Workshop on Weather Ready Nation:
Science Imperatives for Severe Thunderstorm Research,
Held 24-26 April, 2012 in Birmingham AL

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Executive Summary

The National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF) workshop sponsored a workshop entitled *Weather Ready Nation: Science Imperatives for Severe Thunderstorm Research* on 24-26 April, 2012 in Birmingham Alabama. Prior to the workshop, teams of authors completed eight white papers, which were read by workshop participants before arriving at the conference venue. The workshop's 63 participants—representing the disciplines of civil engineering, communication, economics, emergency management, geography, meteorology, psychology, public health, public policy, sociology, and urban planning—participated in three sets of discussion groups. In the first set of discussion groups, participants were assigned to groups by discipline and asked to identify any research issues related to tornado hazard response that had been overlooked by the 2011 Norman Workshop report (UCAR, 2012) or the white papers (see Appendix A). In the second set of discussion groups, participants were distributed among interdisciplinary groups and asked to revisit the questions addressed in the disciplinary groups, identify any interdependencies across disciplines, and recommend criteria for evaluating prospective projects. In the third set of discussion groups, participants returned to their initial disciplinary groups and were asked to identify and describe at least three specific research projects within the research areas defined by their white paper(s) and to assess these research projects in terms of the evaluation criteria identified in the interdisciplinary groups. Each set of group discussions was followed by a plenary session in which a group member provided a brief oral report on the major findings from her or his group's discussion.

The major issues identified within each of the areas defined by the eight white papers were consistent with the recommendations in reports from previous workshops and committees. However, the recommendations from the Birmingham workshop were more detailed and led to 12 specific research recommendations—a) Physical Understanding for Improved Forecasts, b) Wind Effects on Buildings, c) Forecasters' Construction of Warning Polygons, d) Effects of False Alarms on Warning Recipients, e) Effects of Warning Message Content and Warning Context on Population Response, f) Laboratory and Web Experiments on Warning Messages, g) Antecedents of Household and Business Tornado Preparedness, h) Preparedness and Response by Vulnerable Populations, i) Pre-Impact Planning for Post-Impact Community Recovery, j) Tornado Mitigation Adoption, k) Contingent Valuation of Tornado Warning Parameters, and l) Social Science Short Course for Weather Forecasters. Each of these proposed projects is described in terms of its rationale, expected benefits, scope, duration, staffing and budget, and probability of near-term payoff.

In addition, the workshop participants echoed the recommendations of previous workshops and committees in recommending an increase in the number of social scientists who work closely with NWS meteorologists at all levels of the agency. Social scientists can contribute to many aspects of the NWS mission—from staffing, training, and job design all the way through the design of warning messages and the assessment of community weather resilience. Their contributions will be most effective if they are in daily contact with NWS staff ranging from forecast meteorologists to senior administrators.

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Introduction

The National Oceanic and Atmospheric Administration and the National Science Foundation Workshop sponsored a workshop entitled *Weather Ready Nation: Science Imperatives for Severe Thunderstorm Research* on 24-26 April, 2012 in Birmingham Alabama. Prior to the workshop, teams of authors completed eight white papers, each of which was approximately five single-spaced pages. These topics were 1) Physical Understanding for Improved Forecasts, 2) Forecast and Warning Process, 3) Individual/Household Behavioral Response, 4) Population Segments with Disabilities, 5) Household Emergency Preparedness, 6) Pre-Impact Planning for Disaster Recovery, 7) Economic Analysis of Tornado Warning Systems, and 8) Hazard Mitigation (Safety Rooms and Shelters). Each white paper, which was produced in approximately six weeks, briefly summarized the state of the science in that area and made some preliminary research recommendations. All eight papers were distributed before the workshop so participants would have the basic background information about each area that they would need for productive discussions of interdisciplinary issues. This allowed the participants to devote two full days to small group discussions, presentation of group summary reports, and plenary discussion of the group summary reports.

Workshop Activities

The workshop had 63 participants representing the disciplines of civil engineering, communication, economics, emergency management, geography, meteorology, psychology, public health, public policy, sociology, and urban planning. The workshop began on Tuesday morning with a plenary session involving a welcome by Dr. Kathryn D. Sullivan, a summary of Norman Workshop by Steven Koch, and self-introductions by the participants. After a short break, participants reassembled in six breakout groups that corresponded roughly to the eight white paper topics. Because of limitations on the number of groups and the small number of participants who specialized in the areas corresponding to White Papers 4, 6, and 8 (population segments with disabilities, pre-impact recovery planning, and hazard mitigation), participants in these three areas were combined into a single group. The six groups were asked to discuss the Norman Report (http://www.joss.ucar.edu/events/2011/weather_ready/information.html) and their group's white paper(s), identify neglected issues and research needs *within* the research areas defined by their white paper(s), and prepare a ten minute plenary presentation summarizing their group's discussion and recommendations. After three hours of discussion, all participants returned to a plenary session in which the leaders of each of the six discussion groups presented their group summaries. After group summaries had been completed, there was a general discussion—following which the workshop was concluded for the day.

On Wednesday morning, participants moved to interdisciplinary discussion groups to which the workshop organizers had assigned them. The interdisciplinary groups were asked to review the Norman Report, the white paper(s), and the Disciplinary Group Round 1 reports; identify any issues and research needs that had not been identified within any of the research areas; and identify any interdependencies *between* research areas that would be potential impediments to the implementation of other research areas. They were also asked to identify project evaluation criteria (e.g., research funding and other resource requirements, time to research completion, time to implementation, implementation barriers (e.g., interagency and intergovernmental issues), and any other criteria that research administrators should consider in evaluating these research projects; and prepare a ten minute plenary presentation summarizing their group discussion and recommendations. As with Disciplinary Group Round 1, each group engaged in three hours of discussion and then reconvened for a plenary session comprising presentations from each of the group leaders followed by a general discussion.

Late Wednesday afternoon, participants returned to the same disciplinary groups in which they had participated in Disciplinary Group Round 1 on Tuesday. Participants were asked to discuss the reports from Disciplinary Group Round 1 and the Interdisciplinary Groups; identify and describe at least three specific research projects within the research areas defined by their white paper(s); and assess these research projects in terms of the evaluation criteria identified in the interdisciplinary groups. They continued these discussions on Thursday morning, after which they reconvened for a plenary session comprising presentations from each of the group leaders and a general discussion.

