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Contents

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White Paper 1:
Physical Understanding Necessary for
Improving Tornado Forecasts and Warnings

The forecasting and warning of tornadoes requires the understanding of physical processes occurring on many different spatial and temporal scales, from the high and low pressure systems on the scale of 1000s of kilometers, to finer scale features that initiate storms, to details occurring within a particular storm. It is this wide range of relevant physical scales, in part, that makes the forecasting and nowcasting of tornadoes and tornadic storms so difficult. While the forecasting and warning process itself is detailed in a separate white paper, here we focus on the background scientific understanding necessary for those efforts to be successful, and we point out the areas in which improvement in our scientific understanding is needed. We discuss our understanding of the processes involved in forming storms (referred to as convection initiation hereafter), the large-scale atmospheric conditions (referred to as environments hereafter) supportive of tornadic storms, and our limited knowledge of the controls on tornado strength and longevity. In the final section, outstanding scientific problems are highlighted.

Convection Initiation

On one hand, the process by which deep convection is initiated is well understood to (usually) require lifting of air parcels through a layer in which they are negatively buoyant (i.e., more dense than their surroundings) to a level at which they become positively buoyant compared to their surroundings, and these parcels must then remain positively buoyant over a significant depth of the atmosphere. (The CAPE is a measure of the total positive buoyancy integrated with height; larger values of CAPE indicate greater buoyant forcing for the upward motion in the storm, hereafter the updraft.) Interestingly, the layer of negative parcel buoyancy is important for suppressing early, weaker convection and allowing CAPE to continue to increase before stronger convection forms. However, if this layer is too deep or warm compared to the rising parcels, then convection may not initiate at all. This all-important layer is often relatively thin and hard to capture accurately in forecast models, particularly those with coarse grid spacing.

The level at which positive buoyancy is achieved depends on the properties of the parcel of air, usually (although not always) assumed to come from near the surface, as well as the properties of the environment through which the parcel travels vertically. Storms may be expected along atmospheric air mass boundaries, which often appear as fine lines on radar, that provide both lifting of the near-surface parcels and deepening of the moisture to provide a more favorable environment through which the parcels travel. These boundaries could be classic warm and cold fronts, drylines (boundaries between warm, moist and hot, dry air, common in the southern great plains in the spring), or outflow boundaries formed by the cold air produced by a prior storm. The precise locations of these boundaries are difficult to predict, presenting another problem in forecasting convection initiation. Even if the location of a boundary is predicted well, it often remains difficult to know exactly where along the boundary a storm will initiate, as this could be influenced by smaller-scale variations in both the wind and thermodynamic (i.e., temperature, pressure, and moisture) fields along the boundary.

Accurately predicting the thermodynamic properties of near-surface parcels in models, which is essential to accurately predicting convection initiation, requires proper treatment of the exchange of heat and moisture between the surface and the air (i.e., surface fluxes of heat and moisture) as well as accurate airstreams to move (or advect) the temperature and moisture to new locations.

Finally, even if we predict that parcels will be able to achieve positive buoyancy aloft based on their initial low-level properties, it is often very difficult to know how likely the parcel is to retain its original properties as it travels through air that could be colder and/or drier. The process by which environmental air is mixed into a parcel, diluting its buoyancy, is referred to as entrainment and its effects are difficult to quantify as they likely depend on the width of the initiating updraft, the changes in the wind with height (referred to as vertical shear; greater vertical shear generally is associated with greater entrainment), and thermodynamic properties of both the parcel and the environment. The effect of entrainment generally is not captured well in numerical models. Overall, difficulties in forecasting air mass boundary locations and strengths, layers of negative buoyancy for lifted parcels, as well as near-surface parcel properties and effects of entrainment as parcels are lifted make the forecasting of convection initiation a challenging problem.

Environments Supporting Tornadic Storms

Over the past 40 years or so, we have learned a great deal about the environments that support tornadic storms through a combination of computer simulations, observations, and theories based on our understanding of the equations governing atmospheric motion. We know that most strong and nearly all violent tornadoes are associated with a class of storms known as supercells characterized by a strongly rotating updraft. In the middle levels of the atmosphere, this rotation (or vorticity) with respect to the vertical axis comes from the tilting of horizontal vorticity that precedes the storm and that is associated with the large vertical wind shear in a supercell-supporting environment. If this horizontal vorticity is at least partly aligned with the winds (i.e., the vorticity is said to have a streamwise component), then the updraft will rotate. This process is well understood, and we look for reasonable amounts of CAPE together with strong vertical shear having streamwise vorticity (which depends on the expected cell motion) to predict that a given environment will support supercells rather than ordinary convection. While these ingredients sometimes co-exist over a broad area, suggesting the possibility of numerous supercells, many times the region of overlap between the CAPE and the strong vertical shear is relatively narrow and it is not clear that both of these necessary ingredients will be present in the region where storms initiate. It often also is not clear whether the storms that initiate will form a continuous line or will remain fairly independent of one another, the latter mode being more favorable for tornado formation.

The presence of midlevel rotation, however, does not always correlate with the presence of low-level rotation. In fact, one study suggests that only 15% of midlevel mesocyclones (strongly rotating updrafts) are associated with tornadoes. Although it is essential for midlevel rotation, the tilting of environmental vorticity by an updraft alone does not generate significant vorticity very near the ground, because parcels are rising in the updraft as the vorticity is tilted. Thus, the development of low-level rotation requires a different mechanism that appears to rely not on the shear that pre-exists the storm but on vorticity created within the storm itself owing to the variations of buoyancy within the storm's cold outflow. For example, as precipitation falls from the base of the storm, it cools the air below through evaporation, and this cooling creates buoyancy variations. (Note that moisture and precipitation also can influence the distribution of buoyancy as they also influence the parcel density.) When there is a buoyancy contrast in a horizontal plane, there is a tendency to develop a circulation that is oriented along a horizontal axis (i.e., rotation similar to that of a Ferris wheel), with rising in the more buoyant air and sinking in the less buoyant air. Numerical models and observations suggest that the rotation about a vertical axis (i.e., rotation oriented similar to that of a carousel) that is needed for the tornado at low levels comes from the creation and subsequent tilting of the buoyancy-variation-generated rotation within the descending air (downdraft) of the outflow. Once this rotation reaches low levels, if it can enter the main updraft of the storm, it will be contracted to a tighter radius with a dramatic increase in wind speeds (a process known as stretching and similar to the increase in rotation experienced by an ice skater bringing in his or her arms during a spin).

Both tornadic and some nontornadic supercells have been found to have significant rotation at scales larger than the tornado, likely owing to similar processes occurring in their cold pools. This can make it very difficult to distinguish between the two on radar. An outstanding question is why some storms are able to contract this rotation to the tornado scale while others are not. Is there a separate "event" that must occur within the storm to aid the contraction, and is there anything predictable in the environment to distinguish between the tornadic and non-tornadic supercells? Somewhat counter-intuitively, tornadic storms have been found to contain outflow with temperatures that are warmer than their nontornadic counterparts. Although this would not lead to strong buoyancy variations, it would make it easier for the final stretching step to work effectively. Thus, it appears there may be an optimal degree of buoyancy variation that maximizes the outcome after both parts of the process. This is an ongoing area of research, but observational climatologies show that more tornadic storms occur in environments characterized by higher values of relative humidity, consistent with decreased evaporational cooling and warmer downdrafts.

Somewhat surprisingly, the low-level (i.e., 0-1 km) vertical shear in the environment also is associated with a greater likelihood of tornadic storms even though the vorticity associated with this shear does not appear to be directly tilted into vertical near-surface vorticity. Instead, it may have an indirect effect by increasing the strength of the rotation aloft which leads to better lifting and stretching of the outflow air. Understanding the relative roles of environmental and storm-generated vorticity is an ongoing subject of research, as is understanding the relative roles of downdrafts located in different parts of the storm. Unfortunately, these efforts are hindered somewhat by our difficulty in capturing the microphysics processes (i.e., the formation of precipitation and subsequent evaporation or melting) accurately in models. These processes are essential to producing realistic cold pools and realistic vorticity generation in our computer simulations, so improving their treatment in the model is an essential research step.

Although 0-1 km vertical shear and cloud base height (LCL; related to the low-level relative humidity) are helpful in distinguishing tornadic and nontornadic supercells, they do not discriminate perfectly between the two types and thus both misses and false alarms still occur frequently, suggesting we are still missing pieces of the puzzle in relating tornado development to features of the environment. The worst skill at the watch level occurs in the portion of the parameter space characterized by fairly low CAPE and moderate shear. Unfortunately, this is the portion of the parameter space within which the largest number of tornadoes occurs; despite the lower probability of tornado formation in this regime compared to the high-CAPE and high-shear regime, this environment occurs much more frequently, leading to a greater overall tornado total.

Tornado development also may be related to interactions between storms or between a particular storm and an existing air mass boundary in its environment. Some studies have noted tornado occurrence shortly after two storms merge, while other studies noted tornado occurrence as a supercell crossed a boundary. Interestingly, these interactions at times have the opposite effect, diminishing the tornado potential. As such, forecasting the outcome of these events is extremely difficult.

While supercells account for the majority of strong and violent tornadoes, weaker tornadoes can occur in other types of storms. Recent climatological studies suggest that 13-18% of tornadoes occur in quasi-linear convective systems (QLCSs). Unlike supercell tornadoes, these tornadoes often are not accompanied by a rotating updraft aloft, and the mechanism(s) by which they form is an ongoing area of research. QLCS tornadoes are associated with shallow, often transient circulations that are usually poorly resolved by the operational radar network. Given that an even smaller fraction of QLCSs produce tornadoes compared to the fraction of supercells that produce tornadoes, the forecasting and warning problem posed by these tornadoes is especially challenging, making it a vulnerable area to both misses and false alarms.

Other weak tornadoes can form when convection develops above a boundary separating two different air masses. Such boundaries usually already contain significant vertical vorticity due to the contrast in the horizontal winds across the boundary. The pre-existing vorticity is simply contracted (stretched) by the developing updraft. For example, these tornadoes (termed landspouts) often occur in association with the Denver convergence zone. This formation mechanism is entirely different than that for supercell tornadoes. Finally, tornadoes often develop in land-falling hurricanes; and although they are generally weak and brief, numerous F3 tornadoes have been observed in these conditions, with F4 strengths occurring only in two known cases. Thus, the environments supporting all types of tornadoes are relatively broad and we have not solidified the relationship between tornadoes and environmental properties entirely, although we have made great strides in this area.

Controls on Tornado Strength and Longevity

While much research attention rightly has been given to understanding tornado formation, far fewer observational studies have explored the factors governing tornado strength and longevity. A better understanding of what maintains tornadoes after formation is needed to improve the precision of warnings and the forecasting of "long track" tornadoes. Although some of the same mechanisms are likely at play in both formation and maintenance, some of them may differ. For example, recently observed gust-front surges or secondary rear-flank gust fronts are areas of converging air well behind the leading edge of the storm's cold pool. The role of these features, if any, in the formation and/or maintenance of tornadoes is the subject of investigation using numerical simulations and fine-scale observations when available. This is just one example of a recently discovered storm feature that may have an important influence in controlling tornado lifetime.

Tornado strength, which ultimately depends on the amount of available angular momentum and the degree to which it can be contracted, is difficult to assess using commonly available real-time observations, and it is even more difficult to predict in advance. Most of our understanding in this regard comes from laboratory tornado chambers or simplified numerical simulations (i.e., simulating the tornado itself along with an updraft, but without the complicating influences of the rest of the storm). Few observations of the winds at very low levels in a tornado have been obtained owing to the difficulty in positioning radars sufficiently close to tornadoes to have the necessary resolution and low beam height. Thus, our knowledge of tornado structure remains partially unverified observationally.

Suggested Research

When we combine the concerns from the previous sections, several outstanding questions are apparent.

- How do we address the convection initiation problem? Are there limits to our understanding of the processes, or are we simply limited in our ability to simulate them properly given current model resolution and parameterizations? Are higher resolution models the only hope? Can parameterizations affecting processes like entrainment be improved? Modeling studies compared to observed storm formation are needed.
- What are the relative roles of downdrafts in different areas of the storm in tornadogenesis? Fine-resolution observational studies can address this on a case-by-case basis. Improvements in microphysics schemes may be necessary to answer this question more generally using numerical simulations.
- Is there a separate "event" that must occur within a storm to aid the contraction of low-level rotation into a tornado, and is there anything predictable in the environment that can help further distinguish between the tornadic and nontornadic supercells, particularly in the regions of the CAPE-shear parameter space showing the lowest skill? Combinations of observational and numerical modeling studies are needed.
- Can any generalizations be made regarding the outcome of storm mergers or storm-boundary interactions? Combinations of observational and numerical modeling studies are needed.
- What are the most important processes in tornado maintenance and can these be predicted based on the initial environment? Detailed observational and numerical modeling studies are needed.
- How valid are our laboratory- and model-derived conceptual models of tornado structure and winds? Low-level observations within the tornado are needed.

White Paper 2:
Current Challenges Posed to the Forecast and Warning for Tornadoes

Resolving The Risk (Temporally And Spatially)

Resolving the tornado risk is about accurately depicting the temporal and spatial boundaries of the hazard (tornadoes). Most strong to violent tornadoes will come about during the afternoon and evening hours. While not always the case, these are the hours during the day when the potential for a strong to violent tornado is greatest. The diurnal cycle in tornado potential is supported by long-term observations and our meteorological understanding of severe storms. The annual tornado cycle is also well understood and is related to the transition from cool season to warm season and then back to cool season. Tornadoes are increasingly likely to occur from March through May, diminish in number and intensity during the summer, and then again increase slightly in number (and sometimes intensity) in the autumn months, from October through November. The annual, seasonal, and diurnal cycles of tornado potential can be used as a basis for assessing the temporal resolution of the risk. However, for an arbitrary location, the chance of a significant tornado occurring during a time identified as having maximum potential (an evening in May, for example), is very low. Furthermore, the probability is even lower (but not zero) outside of those times identified as having a greater risk.

Spatial uncertainty in tornado prediction also poses a formidable forecast and warning challenge and is another component used to resolve the boundaries that contain the risk. It is especially challenging to define a risk area prior to tornado-producing thunderstorms appearing on radar, and the subsequent issuance of tornado warnings. Even at the point of a tornado warning, when it has been determined that a particular thunderstorm may contain a tornado posing a serious risk to life and property, there remains considerable spatial uncertainty in NWS tornado warnings (Fig. 1).

Just as tornadoes are more likely to occur during certain times of the day and year, there are geographic regions of the United States that have a greater likelihood of experiencing tornadoes. The Great Plains and Southern United States are particularly vulnerable to the formation of larger scale storm systems that bring together the ingredients required for intense thunderstorms and tornadoes (Fig. 2). But here too, there are no hard spatial/geographic limits in the United States where the tornado potential drops to zero. Tornadoes have been reported in every state at one time or another.

