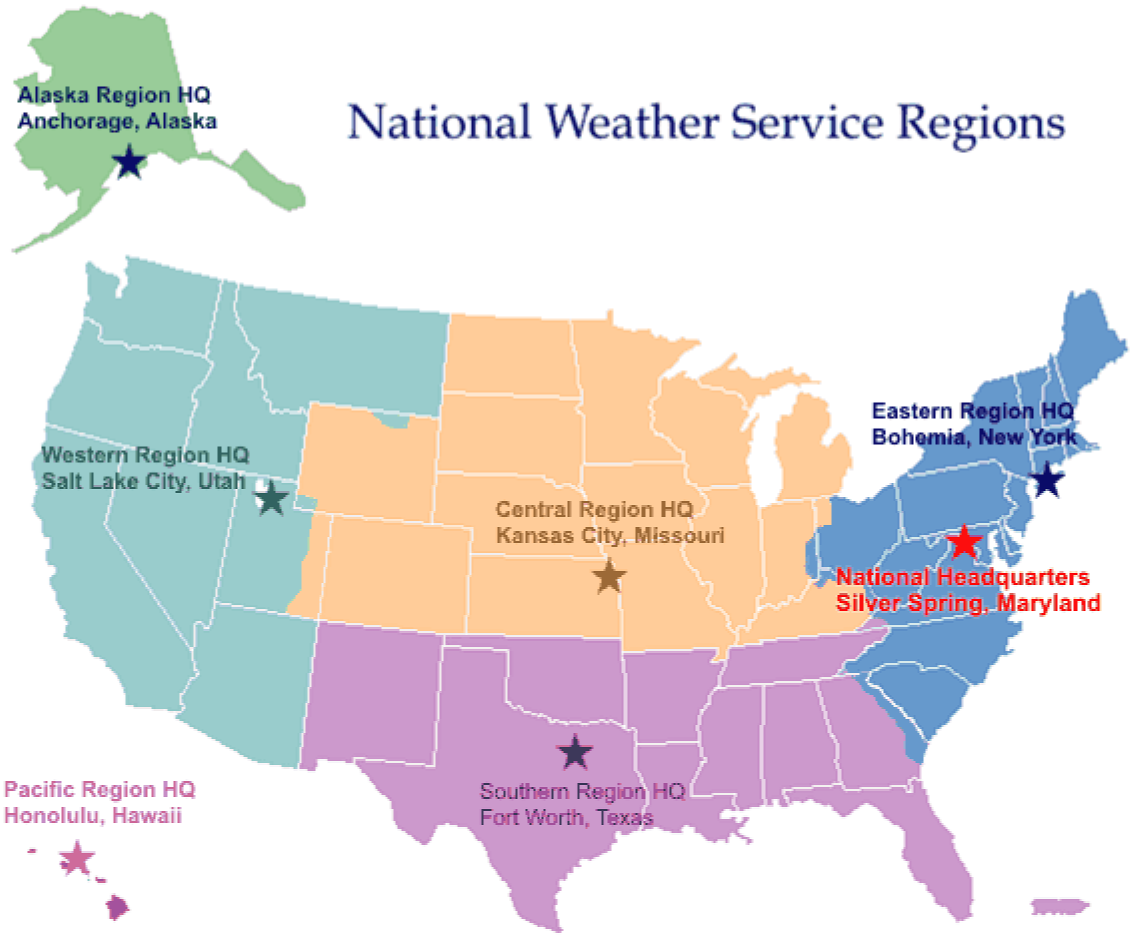
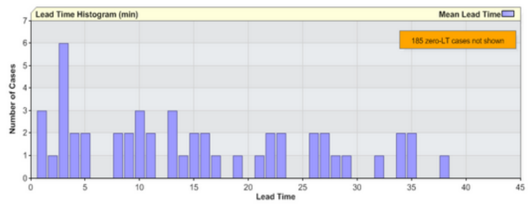


Figure J.1 – NWS regions.

Group	Counts							Statistics							
	Warnings			Events				Scores			Lead Time (min)		Warning Area (sq. mi)		
	Total	Verif	NOT Verif	Total	Fully Warned	Partially Warned	NOT Warned	POD	FAR	CSI	Mean	Initial	Total	Average	County Reduction
2008	36	7	29	17	1	6	10	0.299	0.806	0.134	4.20	3.88	13188.19	366.34	0.93
2009	28	1	27	27	2	0	25	0.074	0.964	0.025	0.48	0.41	15890.88	567.53	0.87
2010	103	22	81	39	8	8	23	0.339	0.786	0.151	5.08	3.21	47016.39	456.47	0.93
2011	54	10	44	28	4	5	19	0.260	0.815	0.121	5.51	4.86	19390.23	359.08	0.95
2012	28	3	25	18	4	0	14	0.222	0.893	0.078	5.97	5.33	14927.43	533.12	0.95
2013	39	3	36	24	1	0	23	0.042	0.923	0.028	0.73	0.00	15644.36	401.14	0.94
2014	35	7	28	32	6	1	25	0.217	0.800	0.116	4.86	3.88	7464.21	213.26	0.96
2015	31	1	30	23	0	1	22	0.022	0.968	0.013	0.17	0.00	13803.54	445.28	0.94
2016	39	4	35	24	4	0	20	0.167	0.897	0.068	1.92	1.25	13997.36	358.91	0.94
2017	5	0	5	3	0	0	3	0	1.000	0	0.00	0.00	1204.74	240.95	0.92
Total	398	58	340	235	30	21	184	0.187	0.854	0.089	3.26	2.50	162527.34	408.36	0.93



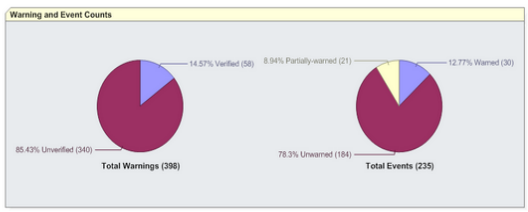
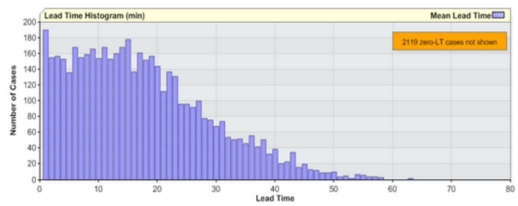


Figure J.2 – Yearly tornado statistics for NWS Western Region.

Group	Counts							Statistics							
	Warnings			Events				Scores			Lead Time (min)		Warning Area (sq. mi)		
	Total	Verif	NOT Verif	Total	Fully Warned	Partially Warned	NOT Warned	POD	FAR	CSI	Mean	Initial	Total	Average	County Reduction
2007	178	27	151	49	25	4	20	0.561	0.848	0.136	9.27	8.49	58845.78	330.59	0.82
2008	2847	649	2198	1067	697	90	280	0.705	0.772	0.208	13.12	12.63	1155797.45	406.54	0.83
2009	2033	463	1570	743	475	66	202	0.692	0.772	0.207	12.40	11.74	768438.50	377.98	0.84
2010	1739	384	1355	657	432	69	156	0.718	0.779	0.203	13.66	12.72	701468.57	403.37	0.84
2011	2940	845	2095	1321	973	107	241	0.787	0.713	0.267	16.44	15.47	1432379.78	487.20	0.82
2012	1620	402	1218	618	397	73	148	0.709	0.752	0.225	11.86	10.92	569292.74	352.07	-14.81
2013	1009	274	735	538	300	55	183	0.612	0.728	0.232	9.80	9.01	379645.37	376.63	0.85
2014	1017	247	770	456	233	46	177	0.581	0.757	0.207	9.91	9.31	353275.61	347.37	0.86
2015	1342	397	945	676	399	64	213	0.646	0.704	0.255	9.30	8.44	395298.95	294.56	0.89
2016	1123	318	805	546	300	79	167	0.635	0.717	0.243	9.27	8.19	351431.81	312.94	0.87
2017	539	156	383	311	160	38	113	0.589	0.711	0.241	9.55	8.42	202989.24	376.60	0.86
Total	16387	4162	12225	6982	4391	691	1900	0.688	0.746	0.228	12.29	11.46	6368863.81	388.84	-0.70



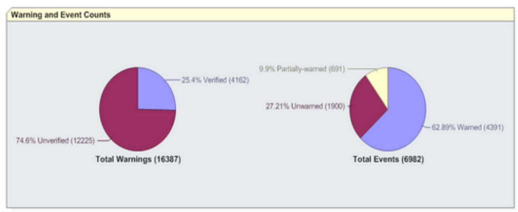


Figure J.3 – Yearly tornado statistics for NWS Eastern and Southern Regions.

