Chapter 5
FINDINGS AND RECOMMENDATIONS

5.1 PRINCIPAL FINDINGS

The National Institute of Standards and Technology (NIST) developed findings based upon information collected during and after the initial reconnaissance, interviews conducted with survivors, and data analyses related to environmental conditions, building performance, and emergency response and communications activities. These findings are enumerated in Sections 5.1.2 through 5.1.4, following the contextual observations presented in Sec. 5.1.1.

5.1.1 Context for Findings

- National model building codes, standards, and practices seek to achieve life safety for the hazards that are considered in design. While these considerations include hurricane and nontornadic wind, flood, snow, rain, earthquake, and ice loads, they do not include tornado hazards (loads due to wind speeds that significantly exceed code–compliant design wind speed and impacts of wind–borne debris). Thus, buildings and other structures are not designed for tornado hazards currently. The sole exceptions are safety–related structures in nuclear power plants and storm shelters or safe rooms.

- There are currently two tornado hazard maps prescribing different tornado hazard regionalization and associated wind speeds for the contiguous United States:

  – The ANSI/ANS 2.3 (2011), NRC/RG 1.76 (2007), and DOE 1020 (2002) map for designing nuclear–related facilities (three regions, 230 mph maximum wind speed); and

  – The ICC 500 (2008), FEMA 320 (2008), and FEMA 361 (2008) map for designing shelters and safe rooms (four regions, 250 mph maximum wind speed).

- Current building codes and standards prohibit the use of aggregate roof surfacing materials or ballast for hurricane–prone regions,[159] but allow their use in other regions based on mean roof height and exposure category. For the City of Joplin, the building code at the time of the May 22, 2011 Joplin tornado allowed aggregate roof ballast for buildings with a mean roof height of less than 110 ft.

- In the State of Missouri, the adoption and enforcement of building codes are prerogatives of local government. The City of Joplin's building department has a long history of code

[159] Defined in ASCE/SEI Standard 7–10 *Minimum Design Loads for Buildings and Other Structures* as: Areas vulnerable to hurricanes; in the United States and its territories defined as (1) The U.S. Atlantic Ocean and Gulf of Mexico coasts where the basic wind speed for Risk Category II buildings is greater than 115 mph, and (2) Hawaii, Puerto Rico, Guam, Virgin Islands, and American Samoa.

adoptions, and typically has adopted the latest national model building codes shortly after they have been issued.

- Like most other municipalities in tornado–prone areas and the contemporaneous model building codes, the City of Joplin does not mandate the construction of shelters or safe rooms in residential or non–residential facilities. Additionally, the City did not own or operate any public storm shelters. The lack of public shelters and requirements for safe rooms in residential or non–residential facilities meant that many residents in the area affected by the May 22, 2011, Joplin tornado, particularly those who were living in multi–family residential buildings or older nursing homes, did not have access to such sheltering options during this tornado.

5.1.2 Findings Related to Tornado Hazard Characteristics and Associated Wind Field

5.1.2.1 Measurements of the Near–Surface Wind Field in Tornadoes (< 20 m)

Finding 1—

Current operational weather radar technology is incapable of determining tornado occurrence and intensity at heights above the ground that are relevant to structural engineering design (i.e. at the heights of buildings). For example, because the nearest operational radars to Joplin were more than 60 miles away they could only measure conditions at altitudes starting at 5000 ft.

Finding 2—

Reliable direct measurement of wind speed in tornadoes, especially the most intense tornadoes, is lacking or non–existent. Wind speed measurements related, but not directly, to the May 22, 2011, Joplin tornado were limited to one location well outside the tornado damage path. The difficulty in measuring tornado intensity discussed in both Findings 1 and 2 have been noted in previous tornado research.

Finding 3—

NIST estimated the maximum wind speeds in the May 22, 2011, Joplin tornado to be 175 mph with up to 25 percent of uncertainty. With uncertainty, the upper bound of the estimated maximum wind speed in the Joplin tornado was 210 mph. The uncertainty was due to the use of indirect wind speed estimation methods (i.e., tree–fall analysis, EF Scale). Due to the lack of radar and direct wind speed measurements, indirect methods served as the sole estimators of wind speeds in the May 22, 2011, Joplin tornado. While existing indirect methods cannot be used to unambiguously determine wind speeds that can be used in structural design, the remaining findings in this study are not sensitive to the level of uncertainty in this methodology.

Finding 4—

The estimated duration and spatial extent of damaging winds in the May 22, 2011, Joplin tornado were significantly greater than those expected based on those used in current tornado hazard models. This finding is consistent with other studies that have estimated wind fields in actual tornadoes. For example, wind speeds in the Joplin tornado that exceeded those associated with EF–3 accounted for approximately twice the spatial area expected based on modeled estimations for an EF–5 tornado.

5.1.2.2 Assessment of Tornado Climatology, Hazard, and Risk for Structural Design

Finding 5—

The probability of occurrence and subsequent risk of tornadoes is significantly underestimated by point–based methodology. It was shown that actual damage in Joplin and other communities affected by damaging tornadoes was greater than predicted using point–based methodology.

Finding 6—

Tornadoes rated EF–3 or lower have accounted for approximately 96 percent of all U.S. tornadoes between 1950 and 2011, over one–third (36 percent) of the approximately 5,600 tornado–related fatalities over the same period, and about 80 percent of the $25 billion in estimated property losses incurred due to tornadoes between 1996 and 2011. Even in a tornado with intensity greater than EF–3, the wind speeds in the majority of the affected area are equivalent to or less than the maximum wind speeds associated with EF–3 tornadoes. In the case of the Joplin tornado, approximately 40 percent of the fatalities and as much as 90 percent of the tornado area were associated with EF–3 or lower wind speeds.

5.1.2.3 Limitations of the Enhanced Fujita (EF) Scale

Finding 7—

The Enhanced Fujita scale lacks adequate damage indicators (DI's) and corresponding degrees of damage (DOD's) for distinguishing among the most intense tornado events. The lack of DI's and DOD's and overall nature of the EF–scale requires subjective, non–quantitative assessment of tornado damage.

5.1.3 Findings Related to the Response of Residential, Commercial, and Critical Buildings, Including the Performance of Designated Safe Areas and of Lifelines Pertaining to the Continuity of Building Operations

5.1.3.1 Building Performance

Finding 8—

Buildings are not designed to withstand tornado hazards and there are no building code requirements for tornado–resistant design. Most buildings in the area damaged by the May 22, 2011, Joplin tornado were subjected to wind speeds close to or above the speeds that would be expected to cause collapse of or major damage to structures designed to the non–tornadic wind design requirements of the building codes applicable to them. Wind–borne debris, which contributed significantly to building damage in Joplin, also is not considered as a hazard in building design.