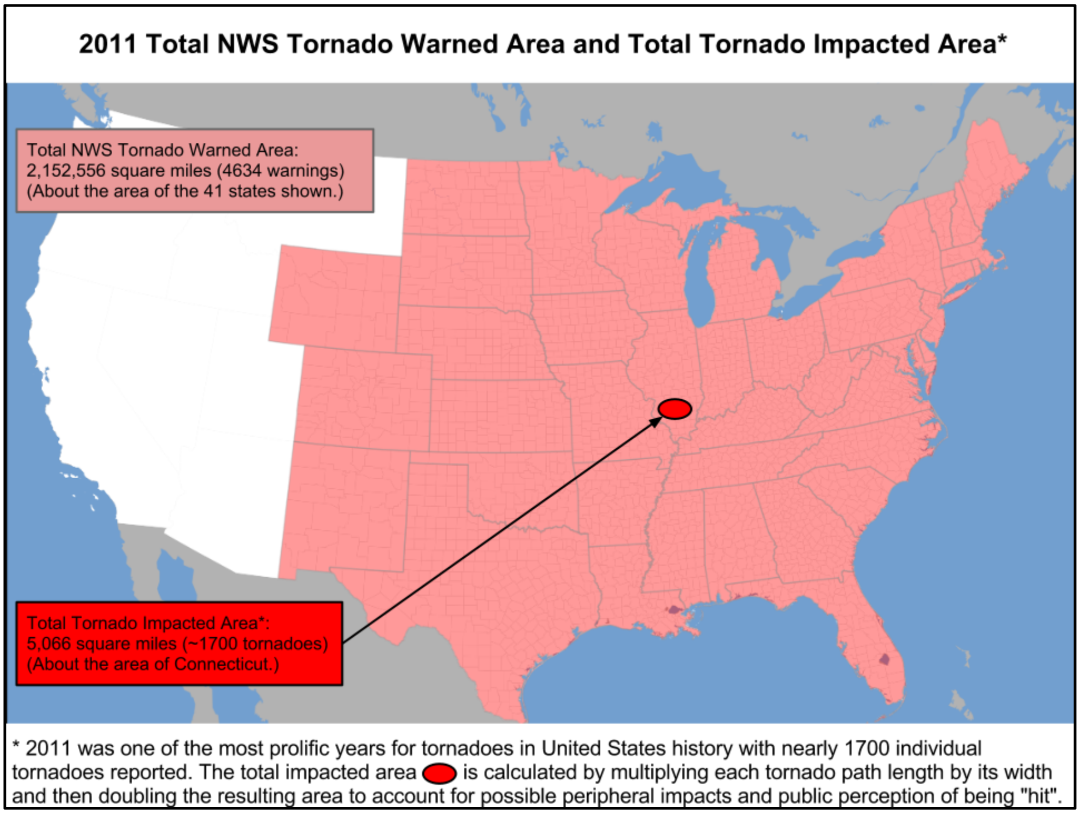

Figure 1. Total tornado warned area in 2011 compared to total area "impacted" (NWS and SPC data).

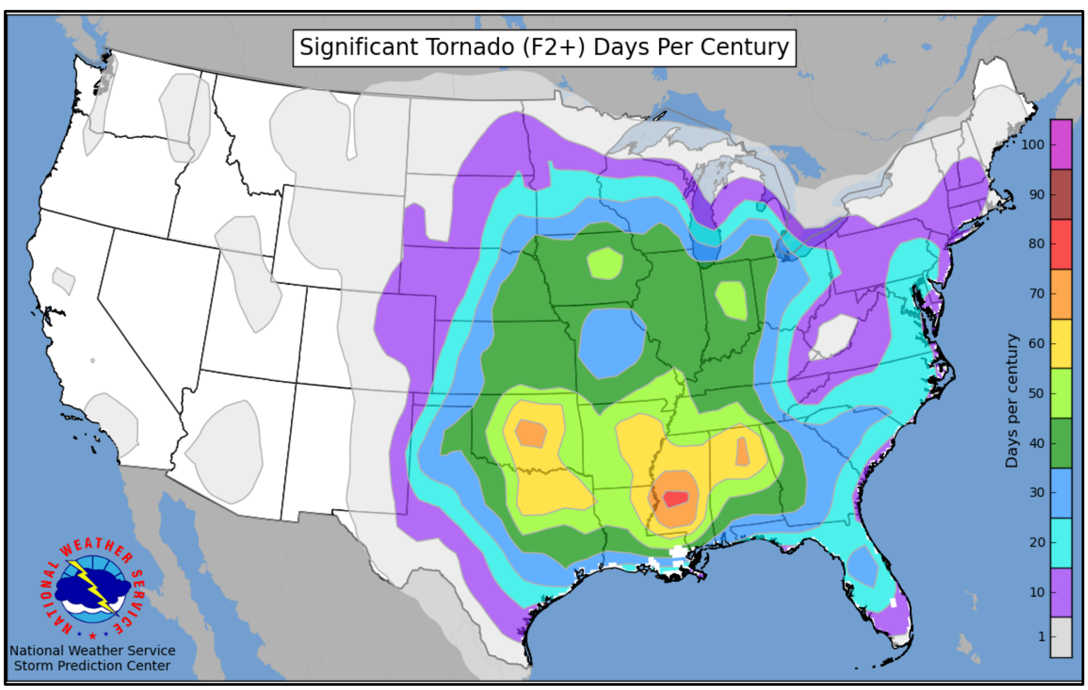

Figure 2. The estimated return frequency of a significant tornado to within 25 miles of any point. (SPC data 1961-2010).

Ingredients Diagnoses, Information Integration, Non-Linearity, Low-Probability But High Impact

Prior to tornado development, one of the most important tasks undertaken by the operational meteorologist is that of atmospheric diagnoses. Similar to a medical doctor assessing a patient's symptoms before recommending a course of treatment, the meteorologist must diagnose the atmosphere before proceeding with a prognosis, or forecast. This task requires rapid assimilation and understanding of an enormous (and ever increasing) amount of data. Meteorologists assess tornado potential using an ingredients-based approach (Doswell et al., 1996). Moisture, instability, and lift are three of the basic ingredients needed in the "recipe" to produce a thunderstorm. In addition to these, vertical wind shear is considered a crucial ingredient for thunderstorm organization and enhanced tornado potential (Weisman and Klemp, 1982).

The challenges associated with the assimilation and understanding of large amounts of complex data in the human brain are complicated further when it is realized that the ingredients evaluated to assess tornado potential are not always distinct from one another and can combine and interact non-linearly. A relative lack or weakness of one ingredient (e.g. instability) can sometimes be compensated for by the relative strength of another (e.g. shear). When the relative magnitudes of the ingredients for tornado formation are unbalanced, or unusual, forecaster confidence in a tornado may be quite low while the actual chance of a significant tornado, if one were to develop, may be quite high (Fig. 3 from Dean and Schneider, 2008). Tornadoes are inherently low probability events that can have substantial impacts on life and property. Given the National Weather Service's mission in the protection of life and property of the American people, it is important to understand both the challenges and limitations in forecasting and warning for these events.

Current Challenges in Tornado Warning Decisions

When the environment is conducive to tornado development, weather radar becomes a primary tool used by forecasters to assess the potential for a given storm to produce a tornado or other high-impact weather. Prior to 1992, radar reflectivity structures, such as hooks in supercell storms, were the chief radar-based indicators of potential tornado occurrence. The installation of the Weather Surveillance Radar – 1988 Doppler (WSR-88D) network in the 1990's provided the capability to directly observe radial velocity signatures associated with tornadic storms. A comparison of tornado warnings issued at National Weather Service Forecast Offices between 1986 and 1999, prior to and following WSR-88D installation, showed a 25% increase in the percentage of tornadoes warned and about a 4 min increase in warning lead time (Simmons and Sutter 2005). Additionally, expected tornado fatalities and injuries were reduced by 45% and 40%, respectively. These warning statistics, however, include missed tornado events and warnings issued following tornado occurrence, both of which were assigned a zero lead time. Extending these statistics through 2011, a plateau in tornado warning lead time of 14 min or sohas existed since 2003 (Fig. 4). The removal of missed tornado events from this data set, though, provides a strikingly different story. *Tornado warning lead time for predicted tornadoes has essentially remained unchanged by the use of Doppler data.* Unsurprisingly, these tornado warning lead times are also higher than those including missed events (Fig. 4).

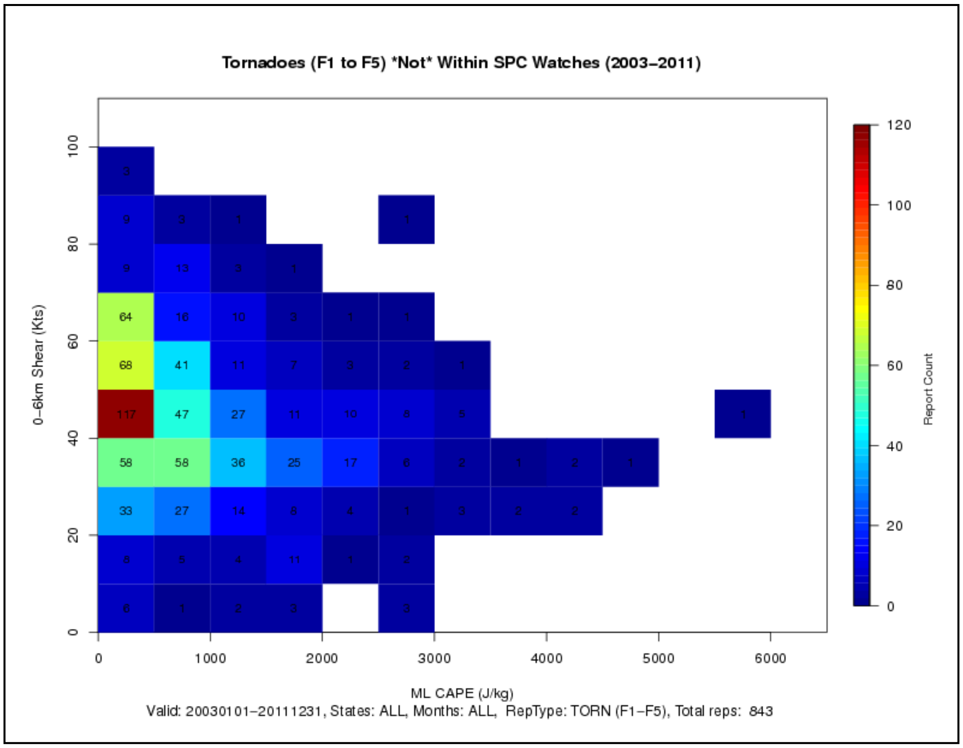

Figure 3."Phase-space" diagram showing those atmospheric conditions most likely to have "missed" tornado events that were not contained in an NWS/SPC watch. The environtments where tornadoes are difficult to forecast are those characterized by low instability (x-axis) and high vertical wind shear (y-axis). These environments are also not uncommon and usually do not result in tornadoes.

The relatively static nature of tornado warning lead time suggests that either a significant leap in scientific understanding and/or a paradigm shift in warnings is likely required to extend these lead times. A signficant scientific challenge is advancing the physical understanding required to better discriminate tornadic from nontornadic supercells. Data analyses from scientific field programs, such The Second Verification of the Origins of Rotation in Tornadoes Experiment (Wurman et al. 2012), were designed to shed light on this challenge. Other tornado-warning challenges include limitations due to radar scan time, spatial resolution, and the earth's curvature effect (e.g., LaDue et al. 2010). Because tornadoes can develop in tens of seconds to minutes, rapid-adaptative-scan radar technologies such as phased array radar are being explored to improve sampling of rapidly evolving storm structures (Zrnic et al. 2007; Heinselman et al. 2008). A study by Heinselman et al. (2012) shows promise in capability of faster updates to improve forecaster confidence and tornado warning lead time. Gap-filling X-band radar networks, such as Collaborative Adaptive Sensing of the Atmosphere (CASA), are simultaneously being examined to improve low-altitude coverage of circulations (Junyent et al. 2010) and other phenomena.

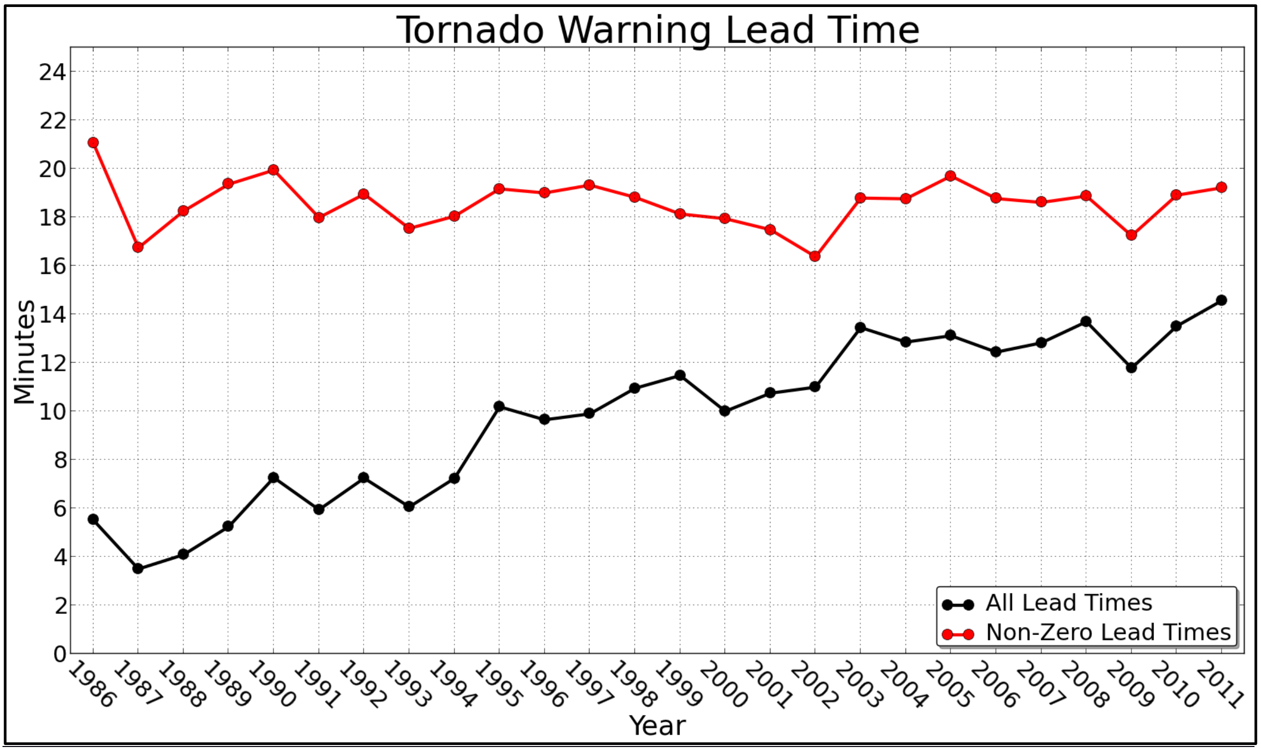

Figure 4. Annual mean national tornado warning lead times according to NWS definition in black (includes misses and warnings issued after a tornado) and excluding non-zero lead times in red. The black line is essentially the red line*POD. Courtesy of Harold Brooks and Patrick Marsh.

Once a tornado warning is issued, forecasters are concerned with obtaining confirmation of tornado occurrence and/or demise. Though storm spotters have traditionally filled this role, the tornado debris signature found in dual-polarization data (Ryzhkov et al. 2005) is another source for tornado confirmation. This signature is most prominent in storms that loft significant debris (rated EF2 and higher) and may be especially helpful at night. The in-progress polarimetric upgrade of the WSR-88D network will provide this capability throughout most of the nation. This upgrade also provides the opportunity to investigate polarimetric signatures across geographic regions and a wide variety of storm types.

Assuming that field programs and advancements in radar technologies and networks will improve scientific understanding of severe storms, an important question to consider is how this new knowledge and these new capabilities may be harnessed to improve the warning process. Will such advances support the planned transition from phenomenon-based to impact-based warnings? Will some aspects of warning accuracy be improved? What improvements in warning accuracy would be most beneficial to society? Might more temporally and spatially specific tornado warnings aid personal decisions in response to them? Will confirmation of tornado occurrence from dual-polarization tornado debris signatures improve public confidence in warnings? Interdisciplinary research efforts are needed to answer these and other related research questions.

Warn-On-Forecast: The Future Of Severe Weather Warnings

While new radar and other observations may provide an increase in warning lead times to values above 20 minutes, transforming the warning paradigm to where lead times of 45 minutes and longer are routinely provided will require the use of weather forecast models as part of the warning process. This transformation will provide new opportunities for how to communicate warning information, as well as new challenges. Owing to the small scales of hazardous weather events, and our inability to observe storms as accurately as we would like, this warn-on-forecast system will have to be an ensemble forecast system in which many forecasts (say 50-100) are produced that are valid over the same spatial area and forecast time interval. By combining the information from all these forecasts, a warn-on-forecast system will generate occurrence probabilities for a variety of hazardous weather events, such as tornadoes, flash floods, damaging surface winds, and hail, as a function of time and location (see Fig. 5). The vision is that a warn-on-forecast system would provide updates every 5 minutes, providing a near continuous flow of information to National Weather Service forecasters and hence to the public.