3. Flash flood performance data for NWS Western Region shows near 36% of flash flood events are unwarned between 2007-2017 (partial year), and another 36% is partially-warned (Figure J.4). This is higher than the national average of 13.59% unwarned flash flood events on average (not shown) but roughly identical in the partially-warned events at 29.11% nationally or for the combined Southern-Eastern region performance of nearly 11% unwarned flash flood events (and 26.5% partially warned) for the same period as shown in Figure J.5. However, Western Region only had 3313 events compared to 20353 events for Southern and Eastern regions, a five-fold plus difference reflecting the dryer regime of the western US.

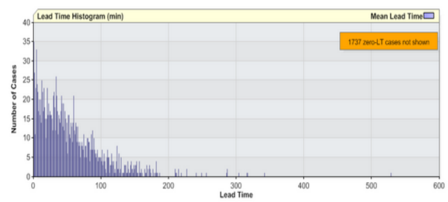
4. This data does not discriminate for topographic differences.

Storm-based Flash Flood Warning Verification

Dates	10/1/2007 - 3/31/2017
Areas	Region - WR
Match Type	Flash Flood / Debris Flow Only (Polygon)
Group Type	National, Region, WFO
Groups Found	2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017
Download Data	Summary [2KB csv file] | Details [2155KB csv file]

Summary Statistics

Group	Counts							Statistics									
	Warnings			Events				Scores			Lead Time (min)		Warning Area (sq. mi)			Event Area (sq. mi)	
	Total	Verif	NOT Verif	Total	Fully Warned	Partially Warned	NOT Warned	POD	FAR	CSI	Area Weighted	Max Event	Total	Average	County Reduction	Total	Average
2007	20	9	11	13	6	4	3	0.685	0.550	0.373	30.56	30.69	17230.68	861.53	0.93	588.22	45.25
2008	478	205	273	215	77	80	58	0.586	0.571	0.329	27.41	31.92	321019.54	671.59	0.95	14376.77	66.87
2009	232	77	155	121	26	41	54	0.437	0.668	0.232	13.75	15.11	90869.10	391.68	0.95	8028.24	66.35
2010	492	223	269	283	63	123	97	0.497	0.547	0.311	21.22	24.35	367902.26	747.77	0.96	20121.18	71.10
2011	482	193	289	241	70	105	66	0.571	0.600	0.308	20.50	24.02	243387.15	507.06	0.96	15287.33	63.43
2012	646	276	370	401	115	151	135	0.533	0.573	0.311	29.37	33.67	261739.85	405.17	0.97	13516.30	33.71
2013	973	401	572	542	154	210	178	0.537	0.588	0.304	26.55	30.70	395110.56	406.07	0.97	29477.57	54.39
2014	762	339	423	535	186	181	168	0.565	0.555	0.331	27.97	31.94	382729.55	502.27	0.96	18011.43	33.67
2015	580	267	313	454	133	145	176	0.485	0.540	0.309	30.62	34.94	313427.77	540.39	0.97	13597.86	29.95
2016	364	162	202	263	66	103	94	0.507	0.555	0.311	24.47	30.37	180585.27	496.11	0.97	11615.91	44.17
2017	152	95	57	245	41	50	154	0.306	0.375	0.258	19.54	19.95	67382.26	443.30	0.95	3295.40	13.45
Total	5181	2247	2934	3313	937	1193	1183	0.514	0.566	0.307	25.71	29.50	2641384.00	510.02	0.96	147916.21	44.65



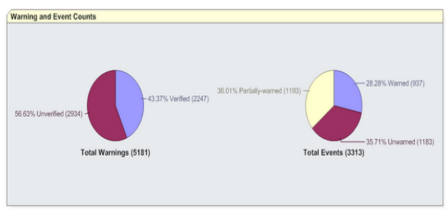
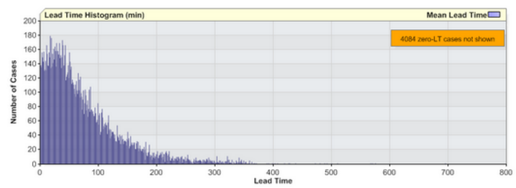


Figure J.4 – Western Region flash flood performance data.

Group	Counts							Statistics									
	Warnings			Events				Scores			Lead Time (min)		Warning Area (sq. mi)			Event Area (sq. mi)	
	Total	Verif	NOT Verif	Total	Fully Warned	Partially Warned	NOT Warned	POD	FAR	CSI	Area Weighted	Max Event	Total	Average	County Reduction	Total	Average
2007	71	56	15	85	41	28	16	0.742	0.211	0.619	36.04	39.78	59205.89	833.89	0.72	5355.87	63.01
2008	2135	1210	925	1805	1063	540	202	0.804	0.433	0.498	59.81	64.02	2305150.17	1081.72	-11.30	78443.95	43.46
2009	2858	1703	1155	2700	1721	725	254	0.839	0.404	0.535	56.50	60.64	3172675.37	1111.27	0.73	124301.81	46.04
2010	2399	1259	1140	2034	1356	466	212	0.834	0.475	0.475	67.97	72.07	2187847.57	912.36	0.73	84541.56	41.56
2011	2480	1282	1198	2078	1270	610	198	0.831	0.483	0.468	66.50	73.97	2606188.81	1051.73	0.73	83495.76	40.18
2012	1689	985	704	1554	966	391	197	0.805	0.417	0.511	47.86	53.32	1296436.05	768.03	0.78	46718.47	30.06
2013	2619	1530	1089	2661	1653	667	341	0.800	0.416	0.510	54.43	60.44	1986737.74	758.88	-7.28	122711.08	46.11
2014	2032	1098	934	1836	1143	479	214	0.810	0.460	0.480	51.00	55.58	1585660.81	781.11	0.78	50874.50	27.71
2015	2943	1822	1121	3107	1984	814	309	0.835	0.381	0.552	64.57	72.73	3173709.50	1078.39	0.76	112623.70	36.25
2016	2244	1315	929	2291	1413	606	272	0.808	0.414	0.514	66.52	76.88	2169017.80	966.59	0.77	193641.06	84.52
2017	784	116	668	202	124	66	12	0.837	0.852	0.144	59.64	70.39	670913.33	855.76	0.78	5506.68	27.26
Total	22254	12376	9878	20353	12734	5392	2227	0.820	0.444	0.496	59.84	66.08	21213543.04	953.85	-1.35	908214.46	44.62



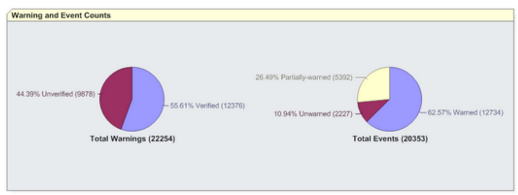


Figure J.5 – Eastern and Southern Regions combined flash flood performance data.

Appendix K – Impact of KLGX Radar (Western Coast of Washington State)

[Writers: STI/Daniel Meléndez]

1. Western Washington state NEXRAD (Langley Hill, WA, KLGX) is the newest radar in the network since the modernization was completed in 1999. Unlike the rest of the NEXRAD network, this particular radar has a lower base elevation angle of 0.2º as opposed to the 0.5º standard minimum elevation.

2. A comparison of flash flood warning performance before and after the operation date of 01 November 2011 shows the following:

   a) Between 2009 and 2010 (period for which there is storm-based data), there were a total of four flash flood warnings issued by the Seattle WA WFO. Neither of these verified, amounting to a 100% false alarm ratio.

   b) Between 2012 and 2017 (there were no events 2010-2012), there was one flash flood warning, which did not verify. There were 20 flash flood events through October 2017, none of which were warned.

3. As a result of the few events founds above, there is insufficient statistical significance to the flash flood warning performance before and after KLGX is operational. However, the available flash-flood warning performance is unaltered by the introduction of KLGX.

4. Regarding tornado statistics, there were three unwarned events between 2007 and 2011 for WFO Seattle, WA (SEW). Exactly the same performance occurred between 2011 and 2017. Therefore, there is no discernible change in tornado performance before/after KLGX.

5. Since KLGX coverage extends to the nearby Portland WFO, verification statistics were combined with that and the Seattle-Washington WFO. See Table K.1. There is a small increase in the detection of tornado events from the period prior to the availability of KLGX but the overwhelming detectability is qualitatively and quantitatively unchanged.