Finding 9—

Regardless of construction type, neither affected residential nor non–residential buildings were able to provide life–safety protection in the May 22, 2011, Joplin tornado. Of the 161 fatalities, 135 (or 83.8 percent) were related to building failure. Of these building failure–related fatalities, 74 (52.5 percent) occurred in residential buildings. Of the buildings that were damaged, 7,411 were residential and 553 were non–residential. All 553 of the non–residential buildings and 3,069 (about 43 percent) of the residential structures sustained either *heavy/totaled* or *demolished* damage classification, resulting in approximately $1.228 billion in insured losses for non–residential property and $0.552 billion for residential property.

Finding 10—

Among the engineered buildings surveyed by NIST, those with redundant lateral load capacity and those that did not depend on bracing from the roof system for lateral stability (such as certain steel and concrete moment frame buildings) withstood the tornado without structural collapse. Those with reinforced concrete roofs or composite concrete and steel roofs also withstood the tornado without structural collapse. Those that relied on bracing from a less robust roof system for lateral stability (such as box–type system (BTS) buildings with light steel roof decks) were prone to structural collapse.

Finding 11—

The structural collapses of NIST–surveyed BTS buildings began with failure of the roof system due to wind uplift (failure of roof–deck–to–joist or joist–to–wall connections), which led to the loss of lateral bracing for perimeter walls, causing them to collapse by rotation at the base due to lateral load. Available design information showed that the roof connections of these buildings were adequate for code–level design wind pressures, making it unlikely that these buildings could have failed in wind speeds under 115–120 mph, which are the "ultimate" (that is, sufficient for failure) speeds corresponding to the code–level winds.

Finding 12—

BTS buildings, surveyed by NIST, that sustained total structural collapse had two common design features that increased their vulnerability to collapse in the May 22, 2011, Joplin tornado: light–gauge metal roof systems, and friction–only wall–to–footing connections (currently accepted practice for areas with low or no seismic risk).

Finding 13—

Pre–engineered metal buildings (PEMB) surveyed by NIST sustained significant damage to their envelopes, but no structural collapses of the primary rigid steel frame.

Finding 14—

Failures of residential wood–frame buildings predominantly involved failure of the connections between structural components, rather than of the components themselves (roof, walls, and floor), with the majority involving disconnection of the roof from walls and walls from foundation. This indicates lack of robustness in the connections and in the continuity of the vertical load path from roof to foundation.

Finding 15—

Better structural performance in one of the NIST–surveyed multi–family residential buildings in Joplin can be attributed to use of robust hurricane connectors, typically only required for residential wood–frame buildings in hurricane–prone regions.

Finding 16—

All NIST–surveyed engineered buildings that did not collapse (steel, concrete frame, and PEMB), as well as engineered buildings that collapsed (BTS buildings), sustained significant damage to the building envelopes and interiors due to the combination of wind pressure, impacts by wind–borne debris, and subsequent water intrusion.

Finding 17—

The failure of building envelopes at St. John's Regional Medical Center (SJRMC), which led to loss of protection and subsequent extensive damage to building interiors (affecting electrical distribution and fixtures, water and gas pipes, HVAC systems and ductwork, and the elevator system and elevator shaft enclosure), was the primary cause for the complete loss of functionality of this critical facility, which occurred despite the robust structural system that withstood the tornado without structural collapse.

Finding 18—

The majority of the impact–resistant windows on the fifth floor (Behavioral Health Unit) of the West Tower of SJRMC remained intact, whereas most regular dual–pane insulated windows at SJRMC were broken when exposed to the same tornado hazards.

Finding 19—

While there was no direct evidence that roof aggregate contributed to any injuries or fatalities in Joplin, there was evidence that roof aggregates contributed to envelope damage in SJRMC buildings and surrounding structures, thus adding to the tornado debris hazard and the potential for injuries or fatalities.

5.1.3.2 Performance of Shelters/Safe Rooms/Designated Refuge Areas

Finding 20—

NIST found that Joplin residents had limited access to underground or tornado–resistant shelters. There were no community shelters or safe rooms in the City of Joplin or Jasper County at the time of the May 22, 2011, Joplin tornado. Also, 82 percent of the homes in Joplin lacked basements. Only a few non–residential buildings were equipped with underground locations (e.g., basements), and none was identified as having a tornado–resistant shelter above ground.

Finding 21—

While many non–residential facilities had designated refuge areas, several of these areas suffered severe damage and NIST found no evidence that these areas yielded positive outcomes with respect to loss of life. Most high–occupancy commercial and critical facilities surveyed by NIST in the tornado–affected area (SJRMC, schools, and big–box stores) had in–facility designated refuge areas for tornadoes. However, the locations of these areas were not always based solely on structural considerations. There are currently no design standards, requirements, or best–practice guidelines for designating refuge areas within existing commercial or critical buildings.

Finding 22—

Currently, there are optional model code provisions for the design of specially purposed shelters, but such shelters are not required.

Finding 23—

Based on a few instances observed in this tornado, in–home shelters did perform well and provided life–safety protection to the home owners. NIST found no statistics on how many of the 7,411 damaged residential structures had in–home tornado shelters.

5.1.3.3 Performance of Lifelines

Finding 24—

All utilities (water, gas, power) were lost in the areas damaged by the May 22, 2011, Joplin tornado. The utility providers restored service to critical buildings (SJRMC, water treatment plant) within 24 hours.

Finding 25—

The failure of building envelopes at NIST–surveyed critical facilities, and resultant severe damage to their interior and internal lifeline distribution systems, was the primary cause of the facilities' complete loss of functionality despite restoration of utility services within 24 hours.

Finding 26—

In critical facilities constructed in Joplin prior to 1998, the design wind speed for high–occupancy buildings was higher than that specified for buildings housing the facilities' backup power generators.

5.1.4 Findings Related to the Pattern, Location, and Cause of Fatalities and Injuries, and Associated Performance of Emergency Communications Systems and Public Response

Finding 27—

During the period from 1950 (i.e., the beginning of official tornado record keeping) through 2011, tornadoes caused approximately 5,600 fatalities in the United States. Within an 80–mile radius around Joplin, 233 deaths (including those caused by the Joplin tornado) were caused by tornadoes during the same period.