The next section of this report provides some context for the findings of the Birmingham workshop by reviewing some of the National Weather Service (NWS) social science research needs and administrative recommendations addressed in previous workshops or reports. The following section summarizes the research issues and organizational recommendations identified in the Round 1 disciplinary groups and Round 2 interdisciplinary groups. It is important to note that these discussions focused mostly on issues at the interface of different disciplines, especially the relationship between the meteorological and social/behavioral sciences. The last section of this report provides relatively detailed descriptions of 12 research projects that were proposed by the workshop participants and, where necessary, supplemented by the editors.

Research Agendas From Previous Workshops

The National Research Council Board on Atmospheric Sciences and Climate conducted a workshop on *Communicating Uncertainties in Weather and Climate Information* that examined some of the lessons learned from five case studies illustrating the challenges in communicating meteorological information to decision makers (NRC, 2003). Workshop participants identified a number of practical recommendations, many of which focused on the importance of addressing uncertainty in communicating with the public. This issue of incorporating uncertainty into weather forecasts was later emphasized by the National Research Council *Committee on Estimating And Communicating Uncertainty In Weather And Climate Forecasts* (NRC, 2006).

OFCM (2010) identified six major thematic areas for social science research to support meteorological operations and services. Briefly, social science support on risk communication was expected to identify more effective ways of communicating uncertainty and reaching vulnerable population segments. It could also identify ways to achieve widespread understanding of key meteorological terms such as watches and warnings, as well as evaluate graphics used in video presentations. An end-to-end analysis would examine technological and administrative mechanisms for transmitting warnings and other weather information, whereas decision support systems would develop improved technologies to support decision makers such as state and local emergency managers and elected officials, as well as senior managers in private sector and non-governmental organizations. Research on knowledge transfer would overcome disciplinary “stovepipes” by disseminating relevant social science knowledge by identifying and enhancing communication between physical and social scientists. Vulnerability assessment/economic valuation would assess economic impacts and the value of improved forecasts; partnerships would promote vertical linkages across different levels of government and horizontal linkages among different government agencies, businesses, and non-governmental organizations).

Finally, UCAR (2012) reported the results of a 2011 Norman Oklahoma workshop entitled *Weather Ready Nation: A Vital Conversation on Tornadoes and Severe Weather*. This workshop identified a number of actions that the NWS could take to improve the nation's readiness for tornadoes. The principal research-related recommendations can be categorized into the areas of emergency preparedness/response, hazard mitigation/disaster recovery, and multipurpose activities. Within the area of physical science contributions to emergency preparedness/response, participants advocated conducting a needs analysis for weather observation technologies and identifying the physical variables that determine tornado genesis and tornado parameters such as intensity, size, track, forward movement speed, and duration. They also emphasized the need for achieving physical science advances that reduce false alarms without reducing the probability of detection or lead time.

Another recommendation for emergency preparedness/response involved identifying the most appropriate warning procedures so NWS forecasters, WFOs, and broadcast meteorologists can standardize (to the extent this is appropriate) throughout the country. Participants also advocated identifying ways to increase warning dissemination as well as warning comprehension and perceptions of risk by developing "clear, consistent, and concise" (UCAR, 2012, p. 7) warning messages. Another recommendation was that NWS conduct a systematic evaluation of warning channels—such as commercial radio and television, NOAA Weather Radio, sirens, Reverse 911, Commercial Mobile Alert System (CMAS)—that differ with respect to their precision of dissemination, penetration of normal activities, specificity of the message, susceptibility to message distortion, rate of dissemination over time, receiver requirements, sender requirements, and feedback (for a discussion of these characteristics, see Lindell & Perry 1992, pp. 109-113; Lindell & Prater, 2010; NRC, 2011).

Participants also recommended assessing the expected social and economic consequences of incremental improvements in tornado warnings (e.g., length of forewarning, probability of detection, false alarm rate). Such assessments should recognize that length of forewarning is determined by rate (and asymptote) of warning dissemination (the distribution over households of the length of time between the initiation of public warnings and warning receipt) as well as forecast lead time (the length of time between tornado detection and the initiation of public warnings). They also should recognize that warning messages are constrained by the information transmission capacity of a warning mechanism. Specifically, mechanical sirens can only alert people that there is danger whereas television can provide verbal, numerical, and graphical information. In addition, there should be an assessment of pre-impact public education programs so it will be possible to determine which programs have been implemented and how cost-effective they have been.

In the area of hazard mitigation/disaster recovery, workshop participants identified a need to develop a better understanding of surface level wind and how it affects buildings. This knowledge could be used to develop more cost-effective methods of retrofitting existing structures that would enhance their wind resistance and to identify more cost-effective methods of constructing safe rooms and shelters. Participants also indicated a need to identify ways to use regulations (e.g., building codes) and incentives (e.g., tax credits) to promote implementation of tornado-resistant retrofits, incorporation of tornado-resistant construction into new structures, and construction of safe rooms and shelters. In addition, there is a need to define community resilience, identify specific indicators for measuring it, and incorporate these indicators into the criteria for designation as *StormReady* communities. Finally, participants in the Norman workshop also identified some activities that would achieve multiple purposes, such as establishing post-storm assessment teams.

Research Issues

The major issues identified in the Birmingham workshop are categorized below in terms of the eight white paper topics. A number of these issues crossed disciplinary lines and, thus, were discussed in more than one of the disciplinary groups. Consequently, the allocation of issues to groups is somewhat arbitrary.

Physical Understanding for Improved Forecasts

The principal point of discussion on this issue was the need for advances in meteorological theory and observational methods that would result in a better understanding of the causes of missed events (i.e., improved probability of detection) and a reduction in the number of false alarms. In addition, workshop participants identified a need for research that would result in a better understanding of wind effects on structures.

Forecast and Warning Process

Most of the groups called attention to the need to improve forecast accuracy and one important research topic related to this need is an investigation of the utility of new storm observation platforms—ranging from storm penetrating aircraft to instrumentation of personal vehicles.

Participants also proposed studies of forecaster staffing and training, as well as the identification and dissemination of "best practices" in local NWS offices. In particular, there is a need for behavioral research on forecasters' judgment and decision processes (e.g., cognitive task analysis, see Crandall, Klein & Hoffman, 2006) and the ways these processes differ across individuals and regions. This includes a need to examine variation among forecasters in the probabilistic meaning of their warning polygons (i.e., do individual forecasters intend the boundaries of their warning polygons to correspond to a 75%, 90%, 99% or other confidence interval—or do they even think of warning polygons in these terms?). Such research could explain the experiential bases for inter-forecaster variation and suggest training and procedural bases for polygon construction.