6. The combined Portland-Seattle WFO flash flood warning performance, also in Table K.1, shows only one flash flood event not warned and 4 warnings that did not verify prior to KLGX. Afterward, 19 events were recorded, none warned. This is similar to the pre-KLGX pattern with both tornadoes and flash flood warnings albeit with a relatively small number of cases.

Table K.1 – Comparison of tornado and flash flood events within the Portland (PQR) and Seattle-Washington (SEW) Weather Forecast Offices before and after deployment of Langley Hills, WA, NEXRAD in 2011.

Period	Number of Events	Events Not Warned (zero-lead)	POD	FAR
Tornadoes (through July 2017)				
2007-2011	8	7	0.077	0.667
2011-2017	11	9	0.182	0.846
Flash Floods (through Oct 2017)				
2007-2011	1	1	0	1
2011-2017	20	0	0	1.0

7. By way of comparison, the tornado warning performance for the state of Oregon (Medford Weather Forecast Office) is nearly identical to that of KLGX. Namely, only two tornado events are registered between 2007 and 2016, none warned. Both central and coastal Oregon have limited to no radar coverage below 10,000 ft AGL. In other words, there are too few events to draw statistically significant conclusions.

In many western US areas, weather events are associated with particular regimes that cluster specific type of weather phenomena. Statistics also show that warning skill is proportional to the number of severe weather events. That is, the more severe weather a given forecaster unit handles in time, the greater the skill statistics. In this sense, frequency (experience) may be more important in raising skill performance. Both Seattle and Portland have low rates of severe convective weather compared to the central and southern U.S.

Appendix L - Surface Networks Supporting Tornado and Flash Flood Detection and Warning Performance

[Writer - OBS/Marshall**]**

Beginning in 2009, Congress directed NWS to establish the National Mesonet Program (NMP), to procure data from the states and the private sector to enhance the NWS forecast and warning mission. This direction came in response to Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks, a report released by the National Academy of Sciences in 2009 that provides recommendations on steps the United States should take to effect an operational observing network that provides the volume and types of observations that are needed to significantly enhance and improve storm-scale numerical weather prediction. Chief among those recommendations was:

"Increased coordination among existing surface networks would provide a significant step forward and serve to achieve improved quality checking, more complete metadata, increased access to observations, and broader usage of data serving multiple locally driven needs"

The NMP is a public-private partnership that already engaged in many of the activities directed in the "Commercial Data Buy" Title of the "Weather Act." (PL115-25) NWS purchases observational data at a discount rate from participating networks (see Figure L.1) and agrees not to redistribute the data to external parties, and the participating networks recoup the remainder of their revenue stream by selling their data into the private market.

The Meteorological Data Assimilation and Ingest System (MADIS) is the operational NWS IT pathway whereby these nonfederal data are ingested into NWS forecast systems, such as AWIPs, and also distributed to external users (Figure L.1)

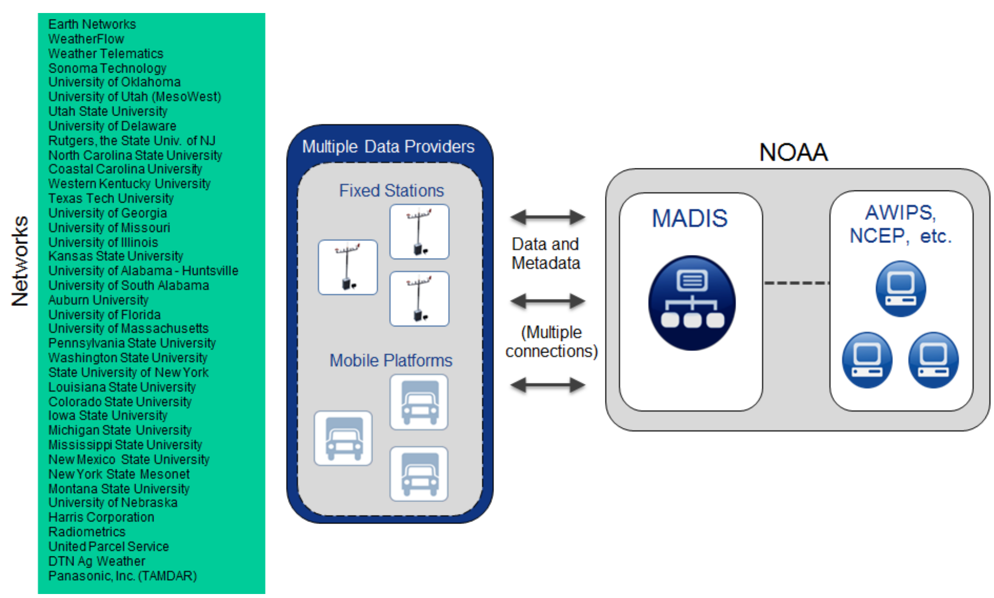


Figure L.1. Networks contributing data to NWS via the National Mesonet Program, and illustration of pathways into NWS operational forecast and dissemination systems.

The NMP procures data from a wide variety of networks and is not just limited to surface observations. Many networks have boundary layer profiling instruments, such as SODARS, LIDARS, tall towers, and radiometers, which give profiles of wind, temperature, and moisture in the lowest several thousand feet of the troposphere. Another important contributor to NMP is Panasonic, which operates the TAMDAR-equipped fleet of aircraft. On ascent and descent, these aircraft provide vertical soundings of wind, temperature, and moisture, from the surface the cruise level, at a volume of approximately 3500 soundings per day across the CONUS and Alaska. The NMP also includes the CASA gap-filling X-band radar network operated in the DFW metroplex (see Appendix M).

All of the NMP data sources are used extensively in NWS forecast and warning operations, from ingest into NCEP's modeling and data assimilation systems to their use in real time detection of severe weather, including flash flooding and severe wind gusts.

When the NMP began in 2009, only nine networks were participants, located mostly in the south-central United States. Today, more than 40 networks are contracted to provide data to NWS, and span all 50 states. Twenty-five thousand surface stations are in the overall assets mix. Figure L.2 illustrates what an enormous capability this provides, above and beyond the approximately 900 surface stations operated as a federal capability by NWS, FAA and DoD (ASOS) [http://www.nws.noaa.gov/asos/].

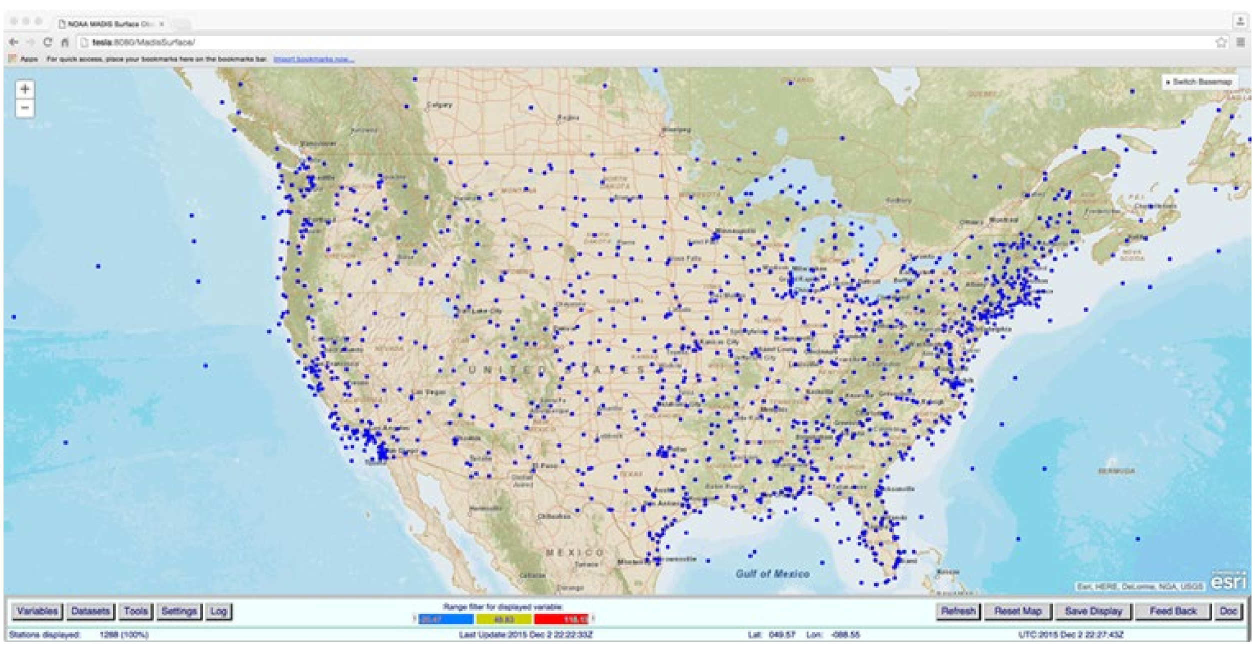


Figure L.2(a): Locations of NWS surface observing stations.