Finding 28—

The Missouri State Police attributed 161 deaths and the City of Joplin attributed more than 1,000 injuries to the Joplin tornado, which affected an area with an estimated population of 20,820.

Finding 29—

Of the 161 deaths resulting from this tornado, 155 (96 percent) were caused by impact–related factors (i.e., multiple blunt force trauma to the body). The others were caused by stress–induced heart attacks, pneumonia, or lightning.

5.1.4.1 Emergency Communication Prior to May 22, 2011

Finding 30—

There was evidence of high false–alarm rates among the storm–based tornado warnings officially issued for Joplin. From 2005 through 2011, 78 percent (14 out of 18) of the official tornado warnings issued for Joplin did not result in a tornado; this percentage was in line with the 2007–2011 national average storm–based tornado false–alarm rate of 74.7 percent. More recently, over the 5–year period from 2007 through 2011, the Joplin area false–alarm rate increased to 92 percent.

Finding 31—

Despite public perception, no evidence was found of high false–alarm rates for Joplin's outdoor siren system. Since 2007, the average rate of activation of the 25–siren outdoor warning system in Joplin was once per year (at most), not including the test activations (1 minute in duration) that occurred weekly.

Finding 32—

Joplin residents interviewed after the Joplin tornado believed that there had been a high number of false alarms in Joplin from official tornado warnings and the City's outdoor siren system prior to 2011, even though the siren activation rate was once per year (on average).

5.1.4.2 Tornado History Prior to May 22, 2011

Finding 33—

Prior to 2011, the roughly 30–square–mile City of Joplin had experienced one tornado rated EF–2 or greater since 1950; this tornado occurred on May 5, 1971. However, also since 1950, 182 tornadoes rated EF–2 or higher had struck within an 80–mile radius of the City.

Finding 34—

Prior to the May 22, 2011, Joplin tornado, scientifically unfounded beliefs about tornado movements and the effects of regional topography contributed to a common public perception that the City of Joplin was immune to a direct tornado strike.

5.1.4.3 Emergency Communication on May 22, 2011

Finding 35—

Two official tornado warnings were issued on May 22, 2011. After the first official warning, Joplin's sirens were sounded but no tornado occurred. After the second official warning, the siren system was sounded again, 4 minutes after the tornado touched down and almost exactly when the tornado entered the City of Joplin. Both siren soundings took the form of a continuous tone of 3 minutes duration.

Finding 36—

The function of an alert is to grab people's attention before/during a disaster; while the function of a warning is to provide information about the event and how the public should respond. Both are necessary in an emergency. Joplin's outdoor siren system, which could generally be heard indoors as well as outside, was the primary means by which individuals were alerted to a tornado event on May 22, 2011.

Radio, television, and word of mouth were the primary means by which individuals were provided with warning information on May 22, 2011.

Finding 37—

The Joplin–Jasper County Reverse–9–1–1 telephone system was not used on May 22, 2011, due to its inability to disseminate information in a timely manner. It had taken up to 3 hours to get emergency calls out during previous uses, so it is unlikely that the system would have worked in this tornado event.

Finding 38—

Functioning as an alerting system, only, the outdoor sirens prompted many Joplin residents and visitors to seek further information on May 22, 2011. The multiplicity of information sources, and the conflicting information provided by those sources, added to the public's confusion about the true hazard as additional information was sought.

Finding 39—

Across the country, there is no standard method for sounding outdoor public siren systems, which has led to variations in siren usage, activation procedures, and sounding patterns among U.S. communities. Also, there are no nationally accepted standard protocols for the issuance of an all–clear alert following a warning.

Finding 40—

Of the 155 impact–related fatalities, 135 (87 percent) involved persons who are known to have been located inside structures during the tornado. The structures in which these people died included both residential (59 percent of the 135 victims) and non–residential (41 percent) buildings.

Finding 41—

Virtually all of the buildings in which the 135 impact–related fatalities occurred experienced maximum estimated winds associated with tornadoes rated EF–3 or higher. The exceptions were the Meadows Healthcare facility, where two of the deaths occurred, and five single–family homes that were the sites of six of the fatalities.

Finding 42—

The hospital towers at SJRMC did not provide life–safety protection for all occupants, even though the towers did not collapse. Twelve impact–related fatalities occurred in the hospital, four of which involved patients in intensive care units.

Finding 43—

Responses to the approaching tornado among members of the public, in many cases, were delayed or incomplete, as was evidenced by the fatalities that occurred among individuals located outdoors, in vehicles, or en route within buildings to safer refuges when the tornado hit.

Finding 44—

Two factors were found to have contributed to the delayed or incomplete public response to the Joplin tornado. The first was a lack of awareness of the tornado. The second was an inability to perceive personal risk due to one or more of the following: receipt of conflicting or uncertain information about the tornado; pre–existing beliefs about Joplin's immunity to direct tornado strikes; and distrust of or confusion about Joplin's emergency communications system.

Finding 45—

The main factor that convinced individuals to take shelter was the receipt of high–intensity cues, including hearing or seeing the tornado approaching or witnessing others' urgency related to taking protection.

Finding 46—

No fatalities occurred in demolished, detached homes in which people took refuge in basements. Additionally, NIST found no evidence that any of those killed were located underground during the tornado.

Finding 47—

A disproportionate number of people aged 60 years or older died or were injured as a result of this tornado. NIST analysis of the fatalities resulting from the Joplin tornado shows that approximately 8 fatalities occurred per thousand people in Joplin aged 60 years and over compared with 2 fatalities per thousand people in Joplin under 60 years. This disproporiate result remains even after removing all hospital and nursing home deaths. Factors that may have contributed to this outcome include a lack of information flow to these individuals, a lack of supportive social networks among individuals, or inability of an individual to withstand or recover from tornado–induced trauma.

5.2 RECOMMENDATIONS

As part of its technical investigation of the Joplin tornado, NIST has developed 16 recommendations for improving how buildings and shelters are designed, constructed, and maintained in tornado–prone regions, and for improving the emergency communications that warn of imminent threats from tornadoes. These recommendations are presented in three groups (Sections 5.2.1 through 5.2.3) that reflect the objectives and findings of the investigation.

The first group of recommendations is focused on the characteristics of tornado hazards and their associated wind fields. The recommendations in the second group concern the performance of buildings, lifelines, and shelters and designated safe areas. The final group of recommendations relates to findings about the pattern, locations, and causes of tornado fatalities and injuries, the performance of emergency communications systems, and the public response to this tornado.