Because of continuing advances in technology, there is a need for research on the relationships among warning channels (NOAA Weather Radio, Emergency Alert System, Integrated Public Alert and Warning System/Commercial Mobile Alert System, sirens, commercial broadcast and print media, websites). Do these channels generally transmit consistent messages and, if not, how do warning recipients resolve inconsistencies? There is a related concern about issues in warning message/channel compatibility such as an inability to transmit spatial information (e.g., warning polygons) via radio or telephone text messages.

Two points that emerged from the discussions were the need for a better understanding of non-meteorological aspects of the warning process and the need for a better understanding of how NWS warnings fit into the multitude of warning sources/messages. Although more social science research should be conducted on these topics, much is already known that could be incorporated into weather forecaster training programs.

Individual/Household Behavioral Response

Forecast characteristics such as timeliness and accuracy have significant behavioral implications, so there is a need to better understand the consequences of current and increased levels of forewarning (i.e., by increasing lead times). Specifically, does more forewarning necessarily reduce casualties and other storm impacts or are there response constraints such as lack of access to safe rooms and shelters that negate the usefulness of increases in forewarning? Do population segments differ in their ability to make use of increased forewarning? Systematic simulation studies should be conducted that model risk area populations' level of forewarning along with their access to structures having different effectiveness to better understand the degree to which increased forewarning can reduce storm impacts. Moreover, there is a need for better understanding of the ways in which population segments with disabilities are constrained in warning receipt and protective action implementation.

Workshop participants in most of the groups identified a need for a better understanding of the ways in which users interpret forecasts and warnings. Major issues are users' interpretations of meteorological uncertainty; their definitions of false alarms (and, more broadly, warning accuracy); and their interpretation of the forecasters' intended representation of uncertainty in warning polygons. In particular, research is needed that involves cognitive analysis of people's warning message interpretation. Such research should examine the transmission of threat information in different formats such as probabilistic/quantitative (wind speed probability and tornado strike probability) vs. deterministic/qualitative (watch/warning) messages. Research that systematically examines the cognitive demands and behavioral consequences of verbal ("very likely" vs. "very unlikely"), numeric (probabilities or odds ratios), and graphic ("confidence/credibility intervals" or isoquants) information would be extremely valuable in developing alternative warning messages. The need for such cognitive research is consistent with some workshop participants' calls for increased laboratory experimentation to examine people's interpretation of forecast and warning products.

In addition to achieve better integration of social science research with current and future forecast/warning products, there is also a need for better integration of social science and epidemiological approaches to post-disaster surveys. Such integration would provide a deeper understanding of the relationships of social and cognitive processes with outcomes such as deaths and injuries.

Individual Differences Across Population Segments (Including Those with Disabilities)

Participants indicated there is a need to identify and understand weather information user groups. A proposed preliminary typology is weather specialists (NWS and private sector meteorologists), emergency managers for communities and facilities (utility, school, hospital, nursing home), the general public (individuals/households in different types of structures at home and work), tourists and other transients, and underserved populations (e.g., population segments with cognitive and physical disabilities). Research needs to identify people's sensory (e.g., sight and hearing), cognitive (especially probabilistic information processing), and physical (e.g., walking distance and speed) limitations and assess the implications of these limitations for receiving, interpreting, and acting on warnings. Such research also needs to assess these population segments' current level of knowledge and, thus, their training needs, as well as identifying optimal protective action for different population segments in different situations.

Household Emergency Preparedness

Research proposed in this area included a better conceptualization and operationalization of fundamental concepts such as community emergency preparedness (i.e., what do communities and households need to do to become storm ready other than the criteria required by the NWS *StormReady* program?—see www.stormready.noaa.gov/guideline_chart.htm) and to identify the antecedents of household, organizational, and community emergency preparedness. To the degree that emergency preparedness is determined by people's beliefs about hazard adjustments (e.g., the effectiveness and cost of safe rooms) as well as their beliefs about weather hazards (i.e., risk perception), investments in public education programs can reduce impacts of weather disasters. However, there may be little that can be done to increase emergency preparedness if it is largely determined by demographic characteristics, which are difficult or impossible to change. There is also a need to better understand the organizational and institutional contexts, such as a local culture of disaster preparedness, within which preparedness occurs.

Pre-Impact Planning for Disaster Recovery

Research in this area needs to define and measure fundamental concepts such as disaster impacts (which are not limited to deaths and injuries, but also include psychosocial, sociodemographic, economic and political impacts, see Lindell, Prater & Perry, 2006, Chapter 6) and community recovery (e.g., how do we assess the level of recovery, the speed with which it is achieved, the distribution of levels of recovery across different population segments, and the degree to which hazard mitigation is incorporated into the recovery process?). There is also a need to develop a repository of better data on storm impacts to support the risk/cost/benefit analyses needed to support policy decisions. In addition, research needs to better explain the factors that determine people's purchase of hazard insurance, the extent to which insurance purchase substitutes for hazard mitigation and emergency preparedness actions, and the role of insurance in the disaster recovery process.

Economic Analysis of Tornado Warning System

Some participants advocated conducting a comprehensive probabilistic, multi-disciplinary risk analysis of high-impact/life threatening weather. This would be an end-to-end analysis that begins with the detection of tornado conditions and follows through the entire forecast, warning dissemination, and protective response process. Such a study would be consistent with other workshop participants' call for an assessment of the economic value of current and alternative warning systems because it would yield a better understanding of public information needs and the most (cost) effective ways to disseminate that information. These comprehensive studies should also expand the criteria for forecast evaluation from forecast error probability (i.e., false alarm rate and probability of detection) to expected forecast error cost (i.e., probability times consequences).

Hazard Mitigation (Safety Rooms and Shelters)

Research in this area should involve a systematic analysis that examines the benefit/cost tradeoffs for individual/community investments in shelters and safe rooms. A related concern for voluntary construction of shelters/safe rooms is the identification of barriers to implementation such as cost (including financing) and constructor expertise. Alternatively, there are concerns about the likely rate of adoption/implementation of building codes that require construction of shelters/safe rooms and the secondary impacts that required shelter/safe room construction would have on housing affordability for different types of housing—single family, multi-family, and mobile/manufactured housing.