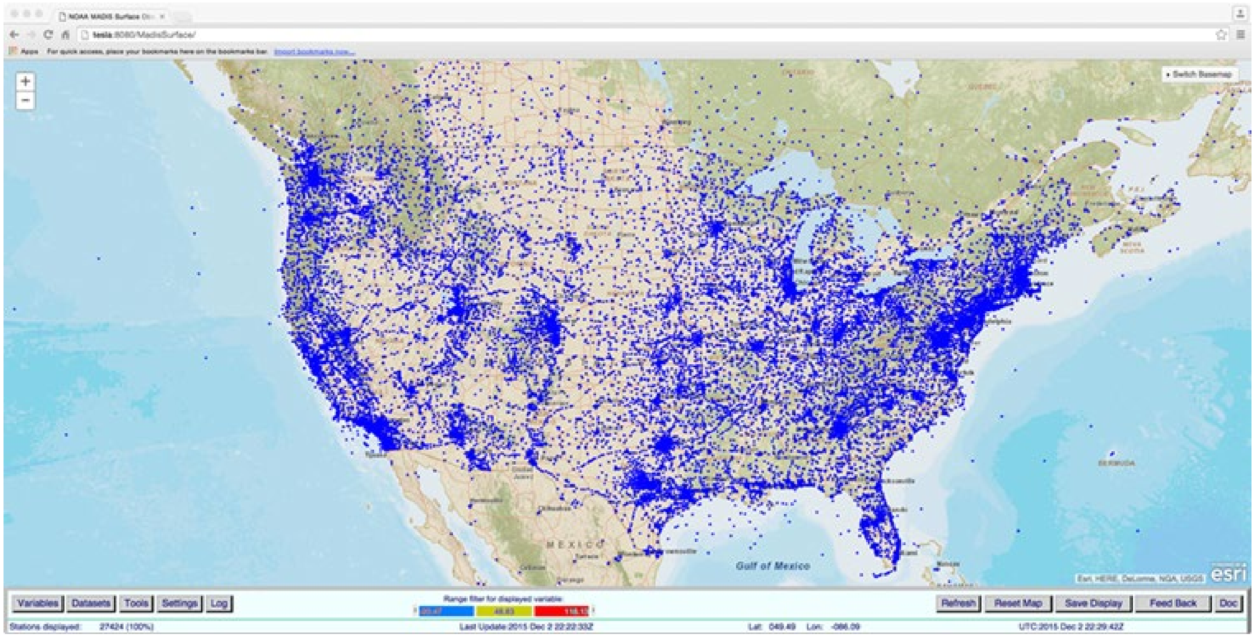


Figure L.2(b). Locations of surface observing stations provided by the NMP.

Appendix M – Additional Observational Sources Available and Operational In Areas of Insufficient Flash Flood Warnings Due to Limited NEXRAD Coverage

[Writers: STI/Daniel Meléndez, OBS: Jessica Schultz, C. Marshall, AFS/K. Abshire, M. Mullusky, CAD/Sokich, NSSL/K. Howard, S. Martinaitis]

Other observational systems besides NEXRAD are available to the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) to provide 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:

- TDWR Radars: Terminal Doppler Weather Radars (TDWRs) are strategically placed near airports and provide radar observations at a greater spatial-temporal resolution than the Doppler weather radar (NEXRAD) network. TDWR data are processed similarly to the NEXRAD radars and are viewable by NWS personnel. The low elevation angles of the radar beam combined with a more frequent temporal resolution are valuable to the detection of short-fused severe weather hazards, especially tornadic circulations. Current limitations with its data make it challenging to obtain accurate precipitation information operationally.

- CASA Radars: The Collaborative Adaptive Sensing of the Atmosphere (CASA) project uses small-scale Doppler radars to determine the feasibility of gap filling radar in regions of inadequate NEXRAD radar coverage. The CASA experiment in the Dallas-Fort Worth Metro area began in 2012 with the installation of the first radar. A total of 7 radars were installed by 2015 at a cost of approximately $3.5 million with annual operating costs of the network around $600k. These radars have a shorter range (around 25 miles) and are more susceptible to attenuation, or degradation of the beam, than the WSR-88D or the Federal Aviation Administration's (FAA) TDWR. The CASA experiment has provided NWS forecasters in Fort Worth rapid updates of high-resolution data during severe weather events in the metropolitan area. This supplemental radar data has enhanced the quality of real-time severe thunderstorm and tornado warning services in some events since 2014. In addition, the high-resolution CASA radar data has expedited post-event storm damage surveys. 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 some funding/support from NWS via the National Mesonet Program (see Appendix L).

- 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 in regions of known radar coverage gaps. One example is the University of Louisiana-Monroe, who has a radar built to similar specifications of the NEXRAD radar fleet. It is placed in a gap between Shreveport, LA and Jackson, MS where the lowest available data from the NEXRAD network can exceed 6500 ft above ground level (AGL). Another example is from the University of Missouri, that employs a radar between Kansas City, MO, and St. Louis, MO, that can help improve coverage over northern Missouri where the lowest available data can be over 8000-9000 ft AGL. Environment Canada also has a radar network providing additional coverage across the northern border of the US. Local forecast offices have access to these university and Canadian radars. There is a large number of TV weather radars having widely different operating characteristics; these are not available to the NWS within their Advanced Weather Interactive Processing System (AWIPS), but the data are available via the Internet and used by the WFOs for situational awareness. Some of this data are available to NWs forecasters through the Multi-Radar Multi System (see below for details).

- 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 (GLM) is employed on the Geostationary Operational Environmental Satellite (GOES) system (GOES-16 and GOES 17 satellites). 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 tens of minutes. 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.

- Satellite Observations: Geostationary and orbiting satellites provide a means to have multiple instrumentation packages assessing environmental and storm characteristics that can improve severe weather and heavy rainfall detection. For tornadic storms, GOES GLM data will help in identifying changes in lightning frequency that are correlated with increase in convective storm intensity, including tornadic development. Precipitation estimation from orbiting satellites can provide rainfall information in areas of complex terrain that cannot be sampled by the NEXRAD network. However, there are also inherent limitations with satellite-derived precipitation data, including challenges with proper estimation, spatial resolution, parallax error, and data latency.

- Precipitation Gauges: Various precipitation gauge networks can provide accumulated liquid precipitation values on different temporal scales. Gauges are commonly referred to as the "ground truth;" however, they do not have the adequate coverage densities to capture the spatial gradients and variabilities of precipitation. In addition, there may be challenges with receiving gauge data due to data latency issues. 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 Hydrometeorologial Automated Data System (HADS) and Meteorological Assimilation Data Ingest System (MADIS) allow for a compiled, more direct access to multiple data sources.

- USGS Gauges: For flash flood events, point observations from United States Geological Survey (USGS) stream gauges can provide information on local waterways in 15-min increments which are generally transmitted hourly. Recording and transmission times may be more frequent during critical events. 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, which can be flown over weather features to improve data collection and forecasting. More details on NOAA unmanned aerial system can be found at http://uas.noaa.gov/. Currently, this is entirely in the research phase and non-operational.

Each of the aforementioned platforms has their own strengths and challenges when it comes to severe weather and heavy rainfall/flash flood detection. There are operational systems and other efforts that are combining multiple platforms to improve the short-term prediction and detection of hazardous weather. One such effort that was developed at the NOAA National Severe Storms Laboratory (NSSL) and made operationally available to the NWS is the fully-automated, real-time Multi-Radar Multi-System (MRMS) system (Zhang et al. 2016). The current operational version of MRMS (as of October 2017) 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 is provided at a 1 km × 1 km spatial resolution with most radar-based products generated every two minutes. Longer duration QPEs and those that are gauge-derived or gauge-adjusted are available every hour.