The recommendations call for action by specific entities with regard to the development, adoption, and enforcement of standards, codes, and regulations; professional and construction practices, education, and training; and research and development. NIST believes that these recommendations are realistic and appropriate, and are achievable within a reasonable period of time.

NIST strongly urges state and local authorities having jurisdiction to adopt and enforce model building codes and standards. Enforcement is critical to ensuring expected levels of safety. Following good building practices also is critical to achieving better performance of structures during extreme events like tornadoes.

5.2.1 Recommendations Related to Tornado Hazard Characteristics and Associated Wind Field

Recommendation 1—

NIST recommends that a capacity be developed and deployed that can measure and characterize actual near–surface tornadic wind fields for use in the engineering design of buildings and infrastructure. This would require enhancement and widespread deployment of advanced technologies, including weather radar.

Justification:
NIST found that current operational weather radar technology is incapable of determining tornado occurrence and intensity for heights at which most structures are built. Recently proven, cost–effective, short–range remote sensing technologies (i.e., Collaborative Adaptive Sensing of the Atmosphere, or CASA radar) can be more widely implemented in tornado–prone areas as an initial step to serve this purpose. Although these technologies would not measure the area immediately adjacent to ground level, they could serve as an important bridge between higher elevations sampled by NWS radar and estimates of the near–surface wind field discussed later in this recommendation. These technologies could also be used to improve warning lead time and false alarm rates for tornadoes (see Recommendation 16).

NIST also found that direct, near–surface wind speed measurements relevant to the Joplin tornado were available from only one weather station situated well outside the tornado damage path. Reliable measurements of near–surface wind speed and other information (e.g., wind–induced pressure) in tornadoes, especially in the most intense portions of them, are lacking or nonexistent due to both the scarcity and durability of measuring devices. This lack of measurements makes it extremely difficult to understand the relationship between damage and wind speed. Improved characterization of the tornado hazards at elevations that are meaningful for engineering design can be achieved by development and use of ruggedized, tornado– and tornado debris–resistant technology capable of directly measuring near–surface wind speeds, wind pressure,impact loading, and turbulence produced by tornadoes and other extreme wind events.

As radar–based and direct measurements of wind speed in tornadoes are lacking, indirect methods (e.g., tree fall) were used to assess the maximum wind speeds of the Joplin tornado. However, considerable uncertainty still exists in these estimations. For example, estimated maximum wind speeds based on tree fall analysis in the Joplin tornado were 175 mph with up to 25% of model uncertainty. Including uncertainty, the upper bound of maximum wind speed was estimated to be 210 mph. Using the EF Scale, maximum wind speeds based on damage to structures surveyed by NIST were estimated to be 150 mph with 10% uncertainty (± 15 mph)due to the large size of the structures rated.. The range of wind speeds for "demolished" residential structures using the EF Scale was 110 mph to 175 mph. Uncertainties in wind speed estimation can be reduced by improving upon existing techniques like tree fall and the EF Scale (Recommendation 4) as described in this report, or by further developing other computational or analytical methods (e.g., back–calculations from structural or structural–element failures, debris flight). The maximum estimated near–surface wind speeds derived from indirect methods suggest that the extent of damage in Joplin could have been caused by wind speeds lower than those associated with an EF–5 tornado (200+ mph).

Improving measurements of the *entire* near–surface tornadic wind field will also be useful for properly assessing tornado climatology, associated probabilistic estimates of the tornado hazard, and for calibrating the EF Scale. Tree fall analysis of the Joplin tornado suggested that damaging wind speeds lasted for a longer duration over a larger spatial area than was expected based on current tornado hazard estimtation approaches. This finding is consistent with other studies that have estimated wind fields in actual tornadoes. In areas subjected to the highest wind speeds in the Joplin tornado, the duration of wind speeds at or above wind speeds associated with the EF–2 range was estimated to be over 1 min and the total area of EF–3 or greater wind speeds was approximately twice that expected under current tornado hazard models. The wind speed duration should be thoroughly considered when assessing damage, estimating wind speeds, and designing structures for tornadoes.

Interested Parties: Academia, Industry, National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS), U.S. Nuclear Regulatory Commission (NRC), National Science Foundation (NSF), U.S. Department of Energy (DOE)

Organization with Lead Responsibility for Implementation: NOAA

Recommendation 2—

NIST recommends that information gathered and generated from tornado events (such as the Joplin tornado) should be stored in publicly available and easily accessible databases to aid in the improvement of tornado hazard characterization.

Justification:
Characterization of the tornado hazard in Joplin benefited from information available from radar and anemometer measurements, pre– and post–storm aerial imagery, ground–based damage surveys, and photographs, as well as from damage and property databases. Archivedstorage of such information in publicly available and easily accessible databases, especially in conjunction with a geospatial software platform that permits detailed mapping of tornado events, would greatly facilitate characterization of the tornado hazard and associated risk.

Interested Parties: Academia, Federal Emergency Management Agency (FEMA), Industry, National Geospatial–Intelligence Agency, NOAA/NWS

Organization with Lead Responsibility for Implementation: NOAA

Recommendation 3—

NIST recommends that tornado hazard maps for use in the engineering design of buildings and infrastructure be developed considering spatially based estimates of the tornado hazard instead of point–based estimates.

Justification:
NIST found that current estimations of the tornado hazard using tornado area (i.e. point–based) are insufficient when considering populated areas. This insufficiency was demonstrated by the larger

spatial extent and longer duration of the wind field in Joplin compared to tornado hazard models (Finding 4) and by the amount and effects of wind–borne debris in Joplin. Debris from structures was shown to have significantly contributed to the overall damage state (Findings 8, 16) and to the potential for injuries and fatalities in Joplin (Findings 19, 29). The extent of damage to residential structures in Joplin was greater than predicted based on point–based estimations of tornado damage. For example, it was estimated that 28 percent of the damaged residential homes had EF–3 or greater damage versus the 12 percent predicted for an EF–5 tornado from point–based methods, and 43 percent of structures were estimated to have EF–2 or greater damage while only 30 percent of the tree fall–based wind field was estimated at EF–2 or greater. This greater–than–expected level of damage has also been noted in other recent, significant tornadoes that have struck populated areas, such as the tornadoes that damaged Oklahoma City in 1999 and Tuscaloosa in 2011.

Also, in populated areas such as Joplin, even though only part of the community is affected physically, the wider community is impacted. For example, 7,411 residential structures were damaged in Joplin, but approximately 20,000 structures were without power following the storm, showing that the tornado hazard and associated risk extended beyond the tornado damage path.