Organizational Recommendations

The discussion groups consistently recommended that NOAA/NWS and NSF place an increased emphasis on the formation of interdisciplinary teams in addressing a variety of research needs. One such need is for systematic quantitative evaluation of existing and emerging detection/forecast/warning systems. For existing systems, interdisciplinary teams could perform rapid post-storm assessments that include the collation and archiving of incident data from multiple agencies; collection of perishable data on storm damage, casualties, behavioral response (e.g., warning reception, risk perception, information seeking, and protective response), and social impacts (i.e., psychosocial, sociodemographic, economic, and political). For emerging forecast/warning systems, interdisciplinary program evaluations should be conducted during all stages of system development including conceptual design (usability analysis), implementation (formative evaluation), and operation (summative evaluation).

Some workshop participants proposed greater institutionalization of social/behavioral science approaches to weather risk management by establishing what one group characterized as a NOAA Directorate of Human Dimensions of Weather. This proposal is quite similar to a recommendation of the SAB/SSWG (2009, p. 7) that NOAA establish an Office of Societal Impacts. It is also similar to Recommendation 2.4 of the National Research Council *Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts* which stated "NOAA should acquire social and behavioral science expertise including psychologists trained in human cognition and human factors, with training in behavioral decision theory, statistical decision theory, survey design and sampling, and communication theory, with special focus on graphics and product development" (NRC, 2006, p. 86). Finally, this recommendation was also echoed in a 2011 workshop in Norman Oklahoma—*Weather Ready Nation: A Vital Conversation on Tornadoes and Severe Weather* (UCAR, 2012).

Participants in the Birmingham workshop suggested that a NOAA Directorate of Human Dimensions of Weather provide social science support to research, development, test and evaluation for a wide variety of NWS operations and products. Previous reports have suggested that these social scientists should work with physical scientists in multidisciplinary centers and should also work with forecast meteorologists on a daily basis to gain a better understanding of the ways in which social science research can contribute to meteorologists' tasks. A related initiative would be to establish a standing social science advisory committee or to incorporate a significant social science component into any existing science advisory committees. This is similar to a previous recommendation by the SAB/SSWG (2009, p. 7) for a NOAA Council of Social Science Advisors. Many workshop participants are aware that NOAA does have some social science support from the Societal Impacts Program at the National Center for Atmospheric

Research. This organization has done an excellent job but it is too small to adequately represent all of the social sciences and the ways in which they can contribute to a more effective weather enterprise.

Workshop participants recommended that proposals for weather-related social science research be evaluated on the degree to which they were likely to produce operational processes or products that met the following criteria: a) feasible amount of resources required (dollars, cross-disciplinary personnel, adequacy of data), b) short time to research completion, c) short time to research results implementation, d) avoidance or successful management of barriers to implementation (e.g., legally-defined organizational domains, pre-existing conceptualizations/organizational culture, legal constraints on public/private partnerships, budget constraints, duplication of efforts/lack of knowledge sharing), e) institutionalization (formation of cross-disciplinary consortia to address specific charges—aka communities of practice, and f) impact on other research projects and operational programs.

Research Recommendations

Based upon the presentations from the discussion groups, the editors compiled the following list of projects.

A. Physical Understanding for Improved Forecasts
B. Wind Effects on Buildings
C. Forecasters' Construction of Warning Polygons
D. Effects of False Alarms on Warning Recipients
E. Effects of Warning Message Content and Warning Context on Population Response
F. Laboratory and Web Experiments on Warning Messages
G. Antecedents of Household and Business Tornado Preparedness
H. Preparedness and Response by Vulnerable Populations
I. Pre-Impact Planning for Post-Impact Community Recovery
J. Tornado Mitigation Adoption
K. Contingent Valuation of Tornado Warning Parameters
L. Social Science Short Course for Weather Forecasters

In the following section, each of these projects is discussed in terms of its rationale, expected benefits, and a general description of the project scope. Each project is also described in terms of its expected duration, staffing and budget, and probability of near-term payoff for an initial project in that area. Some projects, such as Project A *(Physical Understanding for Improved Forecasts*), will almost certainly require multiple grant cycles to produce useful results. At the other extreme, Project L (Social Science Short Course for Weather Forecasters) can be completed within a single grant cycle. The other proposed projects—Projects B through K—are likely to achieve significant advances within a single grant cycle but will undoubtedly raise questions that will require further research. The termination point for these other projects will need to be assessed as research evidence accumulates. In generating project budget estimates, the major cost assumptions common to all projects are that the PI (and Co-PI, if included) salaries will be approximately $13.3K/month and faculty fringe benefits are approximately 17% of salaries plus $500/month for health insurance. It is assumed that GRA salary is approximately $3.3K/month, with fringe benefits of approximately 10% plus $400/month for health insurance and $10K per year in tuition support. The General and Administrative expense (indirect cost or overhead) is assumed to be 46% of total direct costs.

One consistent recommendation from the workshop participants was to encourage research by multidisciplinary teams. One way that NOAA and NSF Program Directors can achieve this goal is to approve larger budgets for research teams that have members from multiple disciplines. For example, an additional one month per year over a three year project would support a meaningful contribution by an additional researcher.

Although these 12 projects are presented separately, there is considerable potential for cross-fertilization if the NWS and NSF concurrently fund multiple projects as a single program (much as with the *Communicating Hurricane Information* program) and conduct at least two program meetings during the course of the grant awards. It would be very useful to have one meeting at the beginning of the grant period (as a kick-off meeting or a Year 1 report) and the meeting at the end of the grant period (as a Year 3 report).

Project A. Physical Understanding for Improved Forecasts

Project Rationale. Even though great strides have been made in the community's understanding of how tornadoes form and behave over the years, there are still major gaps. In particular, initiation and dissipation of tornadoes out of storms requires an understanding of processes within thunderstorms that are finer or involve physical attributes that are not routinely observed. In addition, skill in the forecasting of tornado intensity is very limited. On a time scale of several hours and spatial scale of hundreds of kilometers, it is likely that environmental conditions can provide the information needed to provide reasonably precise estimates of the probability distribution over different storm intensities. Reducing the uncertainty on the scale of individual storms would involve better observations of microphysical processes and fully three-dimensional thermodynamic and wind fields near and inside thunderstorms. Improved ability to model the observed small-scale processes and interpret them in terms of variables that can be routinely observed in order to use that information in operational forecasting is also required.