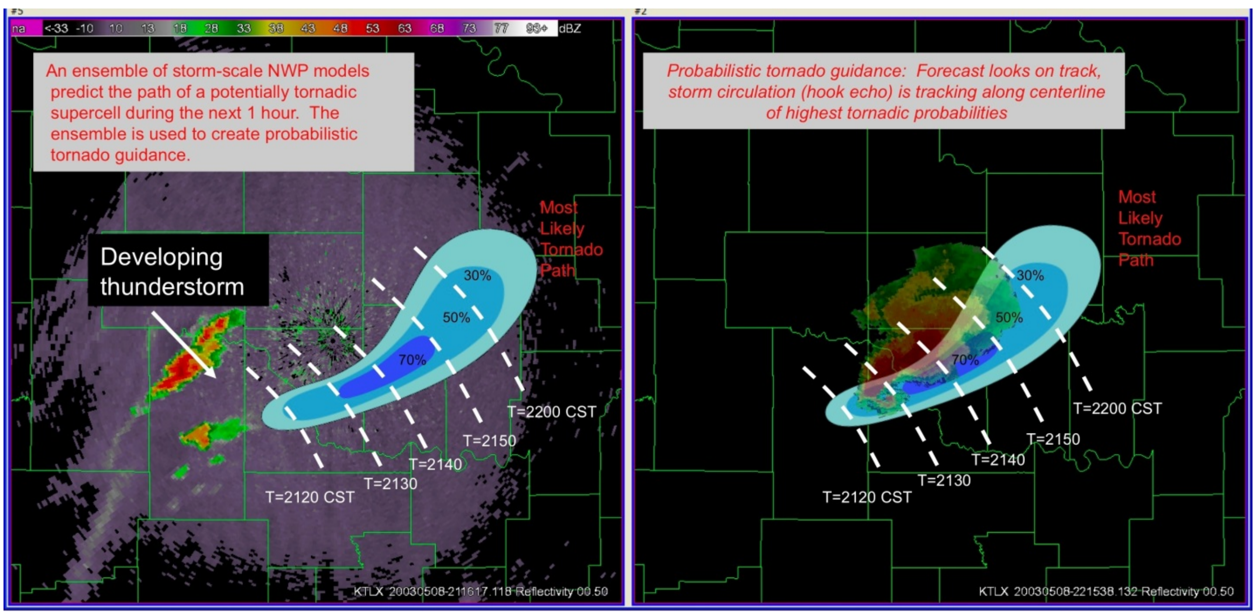

Figure 5. A conceptual illustration of a convective-scale warn-on-forecast system. Developing thunderstorms are observed by radar (left) and assimilated into a convection-resolving numerical weather prediction model ensemble forecast system. Probabilistic predictions of the future evolution of these storms are produced, yielding a tornado probability field valid over the following 90 min (blue color fill). If the warn-on-forecast system is accurate, then the observed storm 45 min later (right) produces a mesocyclone and hook echo that are along the axis of highest tornado probability. This type of predicted probabilistic hazard information would be updated frequently (not shown), perhaps every 5 minutes, and used to make warning decisions. Longer warning lead times are provided than are possible based upon observations alone. From Stensrud et al. (2009).

The hazardous weather probabilities are expected to be smaller for longer lead times and to cover slightly larger areas (Fig. 6). One could easily imagine a scenario where one receives warning information for a tornado threat at your location valid an hour from now, but with a low level of confidence. However, over the next 15 minutes you receive several updates that maintain the tornado threat and show the confidence level increasing. As the time to the event decreases, the threat is maintained and the confidence level continues to increase. When the confidence reaches a certain level or the time to the threat reaches some minimum time interval, a call to action is sent out just like today's warning statements. How would forecasters and the public interpret and use this type of information? How can it be best communicated? How would different user groups (hospitals, schools, colleges, cities, large venue operators, businesses, airport terminals, etc) use this information to make decisions? Similarly, how would these user groups respond to a slightly different scenario in which one receives warning information for a tornado threat at your location valid an hour from now, but with low confidence. Over the next 15 minutes you receive several updates that maintain the tornado threat and show the confidence level increasing. However, the next update indicates that the tornado threat is decreasing and perhaps 10 minutes later the threat is down to zero. Is there some minimum level of confidence needed to maintain trust in this type of probabilistic information? At what point are we providing too much information leading to inattentiveness or the information being ignored? We know that we cannot perfectly observe or forecast the atmosphere, so there will be events for which our predictions may have relatively rapid changes in confidence levels.

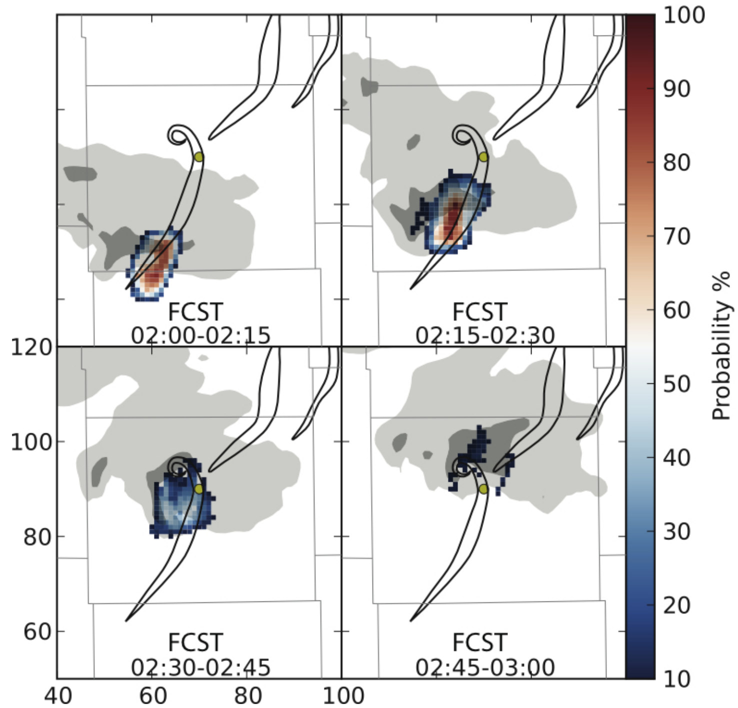

Figure 6. Ensemble probability of low-level vorticity exceeding 0.015 s^{-1} for four 15-minute time windows starting 0200 UTC 5 May 2007 for the Greensburg, Kansas, tornadic supercell thunderstorm. Simulated radar reflectivity regions greater than or equal to 30 dBZ and 50 dBZ are shaded in light and dark gray, respectively, for ensemble member 7 at the beginning of each time interval for each panel. The damage paths of the first 3 large tornadoes are overlaid in each panel for reference, with the first (farthest southwest) track corresponding to the Greensburg tornado. The yellow dot marks the location of the town of Greensburg, Kansas. The time interval (UTC) of each 15-min period on 5 May is indicated in each panel. From Stensrud et al. (2012).

Besides the questions regarding how forecasters and the public could use probabilistic/confidence information related to severe weather warnings, there are a number of physical science challenges that need to be addressed for warn-on-forecast. While the pieces needed for a warn-on-forecast system are available, they all need improvement. The needed improvements include radar data quality control, storm-scale data assimilation and ensemble generation methods, physical process scheme parameterization, verification, post-processing and display techniques.

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White Paper 3:
Household Preparedness and Mitigation

Whether, households, organizations, and communities mitigate hazards and prepare for disasters has concerned the disaster community for many years. Over the last thirty years the greatest number of studies have examined what motivates preparedness and mitigation for earthquakes, particularly in California.[1-1] But research has also examined what increases preparedness and mitigation for a variety of different natural, technological and human-made hazards including floods,[16-19] hurricanes,[20-21] wildfires,[22] landslides,[18] volcanoes,[21] heat,[17] toxic chemical releases,[24] technological disasters,[25] terrorism,[26-31,52,53] and more. Overall, the amount of preparedness and mitigation reported has been modest and has focused on activities that seem easier and less costly to do.[4,10] Many characteristics of households and individuals have been examined in the attempt to understand the circumstances under which households prepare and mitigate.[32]

After briefly reviewing how gender, race/ethnicity, socioeconomic status and risk perception affect household preparedness and mitigation, this paper focuses on the following.

- How different methods of measuring preparedness and mitigation influence findings;
- How past exposure to disasters affects preparedness and mitigation; and
- The role of information in increasing preparedness and mitigation.

Gender

When gender is examined in studies of preparedness, results are mixed. Lindell and Prater[4] reported that women were less likely to make hazard adjustments. In Los Angeles[26] men were less likely to have emergency supplies and plans than women, but these differences disappeared in multivariate models. Fothergill[47,48] suggested that men and women might differ in the kinds of preparedness activities that they do. Mileti and colleagues[6,7] reported mixed results as regards gender, whereas others reported that gender was unrelated to taking preparedness actions.[10,11,24,26]

Nationally, men reported learning how to get information about terrorism and purchasing things to be safer, while women were more likely to avoid cities, tall buildings and national landmarks because of terrorism.[28] In California, males reported completing more preparedness and mitigation activities than females, but they were also more likely to say they did them for reasons other than earthquakes. Gender (male) remained a predictor of preparedness and mitigation in multivariate analyses.[1]

Race and Ethnicity

Like gender, research on how race and ethnicity influence household decisions to prepare are mixed. Some research has found that Whites are more likely to prepare than either African Americans or Latinos[39,49,50]. Lindell and Hwang[24] reported that Whites were more like to have flood insurance, but non-whites were more likely to have made flood adjustments. Peacock [51] reported that African Americans were less likely to prepare, but Hispanics did not differ from White respondents. Others report that race/ethnicity was unrelated to taking preparedness actions.[4,10]

Studies focused on terrorism conducted after September 11, 2001, report similarly mixed results. Torabi and Seo[52] reported that more African Americans than Whites organized supplies as a consequence of the attacks. Eisenman et al.[26] reported that more African Americans established an emergency plan and that Latinos and African Americans were more likely than Whites and Asians/Pacific Islanders to purchase or maintain emergency supplies.

Following 9/11, the types of activities considered for inclusion in studies of preparedness expanded to include decisions to avoid activities and locations that were thought to increase exposure to terrorism. In the immediate aftermath of 9/11, persons were repeatedly advised to avoid national landmarks, reduce their use of airplanes and trains, increase their vigilance, and, during the anthrax scare, change how their mail was handled. A few studies have examined the extent to which people report avoiding situations. Torabi and Seo[52] found that women and African Americans were more likely than men and Whites to limit outside activities or change modes of transportation because of terrorism. In Los Angeles, African Americans, Hispanics, and Korean Americans were more likely than Whites, Chinese Americans, or other Asian groups to "avoid things they wanted to do because of concerns about terrorism."[53,p169]

Nationally Whites and Asians/Pacific Islanders were more likely than African Americans and Hispanics to report doing preparedness activities, but less likely to engage in avoidance activities.[28] In multivariate models gender (female) and race/ethnicity (non-white) had modest indirect effects on preparedness.[31] In California[2] Hispanic respondents consistently reported doing fewer preparedness and mitigation activities than other race/ethnic groups, while White respondents reported more earthquake preparedness and mitigation.[31] Race/ethnicity did not have a significant main effect on preparedness in multivariate models.[1]

Socioeconomic Status

Socioeconomic status is most commonly measured by respondents' education and income. It is generally assumed that hazard adjustment and preparedness increase with education and income, but recent research does not consistently report such relationships and, when found, they often disappear in multivariate models. In Canada[27] there was a positive association between education and individual preparedness behavior for terrorism but no association with avoidance behavior.

A positive association between education and preparedness for earthquake was reported in Istanbul.[12] Lindell and Hwang[24] reported a negative association between income and making hazard adjustments for wind but no associations between education and income and making flood adjustments or buying flood insurance. In multiple regressions, Lindell and Prater[4] found income, but not education, to be a significant predictor of hazard adjustment. A direct association between income and purchasing flood protection devices was found in Germany, which disappeared in multivariate analyses and no associations between education and hazard adjustments.[16]

Nationally[28] households with high income and education were more likely to do preparedness activities, but they were less likely to engage in avoidance activities. In California, households with more education and higher incomes consistently report doing more earthquake preparedness and mitigation. But, when included in multivariate models, income remains positively associated with preparedness but education is negatively associated with preparedness.[1]

Risk Perception and Preparedness

It has been assumed the programs that increased a household's perception that it was at risk from a hazard or future disaster would increase its' mitigation and preparedness activities. Increasingly, disaster researchers have suggested that although risk perception may be a necessary predictor of preparedness, it is not a sufficient predictor and is, in fact, largely mediated or moderated by other factors. Risk perception was a direct predictor of preparedness in some studies[14,18,20-22,27,45] and had no effect on preparedness in others.[4-7,11,12,14,17,25,26] Martin, Martin and Kent[41] reported that risk perception slightly mediated the influence of knowledge and self-efficacy on preparedness for wildfires. Lindell and Hwang[24] found that perceived risk partially mediated the effect of past hazard experience and income on hazard adjustment and completely mediated the effect of gender.

Nationally, risk perception was modestly correlated with engaging in four preparedness activities (developing emergency plans, stockpiling supplies, purchasing things to be safer, duplicating important documents), but its effect was largely mediated by perceived effectiveness of activities, knowledge about terrorism, and milling or proactively seeking information about terrorism.[31]

Measuring Preparedness and Mitigation

Called variously preparedness, mitigation, hazard adjustment and readiness behavior, measures of preparedness have varied widely across studies. Most common have been counts of the number of activities done, with many of these lists either replicating or based on a list developed by Turner and colleagues.[7,8,10,11,15,33,39] In some cases, included within the set of items are questions more appropriately considered as measures of milling behavior[16] or self-efficacy.[33] Individual questions are used[16,20,37] as well as one or more indexes.[8,10,24] Some measures focus on intentions to prepare,[19] attitudes toward preparedness,[12,34] or anticipated reactions to warnings.[36]

Most research focuses on whether households prepare for a particular kind of disaster such as an earthquake or a hurricane, but Turner, Bourque, Lindell and colleagues have expanded their questions beyond the index disaster. Turner et al asked whether 16 activities had been done or were planned for either earthquakes or other reasons.[39] Bourque expanded the list to ask whether 17 activities had been done before and/or after three index earthquakes (Whittier Narrows, Loma Prieta, Northridge) either because of earthquakes and/or for other reasons.[8,10] In the National Survey of Disaster Experiences and Preparedness (NSDEP) Bourque and colleagues asked whether households had engaged in six preparedness activities and seven avoidance activities because of terrorism, natural disasters, other reasons, or any combination of the three.[28-31] Consistent with findings for earthquakes,[8,10] activities reported for protection against terrorist attacks were performed for a variety of reasons – with terrorism being only one among many reasons.

In the California Survey of Household Earthquake Preparedness and Mitigation (CSHEPM) a 43-item inventory asked respondents about: obtaining information (five questions), planning and organizing (four questions), training and practicing (four questions), managing supplies and equipment (17 questions), securing building contents (nine questions), protecting building contents (two questions), and safeguarding finances (two questions).[37] Of the 43-items, 35 asked questions about general preparedness, and eight were specific to earthquakes. For each general preparedness activity that a respondent reported, s/he was asked whether that activity was done exclusively because of earthquakes, exclusively for other reasons, or for both reasons. As was true in NSDEP, households reported investment in more preparedness and mitigation activities when their reasons for doing so were not limited to earthquakes.

Following Russell et al.,[8] Lindell and colleagues suggest that to understand why people do or do not prepare, we need to know more about how they evaluate recommended activities apart from their usefulness in a disaster.[3,5,33,40] Lindell and colleagues examined whether one or more preparedness activities or hazard adjustments were more likely to be adopted when they were judged to be high on hazard-related attributes, such as efficacy in protecting persons, efficacy in protecting property, and suitability for other purposes, and low on resource-related attributes, such as cost, knowledge, skill required, required time and effort, and required cooperation with others. They found that households were more likely to have engaged in one or more preparedness activities when the activities were perceived to have the hazard-related attributes of protecting persons, protecting property, and being suitable for other purposes.

This series of studies suggests that efforts to increase household preparedness may have been too narrowly focused. Instead of focusing exclusively on what people have done to prepare for earthquakes, hurricanes, or terrorism, maybe the questions need to be broadened to ask, first, what households have done and what they have obtained for reasons unrelated to disasters, and then demonstrating the value of those activities for disasters. In encouraging preparedness, practitioners and policy makers need to simultaneously broaden, increase, and simplify their messages. Many households have working flashlights, manual can openers, and first aid kits, but they did not get them to prepare for natural disasters or terrorism. They got them because they were useful for everyday life, for camping trips, or for any of a myriad of other uses. These studies suggest that we need to do a better job connecting "mitigation and preparedness" with those things that households do all the time.