As communities continue to expand, additional risks are created by growing populations and population centers. Risks of populated communities were analyzed using the spatially based methodology across the United States. Results from the NIST analysis show that populated regions are at a significantly higher risk from tornado damage than what is prescribed in current point–based estimations.

Tornadoes rated EF–3 or lower have accounted for approximately 96 percent of all tornadoes in the official record and are associated with significant fatalities and economic losses. Over one–third (36 percent) of fatalities and about 80 percent of insured property losses have been caused by EF–3 or lower tornadoes. Even in tornadoes rated higher than EF–3, the majority of affected areas encounter EF–3 or lower wind speeds. In the case of the Joplin tornado, approximately 40 percent of the fatalities and up to 90 percent of the tornado area were associated with EF–3 or lower wind speeds.

Interested Parties: American Society of Civil Engineers (ASCE), DOE, FEMA, International Code Council (ICC), NRC

Organization with Lead Responsibility for Implementation: NIST

Recommendation 4—

NIST recommends that new damage indicators (DIs) be developed for the Enhanced Fujita tornado intensity scale to better distinguish between the most intense tornado events. Methodologies used in the development of new DIs and associated degrees of damage (DODs) should be, to the extent possible, scientific in nature and quantifiable. As new information becomes available, a committee comprised of public and private entities should be formed with the ability to propose, accept, and implement changes to the EF Scale. The improved EF Scale should be adopted by NWS.

Justification:
NIST found that the EF Scale lacks adequate DIs and corresponding DODs for distinguishing tornado intensity, especially for tornadoes that cause significant damage. This lack of adequacy is due in part

to the small sample size of intense tornadoes striking heavily populated areas. The lack of DIs and DODs and the overall nature of the EF Scale require subjective, non–quantitative assessment of tornado damage. Damage indicators (DIs) not currently in the EF Scale (e.g., tractor–trailers, manhole covers) were used to help determine the EF–5 designation (200+ mph) for the Joplin tornado. Currently there are only five DODs available for use in evaluating the DIs that can result in an EF–5 rating using an expected value of wind speed.

The lack of adequate DIs and DODs and associated guidance in the EF Scale led, in part, to differences in wind speeds that were estimated based on damage to Joplin structures by NIST and other researchers, practitioners, and surveyors. In addition, the EF Scale implicitly regards wind speed estimates for individual structures as point estimates, and cannot accomodate cases such as Walmart Store #59 in Joplin, where some sections of a single, large structure were more heavily damaged than others. NIST's wind speed estimation from tree fall showed that wind speeds varied significantly over the length of the Walmart building. A similar observation was noted by FEMA, after their study of both the Joplin and Tuscaloosa (and other Alabama) tornadoes.

Further refinement of the EF Scale and its procedures will enhance the estimation of maximum wind speeds and subsequent EF ratings in tornadoes, by providing official surveyors with additional and improved guidance. Recent research has stressed that a path toward modifying the EF Scale is a pressing need. An iterative development process will not only enable better wind speed estimation, but also will lead to greater understanding of the response of structures to tornadoes. Ultimately, it will improve estimates of tornado hazard climatology and of the risk that tornadoes pose to the public.

Interested Parties: Academia, FEMA, Industry, NOAA/NWS, NSF, Office of Science and Technology Policy

Organization with Lead Responsibility for Implementation: NOAA/NWS

5.2.2 Recommendations Related to the Performance of Buildings, Shelters/Designated Safe Areas, and Lifelines

Recommendation 5—

NIST recommends that nationally accepted performance–based standards for the tornado–resistant design of buildings and infrastructure be developed in model codes and adopted in local regulations to ensure the resiliency of communities to tornado hazards. The standards should encompass tornado hazard characterization, performance objectives, and evaluation tools. The standards shall require that critical buildings and infrastructure such as hospitals and emergency operations centers are designed so as to remain operational in the event of a tornado.

Justification:
Currently, there are no standards for the tornado–resistant design of ordinary buildings and infrastructure, except for *safety–related structures in nuclear power plants* and *storm shelters* or *safe rooms*. Even in the design standards for *nuclear power plants*, *storm shelters*, and *safe rooms* (ANSI/ANS 2.3 (2011) and ICC 500 (2008)), there are inconsistencies in the way tornado hazards are characterized, as reflected in the different tornado regionalization and associated tornado design wind speeds for the contiguous United States.

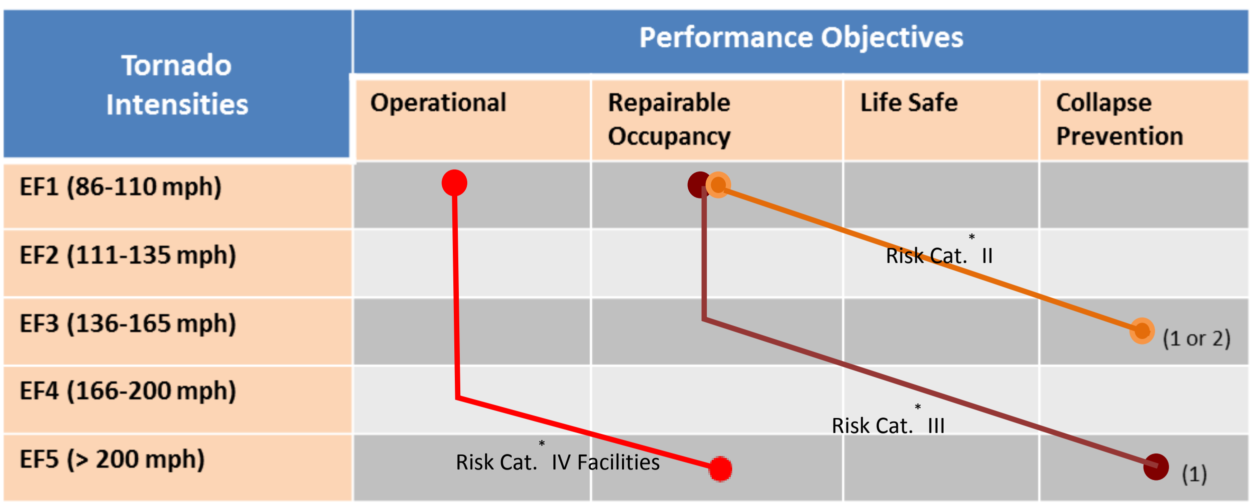
Performance–based standards for tornado–resistant design of ordinary buildings – including critical facilities, commercial and residential buildings – will result in more tornado–resilient communities (in terms of enhanced occupants' life safety and reduced property damage and economic loss) by explicitly considering tornado hazards, which will be characterized by the most up–to–date tornado data and risk–consistent science–based methodologies, as a structural design condition.