Expected Benefits. With a better understanding of the processes that lead to the formation and dissipation of tornadoes, forecasters should be able to make more accurate forecasts of tornadoes for a given amount of lead time or equally accurate forecasts for in increased lead time. Coupled with a better understanding of messaging and public response, the ability to make better forecasts could allow the NWS to set appropriate targets for the quality of tornado warnings in terms of increased lead time, increased probability of detection, and lower false alarms. The ability to predict tornado intensity would bring with it the possibility of tailoring calls to action that provide different information depending on the expected intensity (e.g., shelter in place, evacuate, etc.) This would allow vulnerable populations to take the appropriate protective action when needed.

Project Scope. For the large spatial and time frame studies, consideration of long records of observed environmental conditions and storm intensity will be carried out using well-established statistical techniques. The ongoing creation at the Storm Prediction Center of the necessary database of the environmental conditions associated with thousands of tornadoes should make this relatively easy to accomplish. For studies of individual storms, field observations using remote sensing from instruments such as radars and lidars, and in situ observations from instruments such as disdrometers will be needed to determine what is happening within storms. The observations would be assimilated into high-resolution numerical models in order to fill in the four-dimensional structure of the storm and estimate the importance of various physical quantities and processes in the development, maintenance, and dissipation of tornadoes, as well as their intensity.

Project Duration. Six years.

Project Staffing and Budget. Ongoing NOAA efforts are likely to explore the large spatial and time frame aspects. For the storm-scale field observations, we estimate that on the order of five principal investigators and ten graduate students at any particular time will be needed for to staff these projects. In addition, equipment and the costs of being in the field will be needed. We estimate these costs at $1-2 million per year.

Probability of Near-term Payoff. There is a high probability of near-term payoff from the large-scale environmental studies. The cost from those studies is relatively low but so it the anticipated benefit. There is a lower probability of near-term payoff from the storm-scale studies, but the costs and benefits are higher.

Project B. Wind Effects on Buildings

Project Rationale. Engineering research on wind-structure interaction could lead to the development of designs and materials that would be more effective in resisting wind impacts and do so at lower cost. In addition to identifying the effects of sustained wind speed at altitude, it is important to understand wind speed at ground level, especially the effects of wind gusts and vertical updrafts in affecting the updraft on building roofs. Existing research using vortex simulators needs to be supplemented by studies that verify the degree to which these laboratory models generalize to field settings. Moreover, there is a need to refine existing wind maps to identify maximum expected wind speeds so engineers and architects have a scientific basis for structural designs. A significant part of this project is the development of a capability to carry out post-event assessments of the impacts of the tornadoes on structures when they occur. We envision a model similar to National Transportation Safety Board accident investigation teams operating in the aftermath of major transportation disasters. Detailed surveys of building performance would be inputs for engineering work that identifies the reasons why structures failed and the ways that they can be strengthened in a cost-effective manner.

Expected Benefits. Engineering research that could identify cost-effective ways of improving the wind resistance of new structures would be useful because that would decrease the vulnerability of the building stock over time. Research that could identify cost-effective ways of improving the wind resistance of *existing* structures would be especially valuable because the size of the existing building inventory is very large compared to the number of new structures completed each year. Current methods of retrofitting existing structures tend to discourage building owners from investing in increases in their hazard resistance because retrofits cost substantially more than installing hazard resistant designs and materials in new structures. In addition, a better understanding of storm impacts can identify vulnerability of structures that could lead to improved messaging for the public, as well as community preparedness and response activities.

Project Scope. The project should begin with the coordination of activities among a large number of agencies (Office of Federal Coordinator for Meteorology, Centers for Disease Control and Prevention, American Red Cross, NWS, NSF, National Institute of Standards and Technology, Texas Tech University, FEMA, local police, local emergency management) that maintain a corps of multi-disciplinary damage assessment experts that are on call to respond rapidly after storm impact. The interaction between such field work and laboratory modeling and studies in order to test models' applicability to the observations and make recommendations for improving both current and future buildings would be carried out primarily by engineers. This project would develop a protocol for interdisciplinary teams to conduct immediate post-impact assessments. Project staff would develop a standardized protocol that identifies the disciplines to be represented, the data to be collected, the expected sources for those data, and the procedures for collecting the data. In addition, they would estimate the cost of investigating all major tornadoes (e.g., EF3 and above) to conduct comparative case studies between areas that vary in the extent of disaster impacts: damage to residential, commercial, industrial structures and infrastructure (water, sewer, electric power, transportation, and telecommunications), casualties (deaths, injuries, and illnesses), and social disruption (psychosocial, sociodemographic, socioeconomic, and sociopolitical impacts—see Lindell, Prater & Perry, 2006, Chapter 6). Some of the data these post-storm assessment teams collect could be made available to other investigators for use in developing NSF grants (either RAPID or normal submission cycle). The project staff should also examine the potential for crowd sourcing tornado data collection as the US Geological Survey does with earthquake shaking in their *Did you feel it* program (earthquake.usgs.gov/earthquakes/dyfi/).

Project Duration. Three years.

Project Staffing and Budget. The core project staff would consist of a PI (1.5 month/year) and GRA (11 month/year) who would organize a multidisciplinary workshop of approximately 20 researchers from—at minimum—meteorology, structural engineering, sociology, psychology, geography, anthropology, political science/public administration, economics, and planning. The PI and GRA would develop basic background materials during the first year and disseminate them to the workshop participants for reading before arrival at the workshop. The workshop participants would collaborate in the development of the data collection protocol, after which the PI would summarize the final protocol and its rationale. The budget required for this phase of the study would be approximately $190,000.

The field studies would be staffed primarily by a pool of volunteers qualified to conduct surveys of casualties, damage, social impacts, and behavioral responses to the event. There would be no staff time expenses for these individuals, but they would need to be reimbursed for travel and data collection expenses. It is likely to cost $30,000 per major tornado for the travel and per diem expenses, $50,000 for aerial surveys during larger outbreak days, and $25,000 for behavioral surveys. Assuming a typical distribution of tornadoes, this would require approximately $250,000 per year. The estimated labor for the engineering modeling component of the study would be a PI and Co-PI and four GRAs costing $150,000 per year.

Probability of Near-term Payoff. There is a moderate probability of payoff in the near-term. Currently, national coordinated response for damage assessment in the aftermath of major tornadoes is slow and at a lower level than it was during the 1970s and 1980s. Developing a better understanding of what happens to structures in tornadoes should help with providing better information for community and individual preparedness.