Prior Exposure to Disasters

Emergency planners and disaster researchers often refer to the "window of opportunity" that exists in the immediate aftermath of a disaster, and find that households engage in more preparedness and mitigation during this period. Nguyen et al.[10] and Heller et al.[15] found that households that were closer to the epicenter of the Northridge earthquake, experienced more shaking, and reported financial loss, physical injury, and emotional injury attributed to the earthquake increased their investment in post-quake preparedness and mitigation behavior. Others have similarly found that recent exposure to and damage from a disaster increases preparedness and mitigation.[3,8,39,57-59]

Of interest is how long such an effect lasts after a disaster, how exactly to operationalize "prior exposure," and whether it has a differential effect across households. Both Baker[12] and Lindell and Perry[3] have noted that "experience" is a difficult construct to define and measure and that the way in which it is measured influences results. Russell et al.[8] reported that high levels of fear during and frequent thoughts about earthquakes were weakly correlated with increased preparedness. Lindell and Perry[3] similarly reported that hazard intrusiveness (frequency of thought and discussion about a hazard) modestly increases preparedness. Siegel et al.[55] found that respondents who reported an emotional injury during the Northridge earthquake subsequently engaged in more preparedness activities prior to the 1998 El Niño event.

A number of different measures have been developed to try and capture how prior exposure to or experience in disasters influences future preparedness. Residence in hazardous areas,[12,14] past exposure to a disaster,[13,17,23,31,56] and experiencing damage in a past disaster[6,13,16,56] have been measured in some studies and found to increase preparedness and mitigation behaviors. In NSDEP "exposure" was operationalized in two different ways. First, the national sample was stratified such that households located in areas affected by 9/11 (New York City; Washington, D.C) or threatened (Los Angeles County) were oversampled. Residents of New York City and Washington, D.C., were slightly more likely to develop emergency plans, stockpile supplies, increase vigilance, and reduce train travel exclusively because of terrorism and were more likely to stockpile supplies for a combination of reasons (terrorism, natural disasters, other reasons).[28] In a second paper from the same data set, "exposure" was measured by respondents' spontaneous mention of 9/11 as an emergency event that had affected them. Direct experience as measured here had a modest direct effect on increasing risk perception and a minor indirect effect on preparedness.[31]

There is a lot we do not know about how and when past experience influences future preparedness and mitigation. Looking across the studies where attempts have been made to measure experience, it does appear that there is a "window of opportunity" usually suggested to be two years, within which past experience influences future behavior. Comparing the substantial effect that experience during the Northridge earthquake had on preparedness with the very modest impact exerted by 9/11 on preparedness more than six years later suggests that this is a situation where you "strike while the iron is hot." But are there ways in which that window can be extended? Or the index disaster re-actualized? How proximal or distal does the experience have to be? How does it interact with pressures to return to normalcy and to construct a more resilient community?

Information As a Predictor of Preparedness

When measures of the information received and sought are included in analyses, they usually increase preparedness. Milling or proactively seeking information about hazards, disasters and preparedness has most frequently been the measure included.[1,6,7,9,23,29,31] Mileti and colleagues,[6-7] Perry and Lindell[23] and Paton et al.[9] reported that milling (proactively seeking information) increased preparedness and mitigation. But receipt of passive information or information that was not actively sought also increases household preparedness and mitigation. Relevant measures of passive information include the number of information sources,[1,20,24,29] the number of channels over which information is received,[1,29] the number of types of information received,[1,29] cues or seeing others prepare,[1,6,29] being embedded in a neighborhood information system,[21] and being active in a social network.[15] It is also important to find out from those who have received information whether the messages are consistent (the same) across the different messages received.[3,4,60]

NSDEP examined how receipt of passive and actively sought information combined with knowledge and the perceived effectiveness of preparedness activities to increase preparedness behaviors (developing emergency plans, stockpiling supplies, purchasing things to be safer, duplicating important documents).[29] Earlier we noted that milling or the proactive seeking of information partially mediated the effect that risk perception had on preparedness behavior. Here measures of passive information were included in multivariate models. Thirty-eight percent of the variance in preparedness was explained with cues or observing others prepare having the single greatest impact followed by the perceived effectiveness of actions, the number of types of information received, knowledge, and milling or proactive seeking of information. A similar analysis was conducted in CSHEPM. Here the dependent variable was the 43 preparedness and mitigation activities done.[1] Forty-eight percent of the variance in preparedness was explained by the number of types of information, the number of sources from which it was received, seeing others prepare, and milling. An additional 6% of the variance was explained by demographic and environmental factors. Of particular interest is the fact that the impact of information sources and channels was differential across geographic areas and race/ethnic groups with the number of sources and types of information having a greater impact on preparedness in southern California, and the number of channels and types of information having a greater impact on Hispanic households.

Respondents in CSHEPM were asked if they had received information from 17 sources including local emergency management agencies, state agencies, schools, friends and scientists, and over seven channels including the internet and face-to-face. In preliminary analyses, information from all of the sources increased household preparedness and mitigation, but the most influential sources were employers, the California Seismic Safety Commission, the Homeowner's Guide to Earthquake Safety published by the Commission, insurance representatives, local emergency management agencies, and the US Geological Survey. The most effective channels were newspapers, other print media, the internet, and face-to-face communication.

Findings from NSDEP and CSHEPM suggest that we have not paid enough attention to how information both directly and indirectly increases household mitigation and preparedness. Of importance is the extent to which different sources and channels of information may be more effective for different subgroups in the population and for increasing different types of preparedness and mitigation. Historically we have emphasized the importance of information that households actively look for as the catalyst that increases preparedness and mitigation. These analyses suggest that passive receipt of information is equally important or even more important. We do know that most efforts to increase preparedness are one-shot affairs that are passive in nature and focus on preparing for a specific, narrowly defined event. A single "day of preparedness" or a website is unlikely to increase preparedness. We also know that we live in an era of information abundance that comes at households from all directions.

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White Paper 4:
Individual and Household Response to Tornadoes

Researchers have conducted many studies of the process by which people respond to environmental cues or socially transmitted warnings about environmental hazards (Drabek, 1986; Mileti & Sorenson 1990; Sorensen, 2000; Tierney et al., 2001). Lindell and Perry (1992, 2004, in press) have integrated findings from this research to produce a Protective Action Decision Model (PADM) of the factors that influence individuals' adoption of protective actions. These findings can be diagrammed in a flow chart that provides a graphic representation of the PADM (see Figure 1). The process of protective action decision making begins with environmental cues, social cues, and warnings. Environmental cues are sights, smells, or sounds that signal the onset of a threat whereas social cues arise from observations of others' behavior. Warnings are messages that are transmitted from a source (e.g., emergency manager, forecaster, or neighbor) via a channel (e.g., television, radio, siren, or telephone) to a receiver. These messages are expected to produce effects (e.g., changes in receivers' beliefs and behaviors) that depend on receivers' characteristics such as their physical (e.g., strength), psychomotor (e.g., vision and hearing), and cognitive (e.g., primary and secondary languages as well as their mental models) abilities as well as their economic (money and vehicles) and social (friends, relatives, neighbors, and coworkers) resources.

Environmental cues, social cues, and socially transmitted warnings initiate a series of predecisional processes that, in turn, elicit core perceptions of the environmental threat, alternative protective actions, and relevant stakeholders. These perceptions provide the basis for protective action decision making, the outcome of which combines with situational facilitators and impediments to produce a behavioral response. In general, the response can be characterized as information search, protective response (problem-focused coping), or emotion focused coping (e.g., distraction, denial, or self-medication). In many cases, there is a feedback loop as additional environmental or social cues are observed or warnings are received. The dominant tendency is for such information to prompt protective action decision making, but information seeking occurs when there is uncertainty at a given stage in the protective action decision making process. Once the uncertainty is resolved, processing proceeds to the next stage in the process.

There have been two primary types of research on individual and household response to tornadoes. Most of the research has used the *individual* as the unit of observation and analysis. That is, researchers ask individuals in the tornado impact area to report data about each of the variables in the PADM, after which the data are analyzed to calculate percentages (e.g., the percentage of respondents that heard a siren) and also to calculate the relationships among variables (e.g., the correlation between warning specificity and protective action). Another line of research has used the *tornado* as the unit of observation and analysis. In this paradigm, researchers collect archival data about tornado characteristics (e.g., intensity as measured by the Fujita scale) and path characteristics (e.g., demographic and economic characteristics of the communities in the tornado path). Research using the individual/household as the unit of observation and analysis will be summarized in the next section; research using the tornado as the unit of observation and analysis will be summarized in the section after that. The final section will identify future research needs.

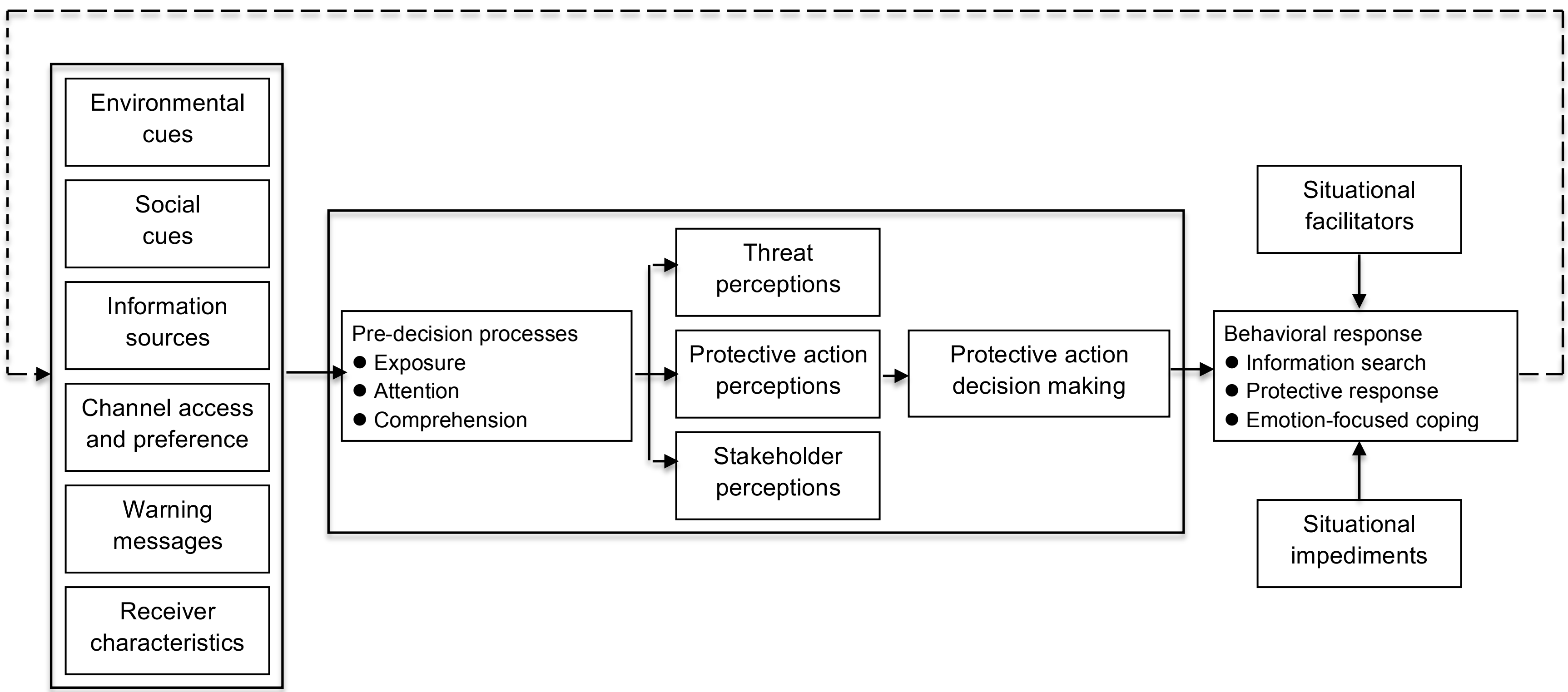

Figure 1. The Protective Action Decision Model (Source: Lindell & Perry, in press).

Individual-Level Data

None of the research on protective action in tornadoes has been based on the PADM but the findings of the available research are generally consistent with the model. Research suggests that those who do not receive a warning are significantly less likely to take protective action (Balluz, Schieve, Holmes, Kiezak, Malilay 2000; Blanchard-Boehm and Cook 2004). This is the case regardless if the cause was due to technical failure such as power outages (Carter et al. 1989; Mitchem 2003); situational circumstances such as being in transit during a warning (Glass, Craven, Bregman, Stoll, Horowitz, Kerndt, and Winkle 1980; Mitchem 2003); the storm happening at night (Schmidlin, King, Hummer, Ono 1998); or the presence of a language barrier (Aguirre 1988.) Lack of warning receipt has been found by many studies to be a significant impediment to successful protective action.

Warning channel is a major focus of analysis in many studies. For example, Brown, Archer, Kruger and Mallonee (2002) found that the most common means of warning was television (80%), followed by sirens (21%), and commercial radio (17%). These warning channels differ in a variety of characteristics (Lindell & Perry, 1987, 1992 pp. 109-113), especially the types of information they can convey. Sirens only provide a general alert, whereas radio can transmit a specific warning message and TV can provide graphic information about probable impact areas. However, warning receipt via radio and TV requires risk area residents to have electric power and to have these devices turned on. Carter et al. (1989) found that most respondents in their study had access to television (51%) or radio (85%) and many (45%) had monitored radio or television during the hour before the tornado struck. However, the storm disrupted electric power so people were unable to receive warnings from these media.

Despite their general importance as warning channels, the electronic media are not the exclusive channels for tornado warnings. Consistent with research on other hazards (e.g., Lindell & Perry, 1987), Schmidlin and King (1995) found that 45% of their sample of tornado survivors received warnings from peers. Remarkably, however, 52% had only environmental cues to warn them.

Channel preferences can be just as important as channel access in affecting people's ability to receive a warning. Aguirre's (1988) study of a tornado in Saragosa, Texas found that the National Weather Service issued a warning 35-40 minutes before the tornado struck, but the popular Spanish language cable TV channel did not carry the warning even though English language radio and TV channels did. The survival implications of channel access and preference can be seen in *Schmidlin and King's* (1995) finding that 70% of those who were watching TV before tornado impact survived whereas only 25% of those who were not watching TV at the time survived.

The characteristics of warning messages are also important in determining people's protective responses. Balluz et al. (2000) reported that receiving specific information about being in a tornado path was a significant predictor (Odds Ratio = 14.9) of people's sheltering responses. Hammer and Schmidlin (2002) also found that people are more likely to respond if informative guidance on protective actions is included in messages. Conversely, Aguirre (1988) contended that an inadequate translation of the English word "warning" into the Spanish word "aviso" (which does not carry the same sense of urgency) contributed to the 29 deaths in Saragosa. Even when warnings are transmitted in languages that recipients can understand, these warnings can be imprecise regarding the projected impact locations (Simmons & Sutter, 2007). Consequently, people often try to confirm the warnings with observations of environmental cues. Tiefenbacher et al. (2001) reported that 54% of their respondents tried to confirm a tornado threat visually before initiating protective action. Among those seeking visual confirmation, 23% searched for less than a minute, another 62% searched the sky for 1-5 minutes, and some looked for 30 minutes or more.

Even though sirens provide only a general alert, they can prompt people to seek information through other channels. Specifically, Liu et al. (1996) reported that 88% of the respondents in an area with sirens received a warning and most of these received their warnings from a siren (62%) or radio/television (34%). By contrast, only a minority (29%) of those in an area without sirens received a warning and 73% of these received their warnings from radio or TV. Consequently, hearing a siren can be a significant predictor (Odds Ratio = 9.2) of people's sheltering responses (Balluz et al., 2000), a finding that was also reported by Liu, Quenemon, Malilay, Noji Sinks, Mendlein (1996). More limited evidence suggests that people who receive a warning from television are also more likely to take protective action (Legates & Biddle, 1999). Although not specific to an official warning channel, Aguirre at al. (1991) found that a lack of environmental cues reduced the likelihood of taking protective action. Training has the potential for increasing appropriate tornado response but might not be effective in achieving this objective. Carter et al. (1989) found that 75% of their respondents knew the recommended locations for sheltering even though only 10% of them had tornado experience. Unfortunately, this knowledge had only limited effect on people's behavior because only 27% sheltered in one of these locations and only 22% hid under something or covered themselves with a mattress.