The recommended standards would:

- Prescribe "tornado–prone areas" for design (i.e., regionalization of expected tornado wind speeds and wind–borne debris loading) based on a review of the most up–to–date tornado data amd hazard mapping methodology;

- Specify "design tornadoes" for buildings (wind speed and debris impact loading) in accordance with the prescribed tornado–prone areas and based on buildings' Risk Categories; and

- Specify "tornado performance objectives" for buildings, also based on buildings' Risk Categories. An example of a tornado performance objectives matrix that prescribes the required performance for buildings of different risk categories is shown below:



(1) Hardened area, shelter–in–place.
(2) Public shelter.
* Based on ASCE 7–10.

Interested Parties: Academia, ASCE, Design and construction industry (American Concrete Institute [ACI], American Institute of Steel Construction [AISC], American Welding Society [AWS], Portland Cement Association [PCA], Steel Deck Institute [SDI], Steel Joist Institute [SJI], The Masonry Society [TMS]), FEMA, ICC, NIST

Organization with Lead Responsibility for Implementation: ASCE

Recommendation 6—

NIST recommends the development of risk–consistent, performance–based tornado design methodologies to ensure that all building components and systems meet the same performance objectives when subjected to tornado hazards.

Justification:
There is currently no methodology for building design that specifically considers the design hazards associated with tornadoes. The minimum code requirements for wind loading in current building codes do not take into account the inconsistent performance of different building components (walls versus roof, structural system versus envelope, structural system versus in–facility lifeline distribution systems (power, gas, water)) when subjected to tornado hazards. It is frequently observed (including in the more recent May 20, 2013 Moore, Oklahoma tornado (NIST SP 1164, 2013)) that the overall outcomes of buildings in tornadoes, in terms of building's structural performance and functionality, can be critically dependent upon the performance of different building components and systems that may not have been designed for the same risk level (buildings' structural systems versus their envelopes, for example). Failure of building envelopes, despite the robust structural system that could withstand the tornado without structural collapse, often resulted in extensive damage to building interiors (affecting electrical distribution and fixtures, water and gas pipes, HVAC systems and ductwork, and the elevator system and elevator shaft enclosure) and ultimately the complete loss of building's functionality).

The new performance–based tornado design methodology would:

- Outline risk–consistent design procedures based on a holistic approach for building design that encompasses the structural system, envelope, and building mechanical, electrical and plumbing lifeline systems.

- Incorporate current best tornado–resistant practices and address design approaches that, while satisfying current minimum code requirements, might not be tornado–resilient based on observed performance for different types of construction, including:

  – For box–type system (BTS) buildings: There is a need to improve robustness and redundancy in lateral load resistance systems by (a) ensuring risk–consistent performance between the roof system and bearing walls, and (b) requiring walls to have rotational restraint capability (instead of friction–only) to reduce dependency on the roof as the sole lateral bracing for collapse prevention.

  – For engineered steel– and concrete–frame buildings and pre–engineered metal buildings: These structures require consistent performance between the building envelope and the main wind–force resisting system (synergy between improved envelope performance using impact–resistant windows and the need to provide protection for special portions of critical facilities, e.g., behavioral health unit in a hospital, should be exploited in planning for protection of the envelope and selection of the best available refuge areas in critical facilities).

– For wood–frame and combined unreinforced masonry–wood roof truss residential buildings: Improved tornado performance in residential construction by requiring a system integrity design approach to ensure a continuous vertical load path from roof to foundation (robust connections between roof, walls, and foundation to ensure they remain connected, albeit damaged). This would improve individual building structural performance and at the same time reduce overall wind–borne debris hazards in tornado–affected communities.

Interested Parties: Academia, ASCE, Design and construction industry (ACI, AISC, AWS, PCA, SDI, SJI, TMS), ICC,

Organization with Lead Responsibility for Implementation: NIST, FEMA

Recommendation 7—

NIST recommends that: (a) model building codes for new buildings require that tornado shelters be designed in accordance with the ICC 500 standard; (b) model building codes develop and adopt a tornado shelter standard specific for existing buildings; and (c) tornado shelters be installed in new and existing multi–family residential buildings, mercantile buildings, schools and buildings with assembly occupancies located in tornado hazard areas identified in the performance–based standards required by Recommendation 5.

Justification:

- NIST found inadequate performance among the *best available refuge areas* in the high–occupancy commercial BTS buildings that it surveyed.

- Without community–based shelters or shelters/safe rooms in multi–family housing and nursing homes, residents of these buildings really had no effective sheltering options during the Joplin tornado.

- Home Depot found that it was feasible to include a hardened refuge area in the store that it built to replace the store demolished in the May 22, 2011, Joplin tornado (the earlier store had no such area).

Interested Parties: Academia, FEMA, ICC, States and authorities having jurisdiction (AHJ) in tornado–prone areas

Organization with Lead Responsibility for Implementation: ICC

Recommendation 8—

NIST recommends the development and implementation of uniform national guidelines that enable communities to create the safest and most effective public sheltering strategies. The guidelines should address planning for, siting, designing, installing, and operating public tornado shelters within the community.

Justification:
NIST found that an overwhelming majority of the fatalities in Joplin (96 percent) were caused by impact–related factors (usually labeled by authorities as multiple blunt–force trauma to the body). A majority of these victims (83.8 percent) were located inside buildings when they were fatally injured. And, many of the buildings they occupied were demolished by the storm, meaning that the roof and walls collapsed, or sustained a “heavy/totaled” level of damage, where there was loss of a significant portion of or the entire roof system, which exposed the building interior to weather damage and debris.

Additionally, NIST found that individuals had often sheltered above ground in these heavily damaged buildings, or in vehicles, and that few among the affected populace had access to underground or tornado–resistant shelters. There were no community shelters or safe rooms (defined as structures designed in accordance with either the ICC 500 standard or FEMA 361 guidance) in the City of Joplin or Jasper County at the time of the May 22, 2011, Joplin tornado. Also, 82 percent of the homes in affected area in Joplin lacked basements. Only a few commercial buildings were equipped with underground locations, and none with tornado–resistant above–ground shelters. Although above–ground residential crawl spaces were often available for sheltering, residents generally did not use them during the May 22, 2011, Joplin tornado because they perceived that they had insufficient time to access them or that the crawl spaces would be too difficult or uncomfortable to use as shelters.