Project C. Forecasters' Construction of Warning Polygons

Project Rationale. Weather forecaster's warning polygons inevitably contain a significant component of individual judgment. Consequently, different forecasters given the same information will produce polygons having different shapes, sizes, and interpretations. The shape might be a quadrilateral or it might have five or more sides. The size might range from a few square miles to hundreds of square miles. The interpretation of the polygon implicitly corresponds to the forecaster's subjective probability contour that the polygon defines. That is, a forecaster might intend the polygon to include 50, 75, 90, 95 or some other percent of the tornado strikes that she or he would expect, given the observed meteorological conditions.

Psychological research in a variety of different domains from stock brokers to radiologists has shown that experts differ in the judgments they make about a given set of information. Moreover, when given exactly the same information at two different times, experts frequently produce different judgments. Given the robustness of these findings across a variety of domains, it is quite likely that this would be true for weather forecasting as well. Judgmental differences between forecasters in response to a given set of information (interpersonal disagreement) and differences in a given forecaster's judgments at different times in response to the same information (personal inconsistency) are potentially problematic. Such disagreements and inconsistencies are important because they affect the percentage of false alarms and missed predictions. Consequently, it is important to assess the degree to which forecasters produce consistent polygons over time as well as the degree to which they agree with each other in the polygons they produce. By identifying the sources of personal inconsistency and interpersonal disagreement it will be possible to reduce or eliminate these sources of error.

Expected Benefits. Careful analysis of the sources of interpersonal disagreement might reveal that some forecasters have identified important environmental cues that the majority ignore. Revealing these differences could stimulate formulation of an agency-wide consensus standard for polygon construction. Moreover, providing trainees with systematic guidance about methods for translating the elements of a meteorological display into the appropriate shape, size, and interpretation of a warning polygon could substantially accelerate their development of proficiency in performing this task. Finally, this research could provide the basis for conducting periodic "recalibration" of experienced forecasters. Such a procedure could be used to identify a forecaster's "drift" away from an agency-wide consensus standard and seek to identify the reasons why it occurred. In some cases, this judgmental drift might be nothing more than random error but, in other cases, it might provide evidence of important lessons learned from the forecaster's experience.

Project Scope. The foundation of any research on warning polygons will be the development of a set of standardized measures for all polygons. Length, width, and area are three obvious measures for very simple forms of convex quadrilaterals such as isosceles trapezoids. However, it will be a challenge to develop standardized measures for more complex forms of quadrilaterals and for polygons with more than four sides—if, in fact, such complexities are warranted by meteorological conditions. Once a set of standardized measures of polygons has been defined, it will be possible to compute derived measures of personal consistency and interpersonal agreement. In turn, these derived measures can be analyzed to determine if there are systematic differences in personal consistency and interpersonal agreement by, for example, level of experience or region of the country. The project staff will need to work with NWS staff to identify a *representative* set of approximately 30-50 weather scenarios that could be presented to forecasters in different areas of the country who have different levels of experience.

Project Duration. Three years

Project Staffing and Budget. This project will require a senior-level PI, Co-PI, and GRA. There will be an above average travel budget for the project staff to travel to different NWS facilities, especially Weather Forecast Offices (WFOs) to develop the set of weather scenarios, pretest these scenarios on a small group of forecasters (approximately five), and administer the scenarios in the main study to a broader sample of forecasters (about 50). The budget required for this study will be approximately $500,000. This does not include the cost of NWS personnel participation.

Probability of Near-term Payoff. This project has a very high probability of near-term payoff (within approximately five years after project completion) because its results can be implemented completely within NWS.

Project D. Effects of False Alarms on Warning Recipients

Project Rationale. Research on hurricane evacuation warnings has shown that there is no detectable effect of false alarms (areas that were warned to evacuate but were not subsequently struck) on evacuation rates in later hurricanes. In general, those who evacuate for one hurricane are likely to evacuate for a second hurricane even if the first one did not strike their community. Conversely, those who do not evacuate for the first hurricane are unlikely to evacuate for the second one. Thus, those who evacuate for the first hurricane but not the second tend to be offset by those who evacuate for the second hurricane even though they did not do so for the first one. It is unclear whether this finding for hurricanes will generalize to tornadoes because of the differences in the two hazards and their corresponding protective actions. On the one hand, tornadoes have a much greater frequency than hurricanes in the most exposed geographical regions. For example, an active year might see dozens of tornado warnings in the Central Plains but the largest number of hurricanes that have struck Florida in a single season is four. It is well known that people are imperfect processers of probabilistic information, so it is likely that the occurrence of many false alarms in a single season will depress people's judgments of the conditional probability of a tornado strike (given a warning) below the level that is normatively appropriate. Thus, their perceptions of personal risk would be unrealistically low. On the other hand, the amount of personal disruption that would be caused by sheltering in-place for a tornado is substantially lower than the corresponding amount of disruption that would be caused by evacuating from a hurricane. If the effect of lower risk perceptions in decreasing response is exactly offset by the effect of lower protective action costs in increasing response (and there are no other relevant causes of protective action), then there would be no net difference between hurricanes and tornadoes in the effects of false alarms. However, it is unlikely that the risk perception and response cost effects exactly cancel and, moreover, there are also other factors that affect the decision to take protective action. In addition, research on aggregate data suggests that there is a false alarm effect for tornadoes (Simmons & Sutter, 2009). Consequently, further research is needed to better understand false alarm effects.

Expected Benefits. A better understanding of false alarm effects might allow forecasters to better balance the tradeoffs between the near-term and long-term effects of warnings on risk area populations. Specifically, increasing the size of a warning polygon increases the probability that it will include the tornado track and, thus, reduces the likelihood of a missed prediction. On the other hand, increasing the size of a warning polygon also increases the number of people who will *not* be struck by the tornado and, thus, are so far away that they consider the forecast to be a false alarm. A better understanding of false alarm effects might allow local emergency managers (broadly defined to include public health officials and the news media (especially national and local television weather forecasters, as well as the American Red Cross and other non-governmental organizations) to provide hazard awareness programs that overcome any tendencies toward decreased risk perception in geographical areas with high rates of tornado activity.