There is also evidence for the effects of situational impediments to appropriate tornado response. The location of many people in the Saragosa community center (a wide-span building type that is structurally vulnerable to high wind) was a major contributing factor to the death toll in that tornado (Aguirre, 1988). Moreover, Balluz et al. (2000) found that people were almost three times as likely to shelter in above ground locations (63%) as in basements (22%) because few houses in their study area had basements. Because so few households have tornado shelters within their homes, some people go outdoors to reach their own or a neighbor's storm shelter. Accordingly, Hammer and Schmidlin (2002) reported that only 53% of those who received a warning remained home when the tornado struck. These people sheltered in a bathroom (39%), closet (37%), hallway (10%), or other rooms (14%). The other 47% of the respondents evacuated their homes. Of these, 47% left on foot and 53% left by vehicle. Almost all of those who travelled by foot evacuated to storm shelters (95%) and the rest sheltered in friends' or relatives' houses (5%). Many who evacuated in vehicles sheltered in their own or neighbors' storm shelters (37%), a friend's or relative's house (20%), or highway overpasses (37%). The remainder sought safe locations outside the tornado path.

Residents of mobile homes are in particularly difficult circumstances because these structures can be destroyed by even relatively weak tornadoes so their occupants are advised to abandon these structures when they receive a tornado warning (Hammer & Schmidlin, 2001). Unfortunately, few mobile home communities have adequate community storm shelters. Moreover, the majority of mobile homes are sited individually so the occupants are unlikely to be able to afford the entire cost of a storm shelter. Since the NWS (no date) advises against using automobiles during tornadoes, many people are forced to choose what seems like the "least worst" alternative. Consequently, many people take actions that conflict with NWS guidance.

There is mixed evidence about the relationship between protective action decisions from one tornado to another. Some suggest that disaster experience increase subsequent actions. Hodler (1982) found that personal experience with a past event made people more likely to believe and to respond to tornado warnings. Others have found that experience also increases the likelihood of people to prepare (Blanchard-Boehm & Cook, 1994) as well as their desire to react more proactively in future events

(Simmons & Sutter, 2007) but the precise effect and duration of influence from experience is unclear. For example, Hanson, Vitek and Hanson's (1979) study found that awareness of a major historical event was more compelling than personal experience. Other research has indicated that protective action decisions can be relatively stable from one tornado to another. In their study of the 1999 and 2003 Moore Oklahoma tornadoes, Comstock and Mallonee (2005) found that 51% of those who experienced both tornadoes took the same action on both occasions, whereas 27% took more protective action and 22% took less protective action in the second tornado than in the first. Reasons for taking greater protective action in the second tornado were better access to safe locations (43%), more knowledge about personal protection (21%), more or better quality warnings (12%), more time to implement protective action (5%) and better instructions from the mass media (3%). Reasons for taking less protection in the second tornado included having less time to implement protective action (52%), fewer or lower quality warnings (28%), perceiving the second tornado as a less severe threat (14%), and inadequate access to safe locations (12%).

Although limited, several studies have explored the influence of demographic characteristics on tornado decision making. They have suggested that being a high school graduate increases the likelihood of a person responding to a warning message (Balluz et al., 2000; Blanchard-Boehm & Cook, 2004) and, conversely, being less educated reduced the likelihood of responding to a warning message (Liu, Quenemoen, Malilay, Noji, Sinks, Mendlein, 1996.) One study suggested that females were more likely to shelter in safe locations than males (Comstock & Mallonee, 2005). Friedsam (1961) suggested that the elderly are less likely to respond to tornado warnings.

Aggregate-Level Data

The case studies and surveys described in the previous section can provide detailed information about warning dissemination and behavioral response but these studies have been conducted for only a small number of tornadoes. This limitation makes it difficult to identify the effects of variation in the characteristics of tornadoes or the social and economic characteristics of the affected communities on people's behavioral response. Moreover, because the number of persons killed or injured in any single tornado is generally small, researchers are limited in their ability to identify the variables that determine these important outcomes.

One useful way to address the limitations of individual-level studies is to use the tornado, rather than the individual, as the unit of observation and analysis. Research using aggregate data (i.e., aggregated over all individuals in the impact area) essentially focuses on the information that goes into the protective action decision process (the block of variables on the left side of Figure 1), aggregate-level situational facilitators and impediments, and the aggregate outcomes (deaths and injuries) that result from people's behavior. Because aggregate-level analyses ignore individual-level social and psychological processes and people's resulting behavior, they cannot control directly for micro-social level processes such as informal warning dissemination, cognitive processes such as situational perceptions, or responses such as the percentage of residents who took shelter. Instead the aggregate-level analyses rely on a large sample (over 20,000 tornadoes and 30,000 warnings) to estimate the *average* effects of all of the intervening variables between tornado variables, warning variables, and community variables on the one hand and casualties on the other hand. Thus, for example, if people never receive, heed, comprehend, or act upon NWS tornado warnings, a warning variable should have a coefficient in regression analysis that is statistically nonsignificant and indistinguishable from zero in magnitude when the demographic and economic characteristics of tornado path counties are held constant statistically.

As expected, research using NOAA tornado warning verification records for the period of county based warnings (1986 to 2006) and Storm Prediction Center tornado records provides evidence of the effects of warnings on casualties (Simmons and Sutter 2011, Chapter 4). Analysis of tornado casualties has found that warnings save lives and reduce injuries, thus indicating that—on average—individuals do respond to warnings. However, the relationship between specific warning variables (e.g., lead time) and specific outcomes (e.g., fatalities) can be complex. Warnings with lead times up to about 15 minutes significantly reduce fatalities by up to 50% relative to a comparable tornado with no warning. However, lead times in excess of 15 minutes generally have no effect and, in some specifications, actually increase fatalities relative to an unwarned tornado. This is in part because many of the deadliest tornadoes have ample forewarning—with lead times in excess of 15 minutes. Consequently, the analysis is limited by a paucity of violent, long track tornadoes for which there is no warning. Results for injuries and lead times are more consistent, with warnings of various lead times consistently reducing injuries by up to 40% relative to no warning. The effect of false alarms has been investigated by constructing a local, recent false alarm ratio, based on all warnings issued in a state over the prior year. A higher false alarm ratio increases expected fatalities and injuries, consistent with a cry wolf effect. The false alarm effect is robust to different methods of constructing this index and demonstrates that warning accuracy affects individual response.

Research Recommendations

Most of the individual/household studies reviewed in this summary are descriptive in nature. That is, they report the percentages of respondents who received a warning from a specific type of source (news media, peers, or environmental cues) or channel (siren, radio, or TV) or who took a specific protective action (sheltered at home, evacuated to neighbor's home, evacuated out of the risk area). Even the descriptive data are incomplete because there is no information about people's perceptions of the threat, protective actions, or stakeholders. Information is also lacking about how warning sources, warning channels, message content, or social or environmental cues affected perceptions of the threat, protective actions, and stakeholders. Nor is there any research on the processes by which those at risk choose among alternative actions—especially the search for additional information and the timing of protective action implementation. It should also be noted that many of the analyses that identify indicators of tornado protective action decision making stand alone as single insights or pairs of observations in need of replication or refutation. One specific area for future research is the effect of experience on protective response. Such research is important because studies of hurricane response provide only mixed evidence for the effect of false alarms on subsequent evacuations (Baker, 1991; Dow & Cutter, 1998; Huang et al., in press). However, tornadoes occur much more frequently than hurricanes so evidence of tornado "warning fatigue" need to be systematically examined to assess its prevalence as well as to identify ways to reduce its effects.

Another important research topic is the assessment of graphic information about tornado risk areas such as warning polygons. Recent research on hurricane information displays has begun to examine the effects of similar types of graphical displays of hurricane track information on people's strike probability judgments (Cox et al., in press; Wu et al., 2012). This research has gone beyond reaction criteria (personal preference for different displays) to assess learning and behavior criteria (see Goldstein & Ford, 2004). Research to date indicates that people's interpretations of the hurricane track uncertainty cone are generally consistent with the meaning that meteorologists are trying to convey. However, warning polygons might not have the same effect, so research to confirm their proper interpretation is warranted.

Several other factors have been identified in theoretical and empirical work focused on other hazards that should also be examined in analyses of tornado related protective action decision-making. For example, our knowledge of demographic effects is very limited; little is known about the influence of affect and emotion; few studies have considered protective action response other than sheltering; and no study has addressed the timing of protective action. The latter may be particularly important as the ability to produce watches hours in advance and outlooks days in advance provides the possibility for individuals and households to begin considering protective actions long before the short window of time warnings provide. Understanding how the public perceives and responds to these different types of information is important. Finally, there needs to be an effort to integrate the findings from research that uses the individual as the unit of observation/analysis with research that uses the tornado as the unit of observation/analysis. Each of these research methods has its strengths and weaknesses, so both are needed in a balanced portfolio of tornado research.

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White Paper 5:
Population Segments with Disabilities

As a whole, scholars suggest that individuals with disabilities are disproportionately affected by disaster (Fox, White, Rooney, & Rowland, 2007; Hemingway & Priestley, 2006; McGuire, Ford, & Okoro, 2007; National Council on Disability, 2009; Peek & Stough, 2010). However, few empirical studies have been conducted on the effects of disasters on individuals with disabilities, and to our knowledge, no published data is available on the effects of tornadoes on this population. However, we believe findings from research conducted on the elderly can be reasonably extrapolated for two reasons. First, the two groups share commonalities in how they are vulnerable to disasters. For example, both individuals with disabilities and elderly adults often evidence similar specific physical disabilities, such as mobility disabilities or sensory impairments. Both also experience socio-economic vulnerabilities, such as poverty, unemployment, or living in housing prone to disaster hazards at disproportionately higher rates. In addition, these types of vulnerabilities are often "layered" in these two groups leading to cases in which individuals are exposed to multiple risk factors. Second, individuals with disabilities and elderly adults do not represent two distinct groups. In fact, most adults will acquire a disability, if only temporarily, at some time during their lifetime. In addition, as adults age, they tend to acquire disabilities, such as hearing losses, visual impairments, and cognitive disabilities, and the severity and number of these disabilities tend to increase with an individual's longevity. Finally, given recent advances in medical science, individuals with disabilities are living longer and increasingly joining the elderly adult demographic. As a result, the two groups overlap substantially, while sharing similar vulnerabilities. We argue here that research is particularly warranted on the effects of tornadoes on individuals with disabilities given the large prevalence of this population throughout the world, the intensity of their social vulnerabilities in disaster, and recent federal mandates that specify equal access for individuals with disabilities to emergency preparedness and response services.

Defining Vulnerable Populations

The Social Vulnerability Paradigm

The social vulnerability perspective of disaster has been primarily developed by researchers from the field of sociology (see Cutter, Boruff, & Shirley, 2003; Peacock & Ragsdale, 1997; Philips & Morrow, 2007), and provides a useful theoretical framework for examining the effects of disaster on populations with disabilities. While disasters are usually perceived as random events, the social vulnerability perspective argues that some groups are placed disproportionately at risk to disaster due to a combination of societal, economic, and political factors (Cutter et al., 2003; Fothergill & Peek, 2004; O'Keefe, Westgate, & Wisner, 1976; Wisner, Blaikie, Cannon, & Davis, 2004). The social vulnerability perspective argues that societies collectively determine who lives in disaster-prone areas and who will subsequently have limited defenses against disasters (Hewitt, 1997). From this perspective, disasters not only affect some groups differentially, but expose pre-existing inequalities that lead to disproportionate damage, loss of property, or even death (Wisner et al., 2004). Women, children, immigrants, minorities, the poor, as well as people with disabilities have been identified as particularly vulnerable to the impacts of disaster (Cutter et al., 2003). For example, the low cost of mobile homes makes it more likely that people living in poverty will rent or buy this type of housing. As a result, when tornadoes occur, those that are poor are more likely to be harmed when they take cover within their home, while those of more affluent means, living in better built structures, are less likely to experience personal or material harm (Daily, 2005). In addition, the affluent have more economic and social capital upon which to draw when reconstructing their homes, while socially vulnerable populations tend to struggle post-disaster and take longer to recover. The social vulnerability paradigm thus serves as an appropriate theoretical lens through which to interpret the joint experiences of individuals with disabilities and individuals who are aging. It also allows for the concept of "layering" of vulnerabilities these two populations experience economically, socially, and politically.

Individuals With Disabilities Defined

Disability as a classification is not consistently defined. Its definition varies across the different medical groups, professional organizations, and governmental agencies that focus on disability issues. Existing research on the effects of disaster on individuals with disabilities similarly has defined disability in a variety of ways (Peek & Stough, 2010). For example, mental health researchers use criteria from the American Psychiatric Association's Diagnostic and Statistical Manual to define types of psychological disabilities. Disaster researchers who focus on physical or mobility impairments tend to use the Americans with Disabilities Act (ADA) (1990) definition of disability as being "a physical or mental impairment that substantially limits one or more of the major life activities of such individuals" (PL 101-336, 104 Stat. 327). Epidemiologists rely on the U.S. Census Bureau definition of disabilities in order to conduct statistical analyses on populations. The emergency management field has traditionally classified individuals with disabilities, together with children, non-English speakers, and the elderly, as "special needs" populations. More recently, the *functional-needs approach* to defining disability-related needs during disaster was adopted by the Federal Emergency Management Agency (2010) in its Comprehensive Preparedness Guide 101 and in the National Response Framework (FEMA, 2010). The functional needs approach uses a five-part taxonomy of needs in the areas of communication, medical health, functional independence, supervision, and transportation (Kailes and Enders, 2007), rather than specifying types of disabilities. For example, individuals with auditory limitations may need modifications in how they receive emergency communications, while individuals with memory or decision-making difficulties may require some supervision while in a shelter. Perhaps the most universal definition, however, is that of the World Health Organization's (WHO) International Classification of Functioning, Disability, and Health (ICF) (2001), which conceptualizes disability as resulting from the interaction between the health condition of an individual and that individual's personal and environmental setting. The WHO definition is also compatible with social vulnerability theory in that it includes the environmental affordances and barriers as part of what becomes disabling for individuals in particular contexts or societies. Disability, like disaster, in this view is a result of societal inequalities rather than a result of bad fortune.

Older Adults Defined

Terms for older adults include "seniors," "elderly," and "aged" and these terms are tied to a chronological age. Other terms such as "frail elderly" or "fragile elderly" are usually used to denote a health, mobility, or health impairment in addition to advanced age. While disability and aging are usually discussed as two separate types of populations, there is actually considerable overlap between the two. Individuals with disabilities, due to medical advances in the last thirty years, are living considerably longer and an estimated 32-36% of the population with disabilities are over 65 (Altman & Bernstein, 2008). In addition, as people who may have previously not had a disability age, there are natural declines in physical and cognitive ability. Declines in vision (e.g., acuity, contrast sensitivity), hearing (e.g., speech discrimination), and fine motor control are all common (Ivy, MacLeod, Petit, & Markus, 1992). Cognitive changes take place as well, including the decline of text comprehension, poorer performance on memory tasks, and greater difficulty in focusing attention on relevant stimuli (Park & Schwartz, 2000). In addition to the natural waning of physical and cognitive abilities, chronic disease-related conditions (e.g. osteoarthritis, diabetes, hypertension, Alzheimers) also take their toll. Approximately 80% of all U.S. seniors have one chronic condition and 50% have at least two (Arslan, Atalay, & Gokce-Kutsal, 2002) thereby increasing the number of "fragile elderly" suffering from multiple comorbidities. These additive consequences of normal aging and disease combine with other social factors to make older adults particularly vulnerable to disaster (Flanagan, Gregory, Hallisey, Heitgerd, & Lewis, 2011; Mayhorn, 2005; McGuire, Ford, & Okoro, 2007).