In this particular storm, the residents of Joplin might have benefited from more sheltering options and potentially sustaining fewer deaths and injuries. However, NIST recommends the development of guidelines that municipalities in tornado–prone areas can use to design and implement their own sheltering solutions, rather than mandating a single sheltering strategy (or solution) for every community located in these areas. The guidelines would allow each community to assess their current sheltering capabilities and to develop the safest, most efficient, and most economical sheltering strategy possible based upon the needs of the community (e.g., population size, public comfort with alternative sheltering solutions, training and education, public vulnerabilities), the types of construction within the community, and cost.

Interested Parties: FEMA, ICC, National Fire Protection Association (NFPA), NWS, NSF

Organization with Lead Responsibility for Implementation: FEMA

Recommendation 9—

NIST recommends that uniform guidelines be developed and implemented nationwide for conducting tornado risk assessments and designating best available tornado refuge areas as an interim measure within buildings until permanent measures fully consistent with Recommendations 5 and 7 are implemented.

Justification:
NIST found that, based on its surveys of affected buildings and its interviews with building occupants in Joplin, practices for selecting best available refuge areas were ad hoc and had varying degrees of effectiveness, and could be based on considerations other than structural safety (e.g., proximity to an emergency exit or bathroom). In addition, NIST found that the guidance currently available on selecting refuge areas within buildings is either too general, on the one hand, or too specific to a given type of structural system, on the other.

NIST found some tornado–resistant design features in the BTS buildings that it surveyed in Joplin, including a partially fixed–end condition for perimeter walls (designed to brace against accidental truck impacts but not required in regions of low seismic hazard) that appeared to have kept walls from collapsing in the tornado. Such features should be exploited in selecting best available refuge areas in BTS buildings in tornado–prone areas. The recommended guidelines would help responsible parties identify such features and select the most effective refuge areas in different types of buildings in tornado–prone areas.

Interested Parties: Academia, FEMA, DHS S&T, ICC, States and AHJs in tornado–prone areas

Organization with Lead Responsibility for Implementation: FEMA

Recommendation 10—

NIST recommends that aggregate, gravel, or stone be prohibited as roof surfacing material or roof ballast for buildings of any height in tornado–prone areas.

Justification:
Section 1504.8 of the 2012 *International Building Code* (IBC) prohibits the use of aggregate as roof surfacing materials and as roof ballast for buildings in hurricane–prone regions and buildings in non–hurricane regions with mean roof heights (MRH) that exceed a specified height limit (limit varies depending on the required basic wind speed and exposure category of the building). For Joplin (90 mph basic wind speed and Exposure Category B), aggregate roof ballast was prohibited only for buildings with a MRH exceeding 110 ft. Several buildings at SJRMC had aggregate roof ballast and the roof aggregates were found to have contributed to the wind–borne debris hazard during the Joplin tornado.

Interested Parties: ASCE, ICC, States and AHJs

Organization with Lead Responsibility for Implementation: ICC

Recommendation 11—

NIST recommends that enclosures of egress systems (elevators, exits) in critical facilities in tornado–prone areas be designed to maintain their functional integrity when subjected to tornado hazards.

Justification:
Section 713.3 of the 2012 IBC stipulates that enclosures for elevator shafts shall be of *materials permitted by the building type of construction*. This could mean non–impact–resistant materials such as gypsum board on steel studs are allowed for use as elevator shaft enclosure, as was the case for the elevator shaft in SJRMC's elevator tower. It was found that the shaft enclosure at SJRMC was damaged due to debris infiltration and thus could have impeded the functionality of the elevator even if the power had not been lost.

Interested Parties: Building owners/operators, ICC

Organization with Lead Responsibility for Implementation: ICC

Recommendation 12—

NIST recommends that owners and operators of existing critical facilities in tornado–prone areas perform tornado vulnerability assessments and take steps to ensure the functionality of (1) backup power supplies (harden the protection of emergency backup power, as region–wide losses of power due to damage to power transmission infrastructure occur frequently in tornadoes), (2) vertical movement within the building (elevator equipment and shaft enclosures), and (3) means of egress illumination (battery–powered lighting in addition to backup power), in a tornado event.

Justification:
Loss of backup power supplies, vertical movement, and means of egress illumination occurred frequently in existing critical facilities during tornadoes. This can result in hazardous conditions for post–tornado rescue and evacuation, and ultimately loss of building functionality. Pre–tornado assessment and identification of vulnerabilities of critical facilities to ensure continuity and integrity of backup power supplies, vertical movement, and means of egress illumination, based on lessons learned from past tornadoes, should result in improved outcomes with regard to rescue operations, safe evacuation and continued operation of existing critical facilities.

Interested Parties: DHS S&T, Building owners/operators, States and AHJs

Organization with Lead Responsibility for Implementation: DHS IP/FEMA

5.2.3 Recommendations Related to the Pattern, Location, and Cause of Fatalities and Injuries, and Associated Performance of Emergency Communications Systems and Public Response

Recommendation 13—

NIST recommends the development of national codes and standards and uniform guidance for clear, consistent, and accurate emergency communications, encompassing alerts and warnings, to ensure safe, effective, and timely responses among individuals, organizations, and communities in the path of storms having the potential to create tornadoes.

NIST also recommends that emergency managers, the NWS, and the media develop a joint plan and take steps to ensure that accurate and consistent emergency alert and warning information is communicated in a timely manner to enhance the situational awareness of community residents, visitors, and emergency responders affected by an event.

Justification:
NIST found that many U.S. communities, even within the same state or region of a state, create and disseminate emergency communications for tornadoes in different ways. In Missouri, for example, according to the emergency manager (EM) for Joplin–Jasper County, it is the responsibility of the EM of each municipality in Jasper County to design the emergency communication system used to alert and warn the local populace about tornadoes. Currently, no federal, state, or local guidance or requirements exist that standardize such systems, which has resulted in different systems and operating practices (at least for the use of outdoor warning sirens for tornadoes) from one

municipality to another. NIST also found that some Joplin tornado survivors expressed confusion regarding the protocol used for tornado sirens in the city. The main aspect of confusion was why the first and second siren soundings stopped after 3 minutes had elapsed, because some associated these cessations as signaling the end of the emergency. However, the 3 minute siren duration was part of Joplin's outdoor warning siren protocol, which was available online as well as in the City's emergency plans.