The MRMS system employs multiple techniques and algorithms to improve the quality of the NEXRAD radar outputs and seamlessly mosaics the radar data together to provide coverage over the CONUS and southern Canada. MRMS features products like lightning densities and azimuthal rotation tracks to help identify storms that have tornadic potential. There is also a suite of different precipitation estimation products. Since most products in the operational MRMS system are radar dependent, MRMS will have similar performance issues in areas where coverage from any NEXRAD radar is poor or non-existent. This includes the performance of QPE values within the MRMS system. Figure M.1 demonstrates the challenges of estimating rainfall with respect to the height of the radar beam above ground level. As the radar beam becomes higher in altitude above the ground, it can overshoot precipitation features. The result of this is the underestimation of precipitation. In cases where the precipitation feature is shallow or if the radar is significantly blocked, the radar can completely miss the event (i.e., it is precipitating at the surface but the radar shows nothing); thus, the MRMS radar-based QPE products will miss the event as well. The failure of radars not capturing QPE and the subsequent impacts of MRMS radar QPE products showing no QPE within these areas of poor radar coverage in the western U.S. has been documented by NWS Western Region Headquarters. These radar-based QPE gaps impact the performance of MRMS products, which subsequently impacts the quality and/or verification of models (e.g., the National Water Model, RTMA, NBM, etc.), since the MRMS radar-based QPE is used by the NWS as a prime source of QPE for major service programs.

MRMS has one operational non-radar-based QPE product called Mountain Mapper QPE, which utilizes gauge observations and background precipitation climatologies to map out precipitation.

The objective of the Mountain Mapper product was to create QPE values in regions where radar coverage is poor or non-existent using quality-controlled hourly precipitation gauge observations. The scheme was designed to work in the mountainous regions of the western U.S. and with stratiform events. Because of its dependence on gauge observations, Mountain Mapper struggles with QPE performance in areas of sparse gauge densities (especially in the western U.S.) where the spatial and magnitude variability of precipitation is not properly observed.

To mitigate radar coverage issues in order to improve precipitation estimations in MRMS, the upcoming operational update of MRMS features a Multi-Sensor QPE product that is designed to fill in radar gaps in the mountainous western United States as well as gaps created by radar outages (Figures M.2–M.3). The Multi-Sensor QPE product is a Joint Technology Transfer Initiative (JTTI)-funded project that will evaluate and potentially incorporate the Mountain Mapper QPE as well as short-term numerical weather prediction models to also fill gaps in radar coverage. This version of the Multi-Sensor QPE will utilize the strengths of Mountain Mapper QPE, and short-term model quantitative precipitation forecasts (QPFs) in regions of poor radar coverage based on precipitation types and topography. The final product will be generated at the top of each hour. This project is scheduled for completion and operational transition to the NWS in 2019. Updates like the Multi-Sensor QPE and other QPE algorithm improvements to the MRMS system will allow these products derived by multiple sensors to be available for use by NOAA's operational models to help with improved flash flood prediction based on their evaluated performance.

Improvements to numerical weather models can also advance the detection of tornadoes and flash flooding. High-resolution model data, especially from convective-allowing models (CAMs), can act as a gap-filler in areas of complex terrain or areas lacking radar or other observational coverage; however, having successful improvements with numerical weather models can be dependent upon data collection readily available for ingest.

Some weather models ingest radar reflectivity and other observations to initialize each model run. An experimental Warn-on-Forecast (WoF) ensemble system in development at the NOAA Earth System Research Laboratory (ESRL) and NOAA/NSSL that ingests high resolution surface, satellite, and radar observations into computer models to help forecast specific hazards (e.g., tornadoes and flash flooding) in advanced to provide additional lead time. One example showcasing the potential of the WoF system is the early tornadic prediction before the town of Elk City, OK was impacted by an EF-2 tornado on 16 May 2017 (http://www.noaa.gov/stories/experimental-model-predicted-tornados-path-hours-not-minutes-before-it-formed); however, this event occurred where the lowest data elevation is 2400 ft AGL where it is relatively well sampled by two NEXRAD radars. Continued studies on how a system like WoF can work in data-limited regions and how additional resources can improve detection of weather hazards.

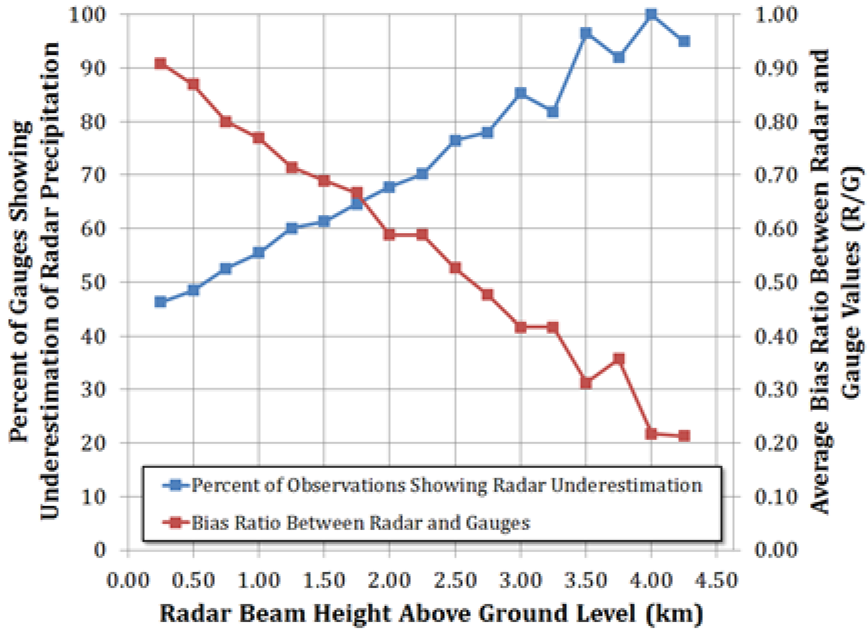


Figure M.1: Percentage of gauge observations showing radar underestimation (blue) and the bias ratio between radar-estimated precipitation and surface precipitation gauge observations (red) as a function of radar beam bottom height above ground level (km). Bias ratio values less than 1.00 describe an underestimation by the radar QPE. Data consisted of rainfall events in the eastern CONUS. Adapted from Cocks et al. (2016).

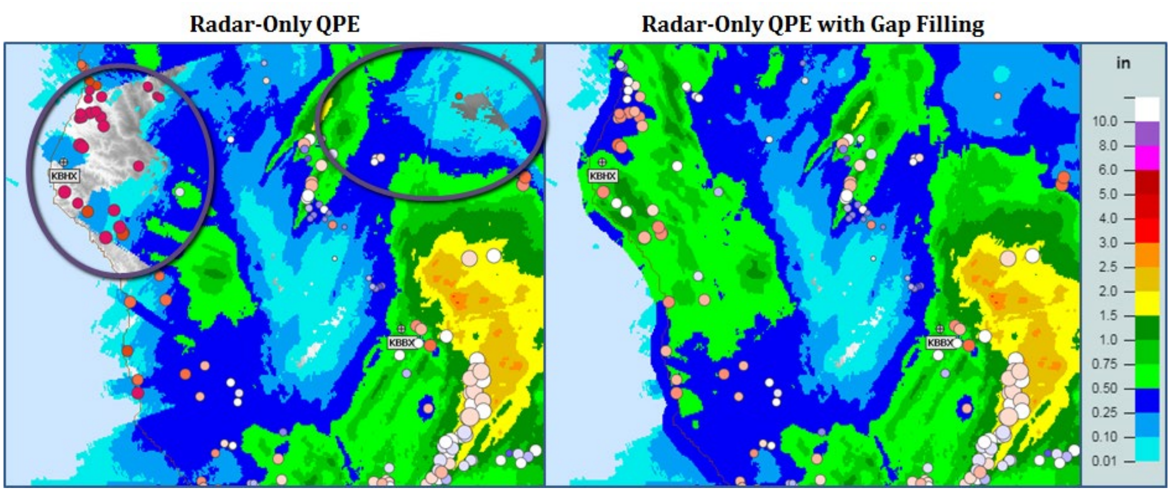


Figure M.2 – 24-hour quantitative precipitation estimation (QPE) totals using radar-only QPE (left) and gap-filled radar QPE (right) from the Multi-Radar Multi-Sensor (MRMS) system ending 1400 UTC 8 April 2017 in northern California. Bubble plots are independent daily observations compared to the QPEs. Red colors indicate underestimations by the QPE, blue colors indicate overestimations by the QPE. Circled areas highlight regions of terrain blockage and a radar outage from the NEXRAD radar KBHX (Eureka, CA).