Demographics and Prevalence

Individuals With Disabilities

The prevalence of individuals with disabilities that occurs within a particular geographic location depends on the definition chosen. Individuals with disabilities constitute a broad spectrum of the population and live in areas vulnerable to disaster throughout the world. According to the WHO (2005), roughly 600 million people—10 percent of the global population—have some type of disability. Disability is highly correlated with poverty, and as many as 80 percent of all individuals with disabilities live in developing countries. In the United States, approximately 16.7 percent of the non-institutionalized (not living in nursing homes, assisted living, or group homes) population reports an illness or condition that substantially limits one or more of their activities of daily living, such as walking or bathing (Brault, 2008). The U. S. Department of Education (2005) reports that 13.8 percent of school-aged children in the United States have a diagnosed disability- a number which highlights that people tend to acquire disabilities as they age. It is estimated that over 200 million children worldwide have some type of disability (UNICEF, 2007).

Older Adults

Consistent with a global trend, the American population is aging at an unprecedented rate (Mirkin & Weinberger, 2000). In 2010, those aged 65 or older numbered 40.4 million, which represents an increase of 15.3 percent since 2000. By 2030, demographic projections reported by the U. S. Administration on Aging (AoA) suggest that there will be about 72.1 million older persons- which is over twice the number reported in 2000 (AoA, 2011). Not only is the percentage of the older adult population increasing but some of the largest growth is in the older cohorts, with those aged 75-84 numbering 13.1 million and those aged 85 or older numbering 5.5 million.

Levels of independent functioning for both the aging population and the population with disabilities are often assessed in terms of Activities of Daily Living (ADLs). ADLs are specific clusters of activities such as eating, dressing, bathing, ambulating, and toileting that classify whether specific persons require help in terms of promoting functional independence (Lawton, 1990). In 2010, 36.7% (approximately 14.3 million) of those 65 or older indicated that they were living with a disability that impacted their ADLs (Houtenville & Ruiz, 2011). Moreover, an examination of age by disability type suggests that some types of disability are more associated with advancing age than others (Altman & Bernstein, 2008). For instance, seeing and hearing difficulty was more likely to be reported by those 65 or older (37.3%) than people aged 18-44 (26.9%). Cognitive difficulties including but not limited to Alzheimer's disease were reported by 44.4% of those 65 or older compared to 22.7% of the 18-44 age group. Movement difficulty was also more likely to be reported by those 65 or older (36.2%) compared to those aged 18-44 (24.6%).

Census data collected in 2010 indicates that 37% of older adults reported some type of disability (i.e., loss of hearing, vision, difficulty with walking, etc.) that impacts daily independent living (AoA, 2011). Severity and frequency of reported disabilities tends to increase with age such that 56% of those aged over 80 reported severe disabilities and 29% of this group reported needing assistance with personal needs. Consistent with the concept of layered vulnerability, the presence of a severe disability within this older population is also associated with lower levels of income and educational attainment that may cascade to impact housing and the presence of social support.

Disability and Aging Interface

From a prevalence perspective, it is unclear how the functional characteristics of aging and disability interact. For instance, what portion of this disabled older adult group developed new disabilities as a result of growing older and what portion was disabled at an earlier age? This distinction in terms of time of onset may be important as people who have been disabled for a longer period of time may develop coping strategies that allow them to adjust to their functional limitations thereby enabling compensatory behavior much faster than those diagnosed more recently (Baltes & Smith, 2003). Because disability type likely differs by age of onset as well (Altman & Bernstein, 2008), it is possible that people disabled at an earlier age will acquire new age-related disabilities in an additive fashion such that they may be able to compensate for "old" disabilities but not for newly acquired age-related disabilities. In this manner, disaster response may differ substantially between groups of older adults with disabilities. For instance, someone who experienced vision loss at an early age may have compensated by learning to rely on her hearing at a younger age. When normal age-related changes in hearing impact auditory sensitivity, this person may find herself differentially disadvantaged when she has to interpret the meaning of a tornado siren or the auditory component of a televised warning.

On the other hand, individuals born with a disability or who acquire a disability during the developmental period include populations with intellectual disabilities (formerly termed "mental retardation") as well as those with genetic or multiple disabilities, and constitute a large part of the approximately 1% of the U.S. population with severe or significant cognitive disabilities (Smart, 2009). In addition, disabilities that occur during the developmental period tend to be accompanied by physical and perceptional disabilities, adding to the supports that are needed by these individuals. In addition, individuals with intellectual disabilities, by definition, are significantly restricted in their ability to comprehend, evaluate, and remember and usually cannot cognitively compensate for these limitations. Although the life expectancy of those with developmental disabilities is usually significantly limited, we can anticipate that the acquisition of age-related disabilities would further decrease their level of function and subsequent ability to prepare for and respond to disasters.

Geographic and Residential Factors

Individuals with Disabilities

Most individuals with disabilities live and work in the community, as do their counterparts without disabilities. The rate of home ownership is lower, however, for households that include a family member with a disability, due to the relative poverty level of these households (Emerson, Graham, & Hatton, 2006; Harrison & Davis, 2001). For the same reason, individuals with disabilities are more likely to live in substandard housing or in mobile homes (Cooper, O'Hara, & Zovistoki, 2011). In addition, the 2009 American Community Survey found that 856,425 people with disabilities live in homeless shelters, group homes, and other non-institutional group quarters facilities. In addition to this group, it is estimated that more than 400,000 or more non-elderly people with disabilities are living in nursing homes and public mental health institutions (Cooper, O'Hara, & Zovistoki, 2011). An important factor for both community-dwelling and institutionalized populations is that caretaker and medical supports are available to provide continuity of care during the disaster event (National Council on Disability, 2009). Caretaker supports are also essential in the case of young children and school-aged children with disabilities who may need supervision from day care providers or teachers, as well as provisions for medical and special nutritional needs during disaster. Similarly, employers who provide supported work environments need to consider needs of their employees with disabilities should a disaster occur during the work day. In both congregate housing and work environments, an accessible built environment (Christensen, Collins, Holt & Phillips, 2007) is an important element to consider when designing areas in which to shelter-in-place.

Older Adults

In 2010, 56.5% of older adults aged 65 or older lived in 11 states: California (4.3 million), Florida (3.3 million), New York (2.6 million), Texas (2.6 million), Pennsylvania (2 million), and Ohio, Illinois, Michigan, North Carolina, New Jersey, and Georgia each had more than 1 million (U.S. Census Bureau, 2010). Alabama was one of twelve states where poverty rates for elderly residents exceeded 10% in 2010. Moreover, a growing trend in seniors' attempts to balance affordable housing with maintaining independence has resulted in an increased movement for older adults in the Midwestern and Southern United States to occupy mobile homes (George & Byland, 2002). Apparently these efforts to age-in-place have been successful because only approximately 4% of older Americans live in nursing care (McGuire, et al, 2007).

To further illustrate the concept of layered vulnerability, it is well understood that older adults are likely to "age-in-place" such that they are less likely to move once they have financially and emotionally invested in a home (Blake & Simic, 2005). Some estimates indicate that as many as sixty percent of older adults have been living in the same homes for at least 20 years (Hermanson & Citro, 1999). In 2007, 23.1 million older homeowners were surveyed and results suggested that the elderly were living in older homes with a median construction year of 1970 and 4.3% reported that their homes had significant physical problems (AoA, 2011). Other findings indicate that older adults are less likely than younger adults to make home repairs within the last two years (Hermanson & Citro, 1999) thereby placing this segment of the population in substandard housing that makes them vulnerable to strong storms (Tierney, 2006).

Research on Disasters and Population Segments with Disabilities

Individuals with disabilities

The bulk of the limited research literature on disability and disaster has focused on evacuation and the disaster impact. Studies completed post-Katrina (see White, Fox, Rooney, & Cahill, 2007; White, B. 2006) have found that systems of emergency notification, for example television and radio broadcasts, were inaccessible to many individuals. In an early work, Tierney, Petak, & Hahn (1988) suggested that people with physical disabilities are at risk when quick evacuation is required to avoid disaster impact. Similarly, Morrow (1999) suggested that older adults who are physically frail and who require assistance to evacuate are at-risk. Evacuation barriers for people with physical disabilities are seen as compounded by building design which requires the ability to descend stairs, exit windows, or open doors (Christensen, Blair, and Holt, 2007). Households usually evacuate together and evacuation behavior has been found to be affected when a household member has a disability: Data from Hurricanes Bonnie, Floyd, and Dennis revealed that households with people with disabilities both delayed evacuation and evacuated at a lower rate than did households without a member with disabilities (Van Willigen, Edwards, Edwards, & Hessee, 2002). Most of these households identified a lack of transportation or of adequate sheltering facilities as primary reasons for their reluctance to evacuate. A survey of 680 evacuees from Hurricane Katrina found 38% of those who did not evacuate before the storm either were physically unable to leave or were caring for someone physically unable to leave (Kaiser Family Foundation, 2005). Similarly, 9% of households with members with disabilities located near a chemical weapons storage site needed evacuation assistance during disaster, however 60% reported that they did not have adequate assistance to do so and 59% reported they did not have adequate evacuation transportation (Metz, Hewett, Muzzarelli, and Tanzman, 2002).

A few studies have focused on disaster impact and the response phase following disaster. Households with a family member with a disability experience significantly more damage to their homes during hurricanes, in part as they are more likely to live in a mobile home (Van Willigen, Edwards, Edward, & Hessee, 2002). The costs of these damages were also significantly higher for these households, representing 80% of their monthly per capita income, four times that of households without a family member with disabilities. Services that individuals with disabilities receive post-disaster also differ. Parr (1987) found emergency personnel and voluntary service organizations failed to consider supports needed by individuals with disabilities in post-disaster exercises. Similarly, Byrne and Davis (2005) reported that volunteers using wheelchairs or portraying a visual impairment during a drill scenario were passed over, ignored, or responded to inappropriately by emergency responders.

Two studies have examined the long-term recovery phase and individuals with disabilities. Van Willigen and colleagues (2002) studied 559 households one year following Hurricane Floyd. Respondents in inland households with a person with a disability were significantly more likely to report that their lives were still disrupted one year later. In contrast, sixty-seven percent of households without a member with a disabilities reported their lives were completely back to normal; whereas, only 58% of households with a member with a disabilities reported things were back to normal a year after the hurricane. Similarly, 65% of households located in coastal counties that included a member with disabilities reported that their lives were completely back to normal; whereas, 75% of households without a disabled member were completely back to normal several months after Hurricane Floyd. In another study, Stough, Sharp, Decker, & Wilker (2010) interviewed 54 disaster workers providing case management post-Katrina.

Barriers to disaster recovery for individuals with disabilities included a lack of accessible housing, transportation, and disaster services. Findings suggested that the disaster recovery process is typically more complex and lengthy for individuals with disabilities and requires negotiation of a service system that is sometimes unprepared for disability-related needs.

Older Adults

In contrast, there is a wealth of previous literature within the hazards research that has evaluated how older adults fare before, during, and after exposure to a natural disaster. By no means is this work comprehensive but it does identify older adults as a vulnerable segment of the population because they are more likely to become casualties during disasters in general (Friedsam, 1962; Hutton, 1976) For example, Bourque, Siegel, Kano, & Wood (2006) found forty-seven percent of the deceased as a result of Hurricane Katrina were over the age of 75. This finding is particularly true for tornado hazards (Ashley, 2007; Eidson, Lybarger, Parsons, Maccormack, & Freeman, 1990). Post disaster, when compared to younger victims, older adults typically underutilize aid from community disaster relief resources (Kilijanek & Drabek, 1979) as well as suffer from more long term psychological distress and somatic symptoms (Phifer, 1990). Potential explanations for this observed pattern of vulnerability vary from social isolation (Klinenberg, 2002) to mobility and sensory impairments resulting in a decreased likelihood of encountering a disaster warning (Eldar, 1992). Although evidence suggests that older adults are just as likely to attempt to comply with disaster warnings (Perry & Lindell, 1997), they have special needs that must be considered when developing emergency preparation plans (Lafond, 1987). Likewise, the special needs of older adults with disabilities may limit the availability of protective actions such as evacuation if shelters are not equipped with medical equipment or at least have the space to accommodate such equipment (McGuire, Ford, & Okoro, 2007).

After disaster has struck, it is noteworthy that older adults tend to be slower in their economic recovery across a variety of hazard types (Bolin & Klenow, 1983). Previous research that investigated the utilization of post-tornado disaster assistance indicates that older adults are less likely than others to seek assistance (Bell, Kara, & Batterson, 1978). When assistance was sought, some of the elderly reported being "confused, intimidated, and frustrated by time delays, complicated forms, and procedural regulations" (Bell et al, 1978, p. 80). As the Census data suggests, disability and age are correlated with lower socioeconomic status; thus, the added financial costs of recovery may have lasting effects especially when considered against the context of lower assistance seeking.

Research on Tornadoes

Individuals With Disabilities

As previously noted, we could found no published studies on the effects of tornadoes on individuals with disabilities. However, extrapolating from the above studies, we anticipate that in sudden onset disasters that permit little warning time, such as tornadoes or earthquakes, individuals with disabilities may have more difficulty in quickly taking protective actions and evading impact. For instance, individuals with cognitive impairments may not understand emergency communications or understand impending signs of danger (Kailes & Enders, 2007) or become anxious and confused in response to emergency alerts (Scotti et al., 2007). In addition, emergency procedures during tornadoes would be likely distressing for most individuals with autism, who typically find changes in routine difficult to manage and become easily agitated and disoriented by stimuli such as flashing lights or loud noises. Deaf individuals may not receive warning signals at the same time as hearing individuals when sirens or radio announcements are used for alerting. In addition, given that English is, in fact, a second language for Deaf individuals who use American Sign Language, captions on television screens or written notices distributed through social media may not be well understood by them. In sum, communicating tornado alerts in a manner in which individuals with disabilities can access them is an area of considerable concern.

Again, extrapolating to predict post-disaster needs, individuals with mobility limitations may be incapable of moving downstairs into a basement and, following a tornado, be unable to use a wheelchair to move around disaster debris. For individuals with visual impairments, navigating the post-tornado environment could be particularly hazardous in that familiar landmarks may have been destroyed or relocated. Individuals with autism or other cognitive disabilities may find the changes in their housing and neighborhoods particularly disorienting and distressing. Individuals across the disability spectrum who use durable medical equipment, such as walkers, wheelchairs, hearing aids, or who require medical supports may be placed differentially at-risk post-disaster when these supports are lost or discontinued. While individuals without disabilities may encounter similar challenges as described here, populations with disabilities are more likely to live in poverty, have smaller social networks, more likely to have experienced damage to their housing, and have fewer personal affordances with which to cope post-disaster. As a result, their ability to recovery post-disaster is of considerable concern.

Older Adults

From work with hurricane hazards (Mayhorn & Watson, 2006), it is known that older adults generally face a number of barriers that impact their abilities to respond to protective action recommendations such as evacuating or sheltering-in-place. For instance, the decision to evacuate is reliant on the financial variable of whether one owns a car or has access to transportation and likewise, a social cost must be realized because there has to be a destination for evacuation. As hurricanes are often preceded by warning periods that last for days, it is likely that older adult response to “short-fuse” hazards such as tornadoes may be more pronounced because warning time may be limited to as little as five minutes (Balluz, Holmes, Malilay, Schieve, & Kiezak, 2000). Consider the physical challenges of urgent, quick action that must be utilized to seek shelter in such a situation. Given statistics that indicate that approximately 32% of American adults aged 70 or older report difficulty walking (McGuire, Ford, & Ajani, 2006) with 3.8% needing the use of a wheelchair and 13% indicating that they use some other assistive device such as a cane or walker (U. S. Census Bureau, 2001), it is likely that many of these disabled older adults will be unable to comply with tornado warnings. Thus, there is a critical need for future research that specifically targets the development and testing of tornado warnings that take these disability and age-related factors into consideration. An added benefit to this line of warnings research is the realization that these universal approaches to design typically result in more user-friendly products and environments that benefit people of all abilities and ages (Vanderheiden, 1997).

Tornadoes and “Layered Vulnerabilities” of Individuals of All Ages with Disabilities

Given the aforementioned disability prevalence statistics and described shifts in demographics, the need for further disaster research on disability is clear. While this research is generally sparse for all hazard types, even less is known about how the characteristics of a specific hazard might differentially impact those with disabilities. For instance, unlike other natural hazards such as hurricanes and wildfires, the protective action for tornadoes does not entail evacuation but rather procedures for sheltering in place. Compounding the issue, short lead times of warnings that precede the arrival of the hazard often necessitate that compliance decisions be made quickly and safety-related actions be taken swiftly.