Project Scope. A significant component of research on false alarm effects would be an examination of the psychological processes by which people classify an outcome as a false alarm (which might be interpreted as an indication of a flawed forecast process) or a near miss (which might be interpreted as an indication of inherent uncertainty in the behavior of storm systems). Specifically, a warning should specify the location, intensity, and timing of tornado impact, so a false alarm is inherently a multidimentional variable rather than the unidimensional variable that it is commonly assumed to be (a warning might be accurate about the timing of tornado impact but not its location and intensity). Consequently, research is needed to better understand which are the dimensions of error to which risk area populations pay attention. In addition, research on false alarms should seek to identify the effects of different warning frequencies (the number of warnings per year) by conducting studies in different areas of the country that vary in this respect. This project should also conduct qualitative research using techniques such as open-ended interviews that provide insights into warning recipients' conceptions of false alarms. This research should also seek to determine if there are individual differences in people's responses to false alarms/near misses that are attributable to cognitive heuristics and biases that could be overcome by improved knowledge of statistical principles.

Project Duration. Three years

Project Staffing and Budget. This project will require at least a PI and a GRA. The travel budget should be comparable to that of a typical research grant. The budget required for this study will be approximately $350,000.

Probability of Near-term Payoff. This project has a moderate probability of near-term payoff (within approximately five years after project completion) because some of its results can be implemented within NWS even though other results will require action by emergency managers, news media, and the American Red Cross.

Project E. Effects of Warning Channel, Content, and Context on Population Response

Project Rationale. Research has found that the most effective warning messages contain five essential elements—the source of the warning (so warning recipients can determine if the source is expert and trustworthy), a description of the hazard in terms of the certainty, severity, immediacy, and duration of dangerous conditions; the identity of areas at risk (and safe areas if these are not obvious); a recommended protective action that is perceived to be effective and feasible; and sources to contact for further information and assistance. In addition to containing accurate and complete information about these five essential elements, warning messages must often be transmitted rapidly. In some cases, there is a tradeoff between dissemination speed and message completeness because warning technologies that are capable of rapid dissemination tend to provide very limited information whereas those that are capable of providing the most complete information tend to have slower dissemination rates. Thus, research is needed to characterize different warning technologies in terms of characteristics such as message specificity, speed of dissemination, susceptibility to distortion, and penetration of normal activities (see Lindell & Perry, 1992; Lindell & Prater, 2010; NRC, 2011).

It is also important to recognize that information about a hazard can be transmitted in verbal, numeric, or graphic formats. For example, uncertainty about the severity of impact at a given location can be conveyed verbally ("There is a high probability of extreme tornado damage in Joplin this evening"), numerically ("There is a 90% chance of an F4 or stronger tornado striking Joplin from 6-9pm today"), or graphically by providing warning polygon or other image. Some formats might be better understood by some segments of the population but it remains to be determined if any single format is better understood by the entire population.

Finally, people's compliance with protective action recommendations can be facilitated or constrained by their physical and social context at the time of warning receipt. Obviously, people cannot comply with a recommendation to shelter immediately in their basements if they have no basements. Thus, some people evacuate to safer structures within the risk area or to locations outside the risk area if they lack confidence that sheltering in interior rooms in their homes will be effective in protecting them.

Expected Benefits. A better understanding of the ways in which different warning technologies, message sources, message content, and facilitating and constraining conditions affect risk perception and response would allow forecasters to design more effective warning messages.

Project Scope. This project should carefully examine past household tornado response research as well as past household hurricane evacuation research (see Lindell, in press) to develop a questionnaire containing the most useful items from past studies. Project staff should use this questionnaire to conduct at least two post-impact surveys that address the major elements of the *Protective Action Decision Model* (see White Paper 4). Specifically, they should address warning sources, message content, and channels; social and environmental cues; perceptions of risk, stakeholders, and protective actions; information seeking; facilitating and inhibiting conditions; protective actions (problem-focused coping actions) that were considered as well as those that were taken; emotion-focused coping actions; home and workplace structural characteristics; and respondent demographic characteristics. Collecting and analyzing data on the timing of household warning receipt and protective action initiation would allow researchers to construct cumulative distributions of these variables over time. In turn, these household-level data would contribute to a better understanding of the reasons why aggregate-level analyses have found that warning lead times greater than 15 minutes appear to have no effect on reduction in casualties (Simmons & Sutter, 2011).

Project Duration. Three years

Project Staffing and Budget. This project will require at least a PI and a GRA. The post-impact surveys will be a significant cost, but travel expenses should be comparable to that of a typical research grant. The budget required for this study will be approximately $350,000.

Probability of Near-term Payoff. This project has a moderate probability of near-term payoff (within approximately five years after project completion) because some of its results can be implemented within NWS but others will require action by emergency managers, news media, and the American Red Cross.

Project F. Laboratory and Web Experiments on Warning Messages

Project Rationale. Post-impact surveys are inherently limited in their ability to make causal inferences about variables that predict individuals' emergency responses because researchers only have access to respondents' retrospective self-reports. This is a problem because post-impact reports of the warning messages they received might be contaminated by factors such as rationalization of the actions they took and post-event discussions with others. Moreover, these studies are limited to studying the effects of the warnings that *actually were* disseminated rather than the range of warnings that *could be* disseminated. Laboratory and web experiments on warning messages can avoid these problems by presenting research participants with warning messages that are systematically varied to assess the psychological effects of different message components. Experimental control prevents respondents from obtaining threat information from any sources other than those provided by the experimenters. This makes it possible to uniquely identify the effects of plausible causal variables. Laboratory experiments, as the name implies, are carried out in university (or research institute) laboratories and thus tend to have relatively homogeneous respondent populations—especially university students. Although students are similar to the rest of the population in many respects, it is sometimes unclear how results from laboratory experiments will generalize to the rest of the population. Web experiments involve participants who can be randomly selected from the adult population and, after they log onto an experiment website, can be randomly assigned to experimental conditions. Like many mail surveys, Web experiments tend to over-represent those with higher education and income, homeowners, and Whites. Nonetheless, these Web experiments can be run using much more demographically diverse samples of respondents than is the case for laboratory experiments.

Expected Benefits. Laboratory and Web experiments allow researchers to systematically manipulate the content and format of warning messages and then assess research participants' attention to and interpretation of different message elements as well as their subsequent information search patterns and their expectations about how they would respond to the message(s) they received. Systematic manipulation is an important feature of experiments because it allows researchers to assess relationship between objective characteristics of a message and participants' subjective reactions to those messages. Of course, experiment participants' expectations about their behavioral response (i.e., shelter in-place or evacuate) are somewhat speculative because they do not experience the same level of threat as they would when an actual tornado was approaching. Nonetheless, the strengths of laboratory and Web experiments almost exactly offset the weaknesses of post-impact surveys and vice versa. That is, experiments can clearly reveal relationships between objective message content and psychological reactions to message content that are difficult or impossible to assess using post-impact surveys. By contrast, post-impact surveys can clearly reveal relationships between psychological reactions and behavior that are somewhat speculative when studied using laboratory and Web experiments. As a result, past research on household behavioral response to tornadoes—which has exclusively consisted of post-impact surveys—needs to be supplemented by laboratory and Web experiments. Ideally, future research on household behavioral response to tornadoes will involve a balance between these two types of research in ways that provide clear guidance to forecasters and emergency managers in formulating effective warning messages.