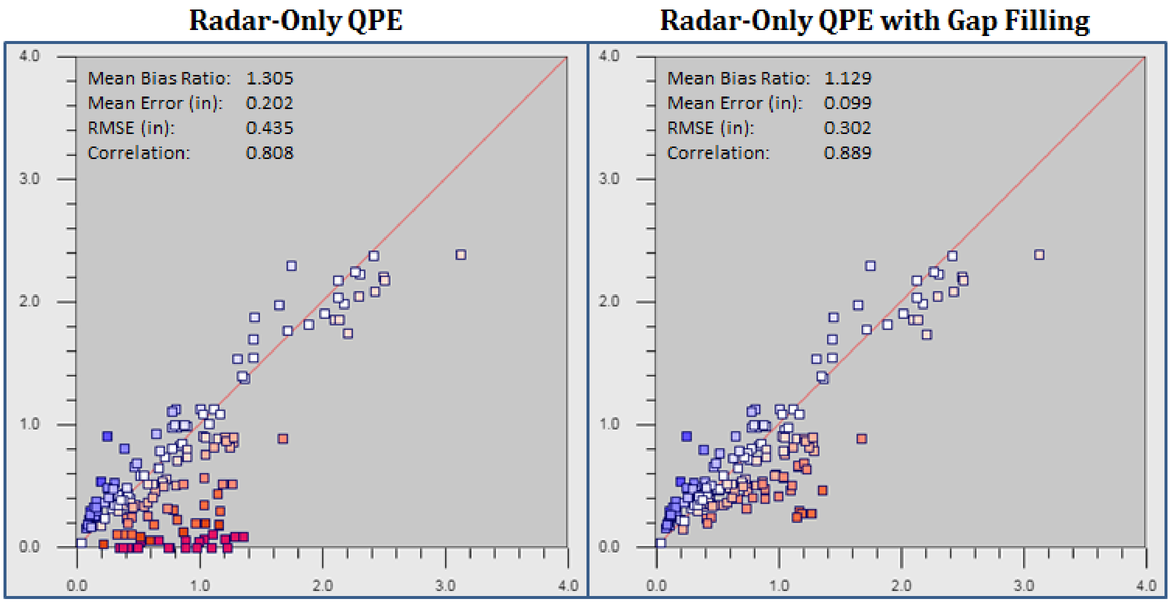


Figure M.3 – Scatter plots with statistics of independent daily observations versus radar-only quantitative precipitation estimation (QPE; left) and gap-filled radar QPE (right) shown in Figure M.2 for 24-hour period ending 1400 UTC 8 April 2017.

References

Cocks, S. B., S. M. Martinaitis, B. Kaney, J. Zhang, and K. Howard, 2016: MRMS QPE performance during the 2013/14 cool season. *J. Hydrometeor.*, **17**, 791–810.

Zhang, J., and Coauthors, 2016: Multi-Radar Multi-Sensor (MRMS) quantitative precipitation estimation: Initial operating capabilities. *Bull. Amer. Meteor. Soc.*, 97, 621–637.

Appendix N – Improvement Options in Warning and Forecasting of Key Weather Effects For Insufficient Warnings Due to Improved Radar Coverage

[Writers: Daniel Meléndez, CAD/Sokich, AFS/Saffle, Schoor, OBS/Jessica Schauer; NSSL/Howard, Martinaitis, Weber]

Improvements in warning and forecasting regarding key weather effects effectively would involve the following, in rough order of relevance. Essentially, what is sought is increased spatial thermodynamic sampling (temperature, moisture, winds) as a function of altitude in the boundary layer up to 1-2 km and with fast temporal sampling. Appendices F, L, and M lists various systems currently in use, and appendices O and P discuss the feasibility of adding radars and new NOAA modeling capabilities being researched, respectively. These all constitute options in so far as they can be enhanced or accelerated to improve key weather event performance. A significant option under research is the potential use of phased array weather radar, technology developed for military applications capable of sampling weather more rapidly. All indications are that this is a costlier option likely requiring multi-agency leverage in order to reduce the unit cost (see SENSR project). A combination of options based on feedback from polled forecasters and historical evidence points to the following alternatives:

1. Greater radar coverage (high-resolution, Doppler) increasing both horizontal and vertical sampling and associated continual improvements. Based on the results of this preliminary analysis, and the impact of NEXRAD when it became operational during the 1990s, this could benefit flash floods the most. Its likely impact on tornadic weather warning performance in areas of limited radar coverage is strongly tied to the frequency of such events (Appendix C).
2. Improved high-resolution convective-allowing numerical model with 1-km 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.
3. Greater space-based multi-band (visible, infrared, microwave) imagery with -1km horizontal resolution or better including winds. In particular, the use of microwave imagery has not advanced sufficiently for overland use in contrast to the benefits shown in overwater weather scanning where the use of various microwave frequencies effectively provide information on rain, ice, and convective depth. A historic improvement in satellite imagery just took place recently with the launch of NOAA GOES-16 satellite, bringing unprecedented spectral coverage and spatial resolution. GOES-16 imagery, and GOES-17 when it becomes operational, are probably the main backup for radar estimation of precipitation, and certainly a valuable alternative operational source for NWS warnings. Compared to NEXRAD, other sensors contribute to NWS warning skill, but in the case of satellite-based precipitation, the estimates have lower resolution in space and time nor do they provide estimates beyond rainfall rates of about 4 inches/hour.
4. 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.

5. Adoption of both unmanned and manned aerial systems to sample particular areas and weather features in an operationally targeted fashion. As discussed in Appendix M, this is an active area of research.

The advances in increased spatial thermodynamic sampling (temperature, moisture, winds) as a function of altitude in the boundary layer up to 1-2 km and with fast temporal sampling and numerical modeling is what is required to take NWS tornado and flash flood warnings to the next level, as described as future goals Section 103 of the Act.

There are significant costs associated with many of these options [see appendices M and O, for example]. Costs for these advancements will be considered as part of normal NOAA planning and budget submissions.

Appendix O – Feasibility of Integrating and Upgrading NEXRAD Network With non-NOAA Weather Radars

Writers: STI/Meléndez, AFS/Abshire; OBS/Schauer, Istok, Saffle. 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.

<u>Integrating data from radars owned, operated, and maintained by third parties:</u>

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. For instance, communication lines and bandwidth would need to be upgraded and maintained to support effective delivery and display of the data. Integrating the data into NOAA's Advanced Weather Interactive Processing System (AWIPS) would require the 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 a third-party weather radar would also require security updates and monitoring. Third party display of the data, such as employing the use of commercial radar data display software, would reduce the costs of NOAA maintaining some software and hardware components, but would require the owner/operator of the radar to make the data available in a public format which may not be desirable for proprietary or liability reasons (i.e., television station radars).

In FY18 dollars, the estimated cost to integrate radar data from radars owned, operated, and maintained by third parties would be approximately $200,000 one-time costs plus $100,000 in yearly maintenance per radar, regardless of its frequency. This would cover hardware, software, and communication upgrades and sustainment costs. Human resources would also be necessary to maintain and sustain the equipment and perform required security monitoring. For every five third-party owned radars in which NOAA ingests data, two new employees would be needed.

Requirements for any third-party weather radars must be established prior to ingesting the data. These requirements should include:

- data from weather radars only
- NEXRAD Level II format
- data quality of sufficient level (as determined by NOAA)
- reflectivity and velocity data available
- dual polarization as high priority

Furthermore, the current NEXRAD and TDWR coverage must be considered. It would not be prudent to incur the costs and responsibilities of ingesting third-party radar data if it would not significantly add to the area's weather radar coverage.

<u>Integrating and upgrading the NEXRAD network with non-NOAA radars to be owned, operated, and maintained by NOAA:</u>

Purchasing third-party radars would present significant yearly costs to integrate into the current NEXRAD network, require additional personnel, and based on previous experience, has proven to lack the radar operational availability of the NEXRAD systems.

S-band dual polarization radars can be purchased on the open market for $3 to $5 million dollars each, which does not include siting/installation or recurring costs. However, these radars do not necessarily meet the stringent hardware, software, maintenance support and data quality requirements/standards of the NEXRAD. In the early 2000s, a third-party radar was purchased for the Evansville, IN area, but was decommissioned and removed after a short period of service. The radar did not meet the operational availability standards demanded of the NEXRAD network, maintenance costs exceeded estimates, and it was not possible to maintain the radar's software or integrate it into the NEXRAD baseline.