With tornadoes, disabled and elderly segments of the population will be faced with challenges at every stage of the event. At the warning stage, these people may be at a particular disadvantage because they will have difficulty interacting with a warning. For instance, poverty may influence whether or not someone has access to emergency messages transmitted via specific media. Likewise, even if a message is received, shortcomings in auditory or visual perception may reduce the likelihood that the message will be interpreted accurately (Mayhorn, 2005). Moreover, the understanding of message content may be further hampered for those with intellectual disabilities or normative age-related declines in cognition in older adults.

If message content is understood and an active decision is made to comply with "shelter-in-place" recommendations, elderly and disabled individuals may have difficulty finding cover from an approaching tornado. Because both aging and disability are correlated with lower socioeconomic status, these segments of the population might be likely to live in mobile homes or substandard housing (Blake & Simic, 2005; George & Bylund, 2002). Thus, it is also likely that neither segment of the population will have access to safe locations such as a basement or underground shelter. Previous research indicates that access to these locations is essential in complying with shelter-in-place instructions (Balluz, et al., 2000; Schmidlin, Hammer, Ono, & King, 2009). These at-risk individuals may be even further endangered due to social isolation (Klineneberg, 2002) as evidence suggests that people will be less likely to seek shelter even when available when they do not know the people who own the structure (Schmidlin et al, 2009).

Should elderly and disabled people gain access to sturdy, safe locations where they can shelter from a tornado, they will be faced with even further physical challenges. Due to reductions in their motoric capabilities, many older and disabled people may lack the ability to physically respond quickly (Vercruyssen, 1997). Even if someone lives in a home with a basement and they receive plenty of warning prior to tornado arrival, people with mobility impairments or visual impairments may find it difficult to descend a flight of stairs quickly or to lower themselves into the protective environment of a bathtub.

Legal Requirements for the Inclusion in Emergency Planning, Response, and Recovery

Individuals with disabilities in the U.S. are entitled to equal access to emergency services, including evacuation procedures and sheltering. The Stafford Act, which gives the Federal Emergency Management Agency (FEMA) the responsibility for coordinating government-wide disaster efforts, specifies that the needs of individuals with disabilities be included in the components of the national preparedness system (FEMA, 2007). Title II of the Americans with Disabilities Act requires modifications to policies, practices, and procedures to avoid discrimination against people with disabilities. This requirement also applies to programs, services, activities provided through third parties, such as the American Red Cross, private nonprofit organizations, or religious entities. Specifically, entities must make reasonable modifications and accommodations, cannot use eligibility criteria to screen out people with disabilities, and must provide effective communication to individuals with disabilities (American with Disabilities Act, 2008). Recent attention on national policies concerning the needs of individuals with disabilities has resulted in changes to the Stafford Act and led to the inclusion of the functional needs approach in the U.S. The C-MIST definition of the functional needs approach to disability is as follows:

> Populations whose members may have additional needs before, during, and after an incident in functional areas, including but not limited to: maintaining independence, communication, transportation, supervision, and medical care. Individuals in need of additional response assistance may include those who have disabilities; who live in institutionalized settings; who are elderly; who are children; who are from diverse cultures; who have limited English proficiency or are non-English speaking; or who are transportation disadvantaged (FEMA, 2010b).

Thus, all individuals with disabilities, including those who have a life-long disability, as well as those who have acquired a disability in senescence, are entitled to equal access and inclusion across all phases of disaster management.

Critical Research Needs

Given the scarcity of empirical literature that has examined the effects of disaster in general, and tornadoes specifically, on individuals with disabilities, it can be argued that any research on this population would be a contribution to the field. However, we suggest the following four suggestions as primary:

- Large-scale epidemiological studies that include disability as a demographic. The U.S. Census, and on a more detailed level, the American Community Survey, allow for analysis of disability as a demographic factor. A limitation is that disabilities can manifest with considerable variability, so that categorized mobility impairments can indicate, for example, either use of a cane or use of a wheelchair.
- Similarly, there is a need for large-scale epidemiological research that distinguishes between different types of elderly populations, specifically elderly who have disabilities of different types. Some elderly adults are easily able to take evasive action while others would need substantial support to do so. Using age as a variable without qualifiers masks the difference amongst individuals in this population.
- Few studies have focused on the post-disaster challenges unique to individuals with disabilities. While we can extrapolate that impact and mortality is probably greater for this population, the longest phase of disaster is the recovery phase. In households that include a family member with a disability, what differential supports are needed to support recovery and what is the differential cost of this recovery? Such research would be helpful in understanding the needs of poor communities and developing countries that tend to have a larger percentage of individuals with disabilities.
- The majority of the scant disability research is on individuals with mobility impairments and individuals with mental health needs. Research on individuals with intellectual disabilities and autism, as two of the most prevalent disabilities, is almost absent in the literature, and sorely needed.
- Research on individuals with disabilities has the potential to inform social vulnerability theory. To date, research on the effects of disaster on people with disabilities has almost exclusively focused on how physical or cognitive impairments intersect with disaster experiences rather than upon the how disability is affected by social and environmental factors (Peek & Stough, 2011). For example,

wheelchair use only becomes a differential vulnerability factor in a building that does not take into take account how people with mobility impairments may evacuate if elevators are not running. Research on the multiplicative effects of social vulnerabilities experienced by population segments with disabilities would contribute to the construction of disaster theory.

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White Paper 6:
Pre-Event Planning for Post-Event Recovery

Few locales ever conduct pre-event planning for post-event recovery, an unfortunate circumstance given the value that such planning can offer. Most elected officials lack basic understanding or education about potential disasters, often learning on the job, and realizing too late that pre-event attention to planning can enhance public safety as a recovery unfolds. In the aftermath of an event, they are often focused on emergency relief, unmet needs, and intergovernmental coordination. Too often, opportunities to incorporate weather-ready measures into recovery planning become lost in the intense focus on handling massive, community-wide needs. Even emergency management agencies and first responders lack long-term recovery planning. Most of these organizations and agencies concentrate on emergency response or public preparedness. Few have the resources or personnel to conduct pre-event recovery planning. After a disaster, implementing risk reduction measures may be difficult economically. After a major ice storm damaged utility lines in Oklahoma, one study looked at underground placement (Oklahoma Corporation Commission, 2008). Though underground placement would afford greater resistance to tornadic activity and ice storms, as well as insure a steadier power supply (especially for hospitals, nursing homes, and those dependent on power at home for various disabilities), the cost to do so was simply unaffordable. The Commission realistically ascertained that underground placement would take place as funds allowed.

Further, disasters are not "salient" events for most of the public, meaning that they do not think about or plan for what seems like an unlikely occurrence in their lives (Tierney et al., 2001). Instead, people spend time attending to daily needs, often waiting too late to integrate preparedness or mitigation measures that increase personal safety. Most lack resources to recover from disasters except for insurance, when it covers the hazard that occurred. It often takes the tragedy of a tornado outbreak, ice storm, flood, firestorm or a major hurricane to generate attention and concern sufficient to spur appropriate action. To examine pre-event planning for post-event reconstruction, this paper necessarily covers the following: (1) what is pre-event planning and its value for post-event recovery specific to building a more weather-ready nation; (2) given a general lack of pre-event recovery planning, what can be done in the post-event recovery time period to build a more weather-ready nation; (3) post-event implementation.

Pre-Event Planning

The purpose of pre-event planning is to design and define a framework for how a community might be rebuilt after a disaster occurs (Schwab et al. 1998). Such a framework should generate a community-wide consensus regarding issues that pertain to economic vibrancy, quality of life, environmental resources, and social and intergenerational equity (Natural Hazards Center, 2001, 2005). Typically, planning focuses on the built environment. Yet, a recovery plan requires that planners and stakeholders participate actively in defining what to do with housing, business sectors, infrastructure and *people* at highest risk for future impacts. Pre-event planning must thus develop as a holistic, people-centered and stakeholder-driven vision. Ideally, a pre-event plan will identify opportunities for risk reduction, including measures that foster disaster resistance and resilience. Such an effort will move participants beyond the built environment to consider fully the range of structural and non-structural elements that can reduce risks, enhance disaster resistance, and encourage disaster resilience.

Pre-event planning focuses on what might take place after an event and prepares a vision and set of resources to implement various initiatives. Land-use planning typically serves as a means to focus attention on what should be done with areas likely to be impacted. Wise pre-event planning sets out measures to introduce or enhance disaster resistant features including preservation of floodplains, increased green space and permeable surfaces (such as through density trade-offs), and stronger building codes. Deciding beforehand expedites action afterwards and, when time presses upon beleaguered officials, offers a route through the post-disaster haze. Being ready to take action means being able to implement measures to increase weather-readiness.

One critical step that can be taken during the pre-event planning period is to design emergency ordinances that can be enacted immediately after an event. Such an effort takes advantage of public concern and support to reduce future impacts. Toward a more Weather-Ready Nation, possible ordinances and actions might include:

- Establishing a Recovery Task Force to immediately implement the plan (Schwab et al., 1998). Such a Task Force should not only identify leadership but a succession plan to retain or replace key leaders as they experience burn out.
- Weather-specific initiatives that address local hazards (safe rooms, flood warning gauge placement, elevation requirements, etc.).
- Zoning maps that identify floodplains to safeguard, green space to protect, and residential areas at risk. GIS overlays should identify populations in need of protection and prioritization for post-recovery actions.
- Building code changes for private and congregate homes that integrate stronger measures that enhance roof retention, resist fire embers, require safe rooms, and increase permeable surface areas.
- Requiring public businesses to add safe room features when undergoing post-disaster reconstruction and to increase roof security in large-scale facilities. Insuring that such locations enhance their efforts to protect customers and personnel including signage, training, and interior protection during weather events.
- Hardening public facilities against weather-related events including wind-resistant windows and doors and strengthen larger-space areas such as gymnasiums.
- Land use changes that allow for underground utility placement, particularly in areas associated with high risk populations such as congregate care facilities.
- Reconsideration of warning system processes and placement (sirens and beyond) that reach higher risk populations including low income populations (public housing, mobile home parks), non-English speaking populations (including Deaf and Hard of Hearing), and non-resident populations (tourists, travelers, campgrounds).
- Environmental restrictions that emphasize native vegetation and xeriscaping to reduce fuel supplies in the wildland-urban interface.
- Promote initiatives that increase the number of StormReady Communities across the nation.

Post-Event Planning for Recovery: Toward a More Weather-Ready Nation

Given the reality that few jurisdictions hold resources sufficient for pre-event recovery planning, most such efforts will occur after a disaster has taken place. Despite the heavy burden and long days that such activities demand, public attention will now be higher than ever. Citizens, elected officials, emergency managers and planners will have a space within which they can identify codes, ordinances, policies, and procedures that will foster disaster resiliency before the next event. A more Weather-Ready Nation can emerge during a recovery planning process.

To do so, it is necessary to build on basic principles that involve all stakeholders in the recovery visioning and planning process. Doing so may be challenging because so many competing demands for people's time now occur. For those most vulnerable to the impacts of a disaster (such as senior citizens, people with disabilities, non-English speaking, and single parents), leaders must design participatory processes and events that connect to their "new" reality: living in temporary housing or with relatives, enduring longer commutes to work, dealing with protracted efforts to secure recovery resources, and juggling child care responsibilities. Typically, recommended procedures task recovery leaders with asking people what they think - such as through a series of publicly accessible charettes, meetings, fairs, or town halls (traditional, electronic, and social media, see Natural Hazards Center, 2001). To be truly inclusive, though recovery leaders must go to where people at risk *now* live and work to invite their participation, secure their visions, and design recovery measures that reduce their risk. Recovery planning, for socially and economically vulnerable populations, must engage those who would otherwise face future risks. Such efforts must be accessible physically and consider the range of languages present in the community (including sign language, see National Council on Disability, 2009).

Imagine, for example, recovery planning initiatives that take place in mobile home parks devastated by a tornado or on the banks of a bayou destroyed by a hurricane. People struggling through shift work and returning home to a mobile home park or trying to mind children after a long day shrimping at sea require convenient places for planning events. Doing so situates recovery planners in the realities of local communities and family life. Seeing, hearing, and experiencing the perspectives of a recent immigrant community as they struggle to comprehend not only the disaster but the language in which recovery planning usually takes place brings their needs to greater visibility. Watching an individual with a disability navigate disrupted terrain speaks to recovery planners who see the value of accessible tornado shelters. Going to people where they live, work and gather—involving their trusted social networks (e.g., family as well as faith, community and business leaders)—in recovery planning brings the pre-disaster lived experiences of higher risk populations to the post-recovery planning table.

Envision, for example, the outcomes of such participatory stakeholder recovery planning efforts:

- Identification of high risk populations typically not considered including pre-disaster homeless.
- Warning messages issued in multiple, local languages that understand and incorporate variations across meanings in terminology and sign language.
- A broader set of warning strategies beyond sirens (or re-crafted messages) that build on the long tradition of social science warning research. Warning messages must link message content to the social networks that disseminate and confirm information.
- Evacuation planning for high risk populations including those at domestic violence and homeless shelters, skilled nursing and assisted living facilities, and schools that serve individuals with varying disabilities. High rise buildings are a particular concern.
- Community-based evacuation planning for non-English speaking populations.
- Accessible underground shelters for people with mobility disabilities.
- Congregate safe rooms for mobile home parks.
- Workplaces that protect customers and staff beyond the routine first aid kids, CPR-designated employees, and basic signage to conduct drills and exercises during business hours and direct those present to sturdy areas of refuge.

- Infrastructure including roads, bridges, ports, and rails fully accessible and designed to expedite evacuation of high risk populations.
- Using the post-disaster period to implement mitigation plans such as placing utilities underground where possible and economically feasible to reduce future impacts.
- Providing accessible weather radios to high risk populations through donated funds.

Post-Event Implementation

Post-event implementation of any recovery plan requires dedicated leaders (elected and appointed), community volunteers, and resources—especially funding. From within the plan, projects must be prioritized and scoped for rapid implementation. Beyond funding, post-event implementation requires, more than anything, a champion to push for action, see the plan to completion, and stay the course through what may be a daunting new reality. Sustaining the vision is key, particularly when competing resources and limited resources thwart efforts to secure a more weather-ready nation. Not to do so, however, simply returns us all to the same risks and losses. It is our neighbors, friends and family members that we seek to save, and to do so, we must serve steadfastly through difficult times. Those who lead communities through recovery must tap into the social capital that exists across their community in order to sustain momentum. Stakeholders must participate in building a more weather-ready nation.

Given the known risks associated with socially and economically vulnerable populations, their risks must be addressed first in order to reduce future impacts. Residents of assisted living and skilled nursing facilities, residents of state-supported facilities (schools, group homes) and pockets of highly vulnerable people (retirement communities or areas of older housing with senior residents) need prioritization for underground utility lines. Such an effort increases their abilities to remain connected to information sources during weather events and to survive in the aftermath. Their dependence on oxygen, motorized devices and assistive technologies requires such prioritization. Populations who typically lack political representation (non-English speaking, lower income families in public housing or mobile home parks) require dedicated attention and advocacy to insure their needs are heard. Pushing for safe rooms, for example, must be a top priority. Those at highest risk must not be thought of as passive participants in the process. Instead, they possess varying kinds of social capital that can be leveraged to provide insight, build collaboration, generate fresh approaches, and link recovery processes to the people likely to suffer the most losses. Strong leaders build collaborative networks that not only reduce future impacts but foster disaster resilience.

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White Paper 7:
Integrating Economics to Improve Tornado Warning and Response

Information about severe weather has economic value primarily in terms of how it affects human behavior (see Letson et al. 2007 on hurricane research; Katz and Lazo. 2011). Tornado forecasts are not free, and establishing their value helps public officials determine if investing in forecast improvements is worthwhile[1]. Economics provides a scientific method to quantify changes in the value to society resulting from changes in the condition or availability of resources. Economists use market and nonmarket information to identify or at least approximately suggest the best choice between alternative options and suggest priorities for decision makers (Lazo et al. 2008). Economics can also help identify unintended consequences of policy decisions, such as the cost of warning areas that are not actually in the path of a tornado. Although popularly many people equate economic value with money, economists interpret value very broadly, meaning all elements of well-being. Thus property damage, loss of life or limb, time spent sheltering, and peace of mind are all components of the value (or cost) of the tornado warning process in the context of this paper. There is a wide range of research methods utilized in economics for the study of human behavior and to support decision making under uncertainty. Thoughtful application of research methods from economics can contribute to life safety and reduce property loss caused by severe storms—especially tornadoes.