Therefore, NIST recommends the development of national codes, standards, and/or guidance for the creation and dissemination of clear, consistent, and accurate emergency communications for tornadoes. Especially important is the inclusion of guidance on both alerts and warning information. Alerts, such as the activation of outdoor sirens, are meant to grab people's attention, whereas warnings provide information on the nature of the emergency and what actions people should take. The provision of warning information along with the siren alerts could have enhanced the public's understanding of why the sirens were sounding in Joplin. Understanding could also have been enhanced had the public received timely and consistent rather than conflicting information about weather developments before the tornado struck. NIST recommends that the joint efforts described above involve emergency management, the NWS, and the media, to avoid conflicting messaging in emergencies.

Interested Parties: Academia, ICC, National Emergency Management Association, NFPA, NWS, U.S. Department of Homeland Security (DHS)/FEMA

Organization with Lead Responsibility for Implementation: ICC/NFPA

Recommendation 14—

NIST recommends that the full range of current and next–generation emergency communication "push" technologies (e.g., GPS–based mobile alerts and warnings, reverse 9–1–1, outdoor siren systems with voice communication, NOAA weather radios) be widely deployed and utilized, to maximize each individual's opportunity to receive emergency information and respond safely, effectively, and in a timely fashion.

Justification:
NIST found that people's responses to the impending storm, in many cases, were delayed or incomplete, which resulted in some fatalities occurring outside, in vehicles, and among individuals rushing to obtain safer refuge when the tornado struck. Among those who did not respond or delayed their response, NIST found that a lack of awareness of the tornado contributed to such behavior. There were individuals within the tornado's damage path who were unaware of the impending tornado because they did not receive any tornado–related alerts or warnings on May 22, 2011, including individuals with hearing loss, individuals who were asleep before the storm hit, and persons who were disconnected from available modes of emergency communication. Additionally, the use of NOAA weather radios or subscription–based mobile alerting systems was not prevalent among Joplin residents and visitors.

Therefore, NIST recommends that the full range of current and next–generation emergency communication "push" technologies should be evaluated for future use in disseminating alert and warning information. "Push" technologies are those that do not rely on the user to actively search for information. One example of an alerting push technology is outdoor siren systems. However, in Joplin the siren system was designed to alert only individuals who were located outdoors, even though many individuals could hear these alerts inside their homes and businesses throughout the city. Additionally, no associated warning information was disseminated with these alerts on May 22, 2011, causing individuals to have to search for additional information about the event.

There are new technologies being explored that deliver both alert and warning information based upon geographic location. One of the newest sources of such technology is the Commercial Mobile Alert System (CMAS). CMAS is a partnership between FEMA, the Federal Communications Commission, and wireless carriers, that allows public–safety authorities (either local EMs or the NWS) to send 90–character, geographically targeted, text–like alerts to the public through their mobile devices. Unlike most mobile services, this is not an opt–in system. Rather, individuals with enabled mobile devices who are within a certain distance of activated cell towers will receive the alert messages. These alerts will bypass the regular networks that often bog down due to increased traffic during emergencies.

However, there are limitations associated with this new and exciting technology. For example, notification resources such as cell phones and social networking sites like Twitter have restrictions on the length of individual alert or warning messages. Additionally, individuals who are sleeping still may not receive these types of mobile alerts, especially those in deeper stages of sleep. Therefore, NIST recommends additional exploration of technologies that are able to reach more vulnerable populations in tornadoes, namely those who are sleeping or have visual and/or hearing impairments.

Interested Parties: Academia, DHS/FEMA, Federal Communications Commission (FCC), NOAA/NWS

Organization with Lead Responsibility for Implementation: NOAA

Recommendation 15—

NIST recommends research to identify the factors that will significantly enhance public perception of personal risk and how such knowledge can be better used to rapidly and effectively respond during tornadic events.

Justification:
NIST found that the prevalent "take shelter now" trigger for individuals responsible for their own protective decision–making (e.g., those located at home) in Joplin was the receipt of high–intensity cues, including hearing or seeing the tornado approaching or witnessing others' urgent efforts to seek protection from the storm. One media source, credited by some with saving lives before the tornado hit, had a broadcast which included a video of the approaching tornado and the station's newscaster pleading with listeners to "Take cover now!" Both the video and the urgent tone of the broadcaster were highlighted as increasing individuals' perceived risk associated with the event, prompting them to take action before the tornado hit.

The NWS is currently testing a new method of including stronger–worded text in tornado warning messages for higher–severity storms. However, little research or guidance is available on how to disseminate messages both visually and audibly to increase risk perception. While human factors and ergonomics research is available on ways of increasing alert or message urgency (e.g., through specific types of tones or voice pacing or frequency), little research or guidance is available on the effectiveness of such technologies in disaster situations. Therefore, research should explore various ways to create and disseminate warnings, as well as to train and educate the public to achieve higher levels of perceived risk among community residents when a tornado is imminent.

Interested Parties: Academia, DHS, ICC, NFPA, NOAA/NWS

Organization with Lead Responsibility for Implementation: NSF, NIST

Recommendation 16—

NIST recommends that tornado threat information be provided to emergency managers, policy officials, and the media on a spatially resolved real–time basis by frequently updating gridded probabilistic hazard information that is merged with other GIS information to supplement the currently deployed binary warn/no warn system.

Justification:
NIST found evidence of high false–alarm rates in Joplin, which were more prevalent among NWS–issued tornado warnings than siren activations. Additionally, NIST found that, prior to the Joplin tornado, there was a pervasive confidence among Joplin residents that a tornado was unlikely to strike their city. One factor that contributed to this confidence was the public's perception of a high number of false alarms in Joplin.

NIST also found that between July 1, 2005 and May 25, 2011, the NWS issued 18 storm–based tornado warnings for all or some part of Joplin. Of these 18 warnings, only 4 were validated by subsequent tornado sightings, which yielded a false–alarm rate for the Joplin area of 78 percent (or 14/18). This rate was similar to the 2007–2011 national average false–alarm rate for NWS storm–based tornado warnings, which was 74.7 percent. Over the most recent 5–year period from 2007 to May 22, 2011, the NWS issued 12 tornado warnings for Joplin, using storm–based warnings, of which only one was verified as an actual storm event. Therefore, during this more recent period, the false–alarm rate for NWS warnings in Joplin had increased to 92 percent.

NIST recommends that the NWS consider improvements to its provision of threat assessments. Rather than the binary warn/no warn system that is currently employed, NIST recommends that the NWS consider moving toward providing frequently updated gridded probabilistic hazard information, which could be merged with other GIS information to provide better hazard information and reduce false–alarm rates.

Interested Parties: NOAA

Organization with Lead Responsibility for Implementation: NOAA