The integration of a third-party weather radar into the NEXRAD network to be owned, operated, and maintained by NOAA would, aside from the initial purchase, cost multi-millions per year to maintain and operate. The yearly costs are not limited to facilities and equipment maintenance support of the radar itself, but include additional resources and personnel needed to establish and sustain multiple weather radar baselines in the NOAA radar program.

One candidate technology is short-wavelength network X-band radar. There are no firm costs associated with this option but using published estimates of $700k per X-band radar, and the nominal unattenuated range of about 60 nm these radars, a network of over 15 X-band radars would be needed to provide volumetric coverage comparable to NEXRAD. Consequently, the initial cost of such a network is over $11M not including operations and maintenance or real estate, therefore becoming comparable to that of a NEXRAD. However, the intent of these X-band radars is not necessarily to replicate a NEXRAD but to fill gaps in populated areas where NEXRAD plus TDWR may not be deemed adequate.

<u>Integrating non-NOAA radars into the Multi-Radar Multi-System (MRMS):</u>

The current operational version (as of October 2017) of the fully-automated, real-time Multi-Radar Multi-System (MRMS) developed at the NOAA National Severe Storms Laboratory (NSSL) and made available to the NWS employs multiple techniques and algorithms to seamlessly mosaic radar data together to provide coverage over the CONUS and southern Canada. MRMS ingests 3D volume scan data from about 146 S-band dual-polarization Weather Surveillance Radar-1988 Doppler (WSR-88D) radars and about 30 C-band single-polarization weather radars operated by Environment Canada (Zhang et al. 2016). All data from MRMS are provided at a 1 km × 1 km spatial resolution with most radar-based products generated every two minutes. Longer duration QPEs and those that are gauge-derived or gauge-adjusted are available every hour.

There are plans to incorporate Terminal Doppler Weather Radars (TDWR) from the Federal Aviation Administration into MRMS and to expand the MRMS domain into the Caribbean. The ability of MRMS to integrate data from multiple radars would allow incorporation of commercial radar data or other radar networks, perhaps including the Collaborative Adaptive Sensing of the Atmosphere (CASA) network into its suite of severe weather and precipitation products. Since most products in the operational MRMS system are radar dependent, MRMS can have performance issues in areas where coverage from any radar is poor or non-existent. This includes the performance of QPE values within the MRMS system.

Appendix P - Augmentation of Severe Weather Coverage by Advanced NOAA Weather Modeling

[Writers: STIO/Meléndez, NSSL/ Heinselman]

Currently, the NWS uses a warn-on-detection paradigm based heavily on the NEXRAD Weather Surveillance Radar–1988 Doppler (WSR-88D) radar observations of parent thunderstorms, as well as knowledge of the mesoscale environment within which storms form and are embedded. Use of the WSR-88D network by NWS forecasters has resulted in remarkable improvements in the accuracy and timeliness of severe thunderstorm and tornado warnings over the past few decades, and helped to reduce fatalities from hazardous weather events in the United States. Furthermore, continuing technological advances such as rapid scanning techniques for the WSR-88D, and adaptive scanning techniques using phased array radars, may allow for continued progress in this arena. However, the potential for significant advances in warning lead time is limited within the warn-on-detection paradigm by the fundamental requirement that a warning is largely predicated on a forecaster's detection of radar-based storm features that are in the process of forming or have already formed. This limitation appears to be reflected by statistical trends in NWS tornado-warning lead times that show the average NWS tornado-warning lead time peaked at about 13 minutes more than 10 years ago.

Transformational improvements in warning lead times for convective hazards will require science and technology advancements that predict the occurrence of these hazards as reliably and accurately as current technologies detect them. This is noted in Section 103 of the Weather Act and moving forward in NOAA as the Tornado Warning Improvement and Extension Program. This is a separate report to Congress. Toward this end, convection-allowing ensemble prediction systems, like Warn-on-Forecast (WoF), are being developed and tested by NOAA/National Severe Storms Laboratory (NSSL) and NOAA/Earth Science Research Laboratory (ESRL)/Global Systems Division (GSD) to meet this requirement and more. Specifically, WoF technologies will not only provide guidance to enable extension of lead times for convective hazards, they will supplement this guidance with calibrated probabilistic threat information that enables judicious decision making by a multitude of different users with different levels of risk aversion and responsibility for life and property. In short, the WoF project aims to play a foundational role in making the United States a "Weather Ready Nation".

One vision for this transformational improvement is a world-class, frequently updated, regional-scale, on-demand convection-allowing analysis and prediction system, invoked as needed by a national center, such as the NWS Storm Prediction Center, to support watch and warning operations within NOAA. Modeling and computing are significant contributors to NOAA operations and comprise a large portion of research funding (see NOAA Research Council Five Year Plan 2013-2017).

The prototype WoF system is aimed at providing probabilistic forecast guidance useful to both NWS prediction centers and weather forecast offices within the watch-to-warning period. Hence, system development is focused ultimately on the 0–3-hr forecast time frame and the capability to produce forecasts encompassing aspects of the convective storm life cycle from initiation to onset of severe weather hazards, to cessation of severe hazards, and ultimately to convective decay. While initial demonstrations and testing of the prototype system will be concentrated in the Plains during the spring severe weather season and the earlier severe weather season in the southeast US via the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) Southeast Program (http://www.nssl.noaa.gov/projects/vortexse/), later efforts will explore its capabilities in other parts of the US during the spring and other seasons in which severe weather hazards can occur.

Once ready for transition to NWS operations, this proposed system would provide the information decision makers at the local, state, and national levels required for achieving the following four improvements:

1) Extend tornado warning lead times from the current average of 13 minutes to up to an hour,

2) Provide more geographically precise high-impact weather information (e.g., projected tornado paths, or severe wind and hail swaths) and confidence in its occurrence,

3) Provide more precise earliest time of arrival and latest time of departure for severe storms and their associated hazards threatening any given geographic location, and

4) Generate detailed precipitation forecasts for very fine space and time scales to predict extreme rainfall events out to six hours in advance.

Ultimately, these improvements will enable weather-sensitive industries and communities to make more user-specific decisions with the potential to not only save lives and protect livelihoods, but to also improve the economy. In 2009, Sutter and Erickson estimated that the reduction in spatial coverage owing to the replacement of count-based with storm-based warnings would result in a savings of at least $100 million in terms of the value of time not spent sheltering. We expect further savings to result from the smaller and more specific warning areas that will be possible using this new WoF system. For example, location-specific warnings will likely provide the opportunity for entities such as outdoor venues to secure infrastructure, such as an outdoor performance stage, and move attendees to safety prior to hazardous weather. This action could allow the "show to go on" following the storm, negating the cost of replacing the stage and/or refunding tickets. Cost-loss ratio and other studies will need to be completed to estimate the expected economic benefits across the United States.

Currently, NWS uses convection-allowing numerical weather models operationally such as the HRRR, the NAM nest, and the HiResWindow, all running at 3-km horizontally. These have the capability of simulating radar observables such as reflectivity and winds, effectively supplementing radar observations in areas of gaps. Model precipitation location skill, for instance, has improved over the years, as is shown for critical success index (CSI) for the HRRR model in Figure P.1. Limited examinations of model reflectivity show the hi-resolution models have some skill (Stoelinga, Development Test Center), and http://nwas.org/convection-allowing-models-changed-world/. There is a Community-Leveraged Unified Ensemble that is being developed to harness the power of ensembles in tornado/severe weather forecasting and to consider whether radar data assimilation extends the ensemble forecasts to longer forecast lengths compared to deterministic models [Clark et al, 2016; https://ams.confex.com/ams/28SLS/webprogram/Paper301307.html]. Strategic implementation plans are being developed around this type of modeling.