This White Paper will focus on the benefits of the tornado warning system, the role of mitigation in reducing tornado impacts, and the effect of losses from convective storms on the insurance industry (including the insurability of such events). Space does not permit discussion of research by economists on other aspects of severe weather, like the impact of tornadoes on a local economy or the recovery of communities after tornadoes. The paper concludes with suggestions for future research. Social science research has to date, been primarily used to validate efforts or investments by the NWS or proposed research by atmospheric scientists. The development of tornado warning systems will generate greatest value to society when it is approached as an integrated process. The integrated process should incorporate social, behavioral, and economic sciences with meteorological research at the earliest stages of development and may even be used to inform research priorities.

The Tornado Warning System

The tornado warning system comprises the series of products beginning with convective outlooks and extending through tornado warnings. The Storm Prediction Center, local National Weather Service Weather Forecast Offices, storm spotters, and local media provide the component products. The system also includes the transmission of these warnings and information through different channels, including NOAA Weather Radio and other emergency alert systems, broadcast (and social) media, and outdoor sirens. Ultimately the system involves the response of stakeholders and the public to this information.

Many authors discuss weather forecasts as public goods or services (e.g., Anaman and Lellyett 1996; Johnson and Holt 1997; Freebairn and Zillman 2002). Public goods and services are non-rival and non-excludable. A good is non-rival when one person's consumption does not diminish another's ability to

[1] It is important that we establish the difference between price and economic value. Items in an accounting for economic value can include the value of: lives saved, injuries avoided, reduction in business interruption, reduction in property loss, peace of mind and many other things of extrinsic and intrinsic importance. The metric commonly used is money since it can be compared directly with the monetary investment required to implement alternatives.

consume the good (e.g., one person knowing a warning has been issued does not diminish anyone else's ability to derive a benefit from the warning). Non-rivalry alternatively means that the cost of supplying the good to one more user is zero. A good is non-excludable if people who do not pay cannot be excluded once the good is provided. Warnings could be sent only to the subscribers of a service and are potentially excludable; this is the basis of private weather forecasting services. But warnings are clearly non-rival with a zero marginal cost of sharing a warning with one more person. The National Oceanic and Atmospheric Administration (NOAA) provides weather forecast products for free on the grounds that forecasts should not be excluded and thus treated as public goods.

Economics has developed a theoretical model to value information (e.g. Laffont 1989) which has been applied widely to value weather forecasts (Katz and Murphy 1997). Convective outlooks and tornado and severe thunderstorm watches and warnings can be evaluated using this model. One economic approach consists of comparing the overall well-being, or what economists call utility, of recipients with and without information. The value of information most typically arises from the actions people take upon receipt of the warning. In the case of tornadoes, the action generally would be moving to a safe (or safer) location upon receipt of the warning and shelter until the threat has passed. The value of information also depends on the accuracy of the information (the probability of detection and false alarm ratio for tornado warnings), the value of the response action, and the cost of the response action. Improved warnings or information are valued using the same approach by considering the net benefits (or improvement in well-being) with the new as opposed to old warnings or information. Given the time horizon involved with the tornado warning process, warnings primarily serve to protect persons from injury, although some efforts could be made to protect property (e.g., moving cars into garages to prevent hail damage, or taking jewelry, important papers or other valuables into a safe room). To date, research has focused on the life saving benefits.

Public goods theory also provides another perspective on the value of tornado warning information. Many approaches are available to estimate the value public goods, including physical linkage (or damage function) methods, revealed preference methods, and stated preference methods (Champ et al. 2003, Mueller, 2003). Revealed preference methods include travel cost, averting behavior, hedonic prices, and the production function approach. Stated preference methods include contingent valuation, contingent behavior, and conjoint analysis. Stated preference methods use hypothetical data from surveys to estimate willingness to pay for public goods. Revealed preference approaches use actual choices, which economists view as a strength, but must rely on behavioral trails in the market. Stated preference approaches offer flexibility, can be used when there is no market data, and can value options that do not currently exist. The hypothetical nature of survey choices leads to concerns over the reliability and validity of stated preference methods. Carson et al. (1996) reviewed comparisons between stated and revealed preference method results (primarily travel cost and hedonic prices) for valuation of comparable quasi-public goods and conclude that the stated preference results are comparable to the revealed preference results. Stated preference methods have been used to value daily weather forecasts (Lazo 2008. Lazo et al 2009) and hurricane forecast information (Lazo et al. 2010), but not applied to date to tornado warnings. The stated preference method could be used to value changes in forecast accuracy, improved communication approaches, or even impacts such as the value of warnings in reducing (or creating) anxiety among residents. Expenditures by the public on NOAA Weather Radios or private sector alert products allow application of powerful techniques combining revealed and stated preferences (Louviere et al. 2000, Whitehead et al. 2008).

Detailed records of tornado events and warnings (NOAA warning verification records date to 1986) exist, and statistical analysis can and has been applied to determine if warned tornadoes result in fewer fatalities or injuries than unwarned tornadoes, or if longer lead times further reduce casualties.[2] Sufficient variation in contemporary warning performance exists to allow estimation of an econometric model.[3] Warnings are just one factor affecting the number of casualties expected to occur in a tornado, and so the analysis must control for other relevant factors like the rating of a tornado on the Enhanced Fujita scale, the length of the damage path, and the population of the path area. Such statistical methods control for NWS warnings but do not measure or control for warning response directly. Consequently these methods test for a joint effect of the warning and response to warnings.

Simmons and Sutter (2011, see Chapter 4 for a summary) established that warnings significantly reduce both fatalities and injuries. The greatest reductions in fatalities and injuries (40 to 50 percent relative to a tornado with no warning) occur for warnings with lead times of 6 to 15 minutes. Lead times beyond 15 minutes do not appear to produce additional reductions in fatalities or injuries, nor does whether a tornado occurs within a valid tornado or severe thunderstorm watch. A higher local, recent false alarm ratio increases fatalities and injuries, consistent with a cry wolf effect.[4] The NWS appears to be balancing the probability of detection with the false alarm ratio to minimize tornado casualties. Research also establishes a number of patterns in casualties that may be related to the warning process. For instance, tornadoes at night are substantially more deadly than comparable tornadoes during the day (see also Ashley et al. 2008), which is likely further evidence of life saving effects of the warning process. Substantial variation in tornado casualties occurs across months of the year and regions of the nation, even when controlling for other factors, which may be related to differences in warning response. Lastly, coverage by local broadcast meteorologists appears to reduce casualties in addition to the effect of NWS warnings, reinforcing the warning process (Simmons and Sutter 2012a).

The tornado warning process might also produce several other types of societal and economic[5] benefits not examined to date. For instance, emergency managers use convective outlooks and tornado watches and warnings, and the tornado warning process might allow assistance to reach affected communities more quickly after a disaster. Tornado warnings can both create and reduce anxiety: anxiety occurs when sirens or Weather Radios go off to announce a threat, while the absence of a warning can reduce anxiety that a menacing thunderstorm is about to spawn a tornado (Stewart 2009). Tornadoes and severe thunderstorms can disrupt business operations and logistics, and businesses may be using warnings and other information to minimize these impacts. Finally, many school districts now cancel classes when tornadoes threaten, which is another use of warning process information.

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[2] Economic methods can be used to assess the value of information about tornado events as well as to evaluate potential improvements in the quality of data collected about tornadoes – especially if analysis of tornado impacts is based on potentially faulty data about measures such as tornado track or intensity.

[3] "Econometric" modeling is basically statistical analysis usually applied to economic data. Given advanced statistical methods used in econometrics these approaches are often used on "non-economic" data as well.

[4] The potential existence of a "cry wolf" effect is an empirical question that has not been adequately research or evaluated to permit policy decisions or broad statements to be made about behavioral response with respect to warnings (Dow and Cutter, 1998)

[5] While economists do not distinguish specifically between societal and economic benefits (all societal benefits are essentially economic benefits), we use this phrase to suggest that benefits are not only monetized as many people consider "economic" benefits to refer to.

Value of Improvements in the Tornado Warning System

Tornado warnings could be improved in numerous different ways, including longer lead times, an increased probability of detection, a reduced false alarm rate, improved path forecasts, and a reduction in the area warned. Warnings could also begin to convey completely new types of information, for instance, the strength of a tornado. Other elements of the warning process like watches or convective outlooks could be improved. Economic research tools can be used to demonstrate retrospectively the value of prior modifications in the warning process or project the value of different types of warning process improvements.[6]

The net value of the warning process depends on the societal impacts avoided and cost of actions taken to reduce impacts. Consequently improved warnings and information can create benefits to society either by further reducing impacts or by reducing the cost of actions taken to reduce impacts. NWS installation of the network of Doppler weather radars by the NWS in the 1990s improved tornado warnings and reduced casualties (Simmons and Sutter 2005), yielding benefits of the first type. The introduction of Storm Based Warnings (SBW) for tornadoes nationwide by the NWS in 2007 reduced the time spent nationally under tornado warnings without compromising safety (Sutter and Erickson 2010). SBWs reduced the cost of protective actions and represent the second type of benefit.

Empirical research on the effect of severe weather warnings on impacts can be used to estimate benefits from improvements, presuming that improved warnings will be used in a similar manner as current warnings, only with better quality information. For instance, if a tornado warning reduces casualties by 40% relative to an unwarned tornado, the value of an improvement in the probability of detection can be a straight-forward calculation. Sometimes, however, improved warnings will allow people to take actions not currently feasible given current warnings. Longer lead times combined with better path forecasts may allow residents to move to a community shelter. Stated preference methods may be particularly useful in valuing such warning improvements. Economists generally assume that protective actions and warning response exhibits diminishing marginal returns, so that five minutes of lead time relative to no warning will save more lives than five minutes added to a 20 minute lead time. Because new types of response actions can become feasible, the law of diminishing returns may not hold with respect to every increase in lead time.

The value of an improving one component of the warning system is not independent from improvements in other components. We might estimate that improved lead time for tornado warnings might be worth $40 million per year while an improvement in one day convective outlooks worth $20 million per year. One might presume that both improvements together would be worth $60 million per year, but this might not be so. Each of these estimates is generated likely through an analysis holding other components of the warning system constant. Generally various types of information will be substitutes, and several simultaneous improvements will not be worth as much together as the sum of each separately. Consequently potential improvements in severe weather warning information must be evaluated as a package to ensure that one research project does not render another irrelevant.

Tornado Shelters

[6] Economic methods can also be used to value investments in research to improve forecasts (Lazo et al. 2010).

The warning process succeeds if residents threatened by a tornado receive and respond to a warning by taking shelter. The availability of places to shelter and survive a tornado determines in part if the warning process saves lives. The key in saving lives is relative safety: as long as people shelter in a relatively safe place, casualties will be reduced. Tornado shelters or safe rooms provide a very high level of safety for residents, while mobile homes can be destroyed by even weak tornadoes. Most site-built homes and commercial and other engineered buildings provide adequate shelter for a majority of tornadoes, but can be destroyed by violent tornadoes.

Tornado shelters have been valued using the physical linkage, revealed preference (Simmons and Sutter 2007a,b), and stated preference methods (Ozdemir 2005, Ewing and Kruse 2006). Thousands of homeowners have purchased shelters and reveal by this decision that they estimate the benefits to be greater than the cost. But the proportion of homes with shelters is small even in tornado prone regions. Research shows that people often ignore or under prepare for low probability events like natural hazards (Meyer 2006, Camerer and Kunreuther 1989), and tornado shelters may be another instance of such behavior. If so, there may be a rationale for public policies like subsidies, tax credits or mandates to encourage greater adoption of shelters. Tornado shelters in permanent homes save relatively few lives because of the relative protection site-built homes provide but appear to be a key in reducing tornado fatalities in mobile homes (Simmons and Sutter 2011, Chapter 5). Many mobile home parks in traditional tornado alley states like Kansas and Oklahoma offer community shelters for residents, but the southeastern states where the mobile home fatality problem is worst have lagged behind (Schmidlin et al. 2001)

Shelters have potentially significant interaction effects with the tornado warning system. The warning system will save lives only if people can find adequate protection when warned, and wider adoption of shelters will save lives. The complementarity of lead time and adequate shelter is only true up to a point. Lives saved through improved warnings and warning dissemination reduce the cost effectiveness of shelters. In addition, widespread adoption of shelters could reduce the benefits of longer lead times for tornadoes implying that past a certain threshold warnings and shelters become substitute risk reduction measures.

Property Damage: Could Insurers Stop Covering Tornado Losses?

Insurance, as a market mechanism, can also play an important role in (a) signaling the level of risk individuals and businesses face (if prices can reflect the risk); (b) providing reward to those who undertake some risk reduction measures to lower their exposure (i.e. lower premiums, lower deductibles, higher limits, less exclusions).

Thirty years ago, large-scale natural disasters were considered low-probability events. Hurricane Hugo, which struck South Carolina in September 1989, was the first natural disaster in the United States to inflict more than $1 billion of insured losses. Times have changed. Today, large-scale disasters have triggered unprecedented levels of insurance payment. The 25 most costly insured catastrophes anywhere in the world between 1970 and 2011 all occurred after 1987, with two thirds just since 2001 (2011 prices; Kunreuther and Michel-Kerjan, 2011).

Until very recently, tornadoes were not usually considered one of the larger risks for the insurance industry. But the 2011 U.S. tornado season, which inflicted over $20 billion in economic losses[7], would rank as the fourth-costliest disaster for insured losses in U.S. history. That has clearly put tornado losses

[7] Simmons et al. (2012) show that the 2011 tornado season ranks third since 1950 in normalized damage.

on the disaster risk financing agenda. If experience from other catastrophe insurance lines offers some insight, the *insurability* of tornadoes will soon have to be revised. That is, how much should be covered, at what price, where? Where should premiums be increased, by how much and where could some insurers simply refuse to cover homeowners anymore?[8]. This might have serious implications for those living in tornado-prone areas of the country. Advanced research in that field is urgently needed to better evaluate the most effective and sustainable financial solutions to be implemented locally, state-wide and at a national level.

Directions for Future Research

Economics possesses a rich array of methodologies that can be applied to analyze the impacts of tornadoes and the value of current and future warning systems broadly conceived. At least three types of research could be conducted in the next several years, and each could be broadened to include thunderstorms (or all weather and weather information processes) in addition to tornadoes. One set of research projects could quantify the benefits of the warning system not tied to safety. Emergency managers, school districts and private businesses all also use warning information in ways that may produce other benefits.

A second set of research projects could quantify and offer guidance on improvements in the tornado warning process. Two directions for improvement are warn-on-forecast, offering the potential for lead times of one hour or more, and reducing the area warned and warning window, as occurred with Storm Based Warnings. Research indicates that refining the area warned offers substantial benefits, while lead times beyond 15 minutes (including tornado watches) do not appear to further reduce casualties, but additional research could provide more specific guidance.

A third set of research projects could assess the value offered by new and different types of tornado information and forecast products. Localized tornado climatologies or probabilities of damage from strong or violent tornadoes could aid in decisions for strengthened construction, shelters, and insurability of tornado losses. Seasonal, regional forecasts could also assist with reducing property damage, or climatological outlooks of a week or longer.

(Re)statement of the Need for Integrating Social, Behavioral and Economic Science Research

While this has been stated and restated many times it bears repeating that unfortunately social, behavioral, and economic science (SBE) research is often only brought in at the end to validate the benefit to society of research by meteorologists. Meteorological research on convective storms will generate the greatest value to society only to the extent that cross-fertilization occurs between SBE sciences and atmospheric science research to address fundamental issues with respect to the communication, reception, understanding, use, and value of meteorological information (e.g., tornado warnings).

[8] A similar re-evaluation of the insurability by the private market alone happened after all major disasters in the United States (Hurricane Andrew in 1992, the Northridge earthquake in 1994, the 2001 terrorist attacks, the 2004-2005 hurricane seasons). Every time this led to a modification of the risk-sharing arrangement between exposed homeowners and business and the public and private sectors. (Michel-Kerjan, 2010; Michel-Kerjan and Kunreuther, 2011).

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White Paper 8:
Hazard Mitigation (Safety Rooms and Shelters)