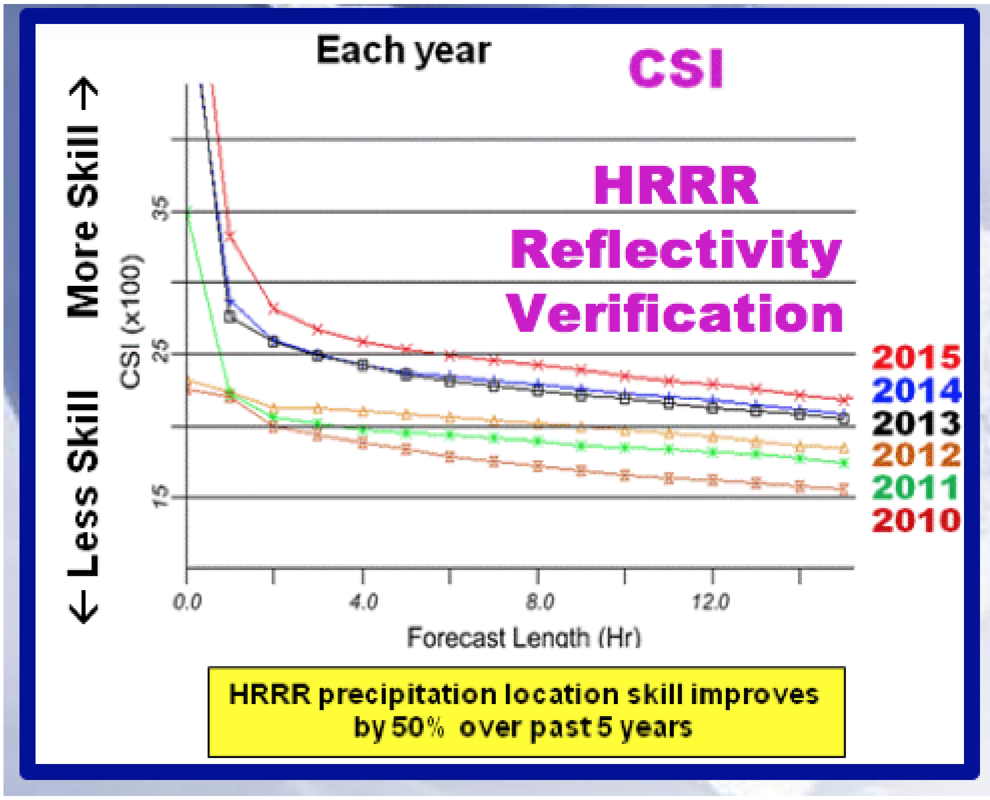


Figure P.1 - Critical success index (CSI) for the HRRR model location of precipitation between 2010--2015, showing yearly improvement. Location of precipitation is a spatial variable such as that obtained from weather radar.

Appendix Q -- Georeferencing of Tornado and Flash Flood Events with Respect to Radar Coverage Boundaries

Writers: STIO/Meléndez, K. Sheets, NWC/M. Stone

As part of the warning performance evaluation, 12296 tornado track segments from 2008 through 2016 were geospatially analyzed to determine whether they began inside or outside the 6 kft-AGL radar coverage area(s). Using a geographic information system (GIS), the given starting point of each tornado track segment was mapped as either inside or outside the polygons representing the specified radar coverage area(s). Of the 12,296 tornado track segments, 9195 began inside the WSR-88D 6 kft AGL coverage, and 9795 began inside the combined WSR-88D and TDWR 6 kft AGL coverages.

An alternate GIS analysis was completed by comparing the location of the NWS tornado database by constructing a line between the start and end point of the tornado. The purpose was to confirm the findings of parity between the fractions of events warned and unwarned inside and outside the threshold radar coverage chosen (which it did). These lines were then analyzed against the radar coverage to create two categories, within or outside radar coverage. The first step was to select the event lines which fell within the radar coverage polygons. A new file was exported which only included these event lines completely within the radar coverage polygons. A switch selection was then performed to select the event polygons that were outside radar coverage which was exported to create an outside coverage file. When investigating this file it was discovered that the outside coverage also included the events which crossed the radar boundary. In order to see how many events this affected and additional analysis was performed to indicate how many of the "outside" events actually crossed the radar coverage boundary. The event files were then subdivided by their warned (yes or no) attribute to create the 6 final files and counts - warned within radar, warned outside of radar, warned crossed radar, unwarned, within radar, unwarned outside of radar and unwarned crossed radar. The attributes of each of these files were also analyzed to include counts of injuries, deaths, and significant property damage.

Appendix R - Local Storm Reports (LSRs)

The National Weather Service (NWS) collects weather event impact data via Local Storm Reports. While Storm Data serves as official input to the NWS verification system for select programs, the primary purpose of Storm Data is to accurately describe events, regardless of the impact on verification scores. Some information appearing in *Storm Data* may be provided by or gathered from sources outside the NWS, such as the media, law enforcement and/or other government agencies, emergency managers, private companies, individuals, etc. An effort is made to use the best available information, but because of time and resource constraints, these sources may be unverified by the NWS. Accordingly, the NWS does not guarantee the accuracy or validity of the information. Further, when information appearing in *Storm Data* originated from a source outside the NWS (frequently credit is provided), *Storm Data* users requiring additional information should contact that source directly.

The source of most of the data used in this report comes from the Local Storm Reports (LSRs). A detailed description of the LSRs can be found in https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwiguNWlxKXWAhVJslQKHTaGBysQFggoMAA&url=http%3A%2F%2Fwww.nws.noaa.gov%2Fdirectives%2Fsym%2Fpd01016005curr.pdf&usg=AFQjCNHVdBOcrLP4YJ09toHyuUPuy3dzjQ.

Appendix S - Listing of NWS Weather Forecast Offices

This appendix lists the acronyms of the National Weather Service Forecast Offices (WFOs). A detailed listing can be found at https://www.weather.gov/gis/CWABounds.

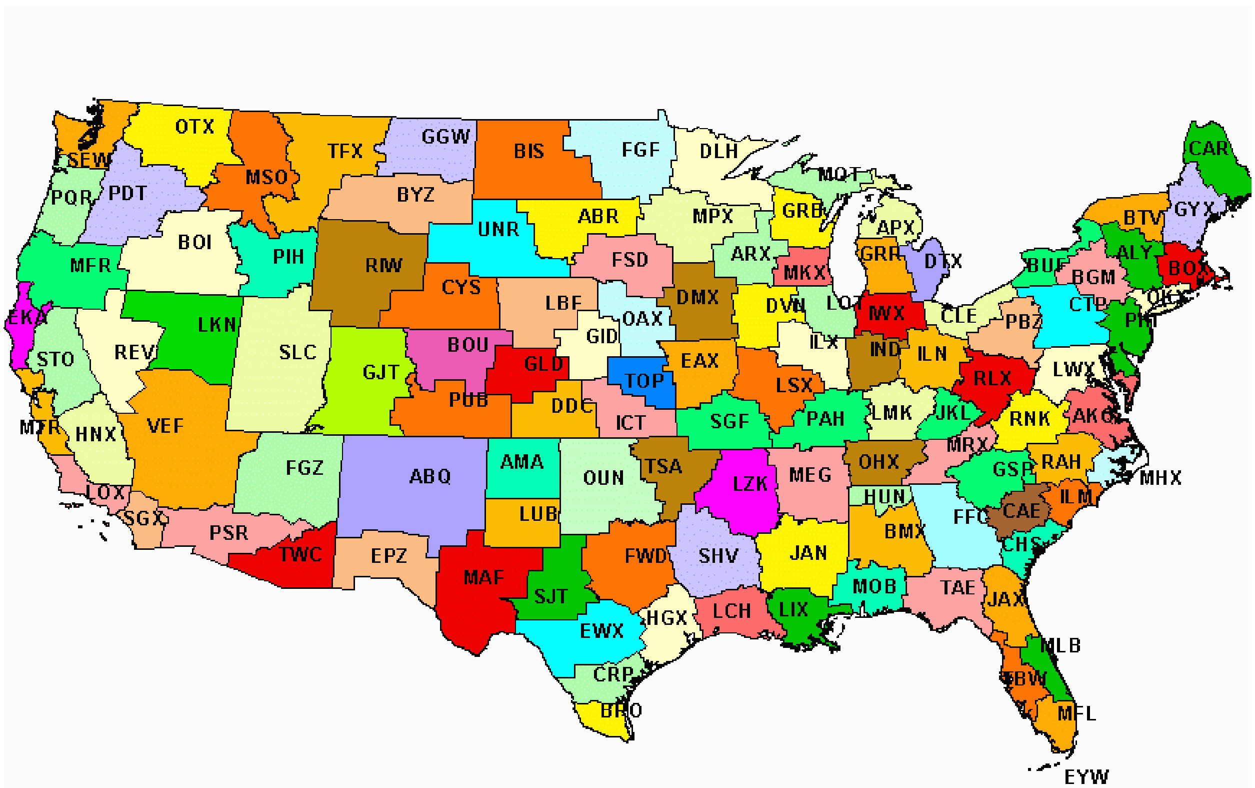


Figure S.1 - Locations and abbreviations of NWS Weather Forecast Offices in the Contiguous U.S. A detailed listing including Hawaii, Guam, Puerto Rico and American Samoa can be found at https://www.weather.gov/gis/CWABounds.