Project Scope. Project staff should carefully examine the types of warning messages that different sources have disseminated in past tornadoes. These laboratory and Web experiments should begin by carefully specifying contextual variables such as the locations of the rest of the household and proximity to different levels of shelter. Then, the researchers should present carefully constructed messages to determine how warning recipients are likely to attend to and interpret the elements of these messages, as well as how the message elements affect perceptions of risk (certainty, severity, immediacy, and duration of personal risk), stakeholders (perceived expertise, trustworthiness, and protection responsibility), and protective actions (especially efficacy in protecting people and barriers to implementation). Some studies should also be conducted that include messages from peers—such as friends, relatives, neighbors, and coworkers—that conflict to varying degrees with information from authoritative sources. Finally, project staff should assess warning recipients' intentions of taking different protective actions. In addition, project staff should examine the types of messages that NWS is contemplating using in future tornadoes. Specific examples include the use of tornado categories (e.g., the Weather Channel's TOR:CON index of the likelihood that a tornado will occur within 50 miles of a specified area) and tornado probability contours over a specified area.

Project Duration. Three years

Project Staffing and Budget. This project will require at least a PI and a GRA. Web experiments will cost more than laboratory experiments because of the need for participant payments, but travel expenses should be comparable to that of a typical research grant. The budget required for this study will be approximately $350,000.

Probability of Near-term Payoff. This project has a moderate probability of near-term payoff (within approximately five years after project completion) because some of its results can be implemented within NWS but others will require action by emergency managers, news media, and the American Red Cross.

Project G. Antecedents of Household and Business Tornado Preparedness

Project Rationale. Both emergency response and disaster recovery by households, businesses, and local communities are much more effective when people have prepared for the crisis by developing plans and acquiring the material resources they will need. As Bourque observes in White Paper 3, there has been a significant amount of research on household preparedness for earthquakes and other hazards but there appears to be little such research on tornado preparedness. The conditions that promote and impede tornado preparedness are likely to be similar to those involved in preparedness for other hazards but such similarity needs to be demonstrated empirically rather than assumed *a priori*.

Expected Benefits. A better understanding of the processes by which households, businesses, and local communities become better prepared for tornado emergency response and disaster recovery will benefit local emergency managers by helping them to reduce the physical (damage and casualties) and social (psychological, social, economic, and political) impacts of disasters in their communities. The results of this research will also accelerate the rate of household, business, and community disaster recovery.

Project Scope. This project should assess the level of tornado preparedness by households, businesses, and local government agencies in at least two communities. Because of the substantial differences in tornado exposure across the country, one survey should be conducted in a high exposure community and the other should be conducted in a low or medium exposure community (see Lindell & Prater, 2000, for a similar study design involving household earthquake preparedness). The researchers should administer a questionnaire that has a multi-item list of preparedness actions (e.g., learning the location of nearby emergency medical facilities) and items (e.g., battery powered radio and spare batteries). This list of actions and items should be derived from lists used in earthquake preparedness research supplemented by actions and items recommended by FEMA (www.ready.gov/) and the American Red Cross (www.redcross.org/). Project staff should include variables such as risk perception, hazard intrusiveness, stakeholder perceptions, hazard adjustment perceptions, sources of information about hazards and hazard adjustments, hazard experience, hazard proximity, and respondent demographic characteristics.

Project Duration. Three years

Project Staffing and Budget. This project will require at least a PI and a GRA. The post-impact surveys will be a significant cost, but travel expenses should be comparable to that of a typical research grant. The budget required for this study will be approximately $350,000.

Probability of Near-term Payoff. This project has a low probability of near-term payoff (within approximately five years after project completion) because almost all of its results will require action by emergency managers, news media, and the American Red Cross. However, the payoffs can be accelerated by incorporating the results of this research into the *StormReady* and *TsunamiReady* community programs.

Project H. Preparedness and Response by Vulnerable Population Segments

Project Rationale. Some vulnerable population segments have physical or mental impairments that restrict their ability to perform critical emergency response activities such as receiving and understanding social warnings, observing and interpreting environmental cues, communicating with others, and implementing protective actions such as moving themselves to in-place shelter or evacuating. Other vulnerable population segments will require special medical treatment after disasters until they can return to normal routines, lack functional independence, or otherwise require competent supervision. The ways in which vulnerable population segments are impeded in disaster response and recovery is under-researched, so there is relatively little scientific research on the specific strategies and resources that members of vulnerable population segments use to prepare for tornadoes and respond to them when they occur. Moreover, there is limited research on the effectiveness and cost of different strategies and resources that governmental agencies and non-governmental organizations use to prepare for vulnerable population segments that have been affected by tornadoes.

Expected Benefits. This research would significantly benefit local emergency management and social services agencies by documenting and evaluating strategies and resources that households, government agencies and nongovernmental organizations use to prepare for, respond to, and recover from tornado impacts.

Project Scope. This project should identify the impediments that prevent the elderly and those who have disabilities from achieving adequate levels of tornado preparedness, warning response, and disaster recovery. Project staff should interview personnel from governmental (e.g., social service) agencies and nongovernmental organizations (e.g., home health care organizations) that routinely work with vulnerable population segments. These interviews should identify specific strategies and resources that members of vulnerable population segments need in order to prepare for tornadoes, respond to them when they occur, and recover from their impacts. These interviews of government agencies and nongovernmental organizations should be followed by interviews of members of vulnerable population segments who have a range of different types of physical and mental disabilities. These interviews should elaborate on the knowledge gained from the interviews with government agency and nongovernmental organization staff. Project staff should follow this qualitative research by conducting at least one survey using questionnaires that are as similar to those used in studies of the public at large—Project E (*Effects of Warning Message Content and Warning Context on Population Response*), and Project G (*Antecedents of Household and Business Tornado Preparedness*)—although laboratory or Web experiments such as those conducted in Project F (*Laboratory and Web Experiments on Warning Messages*) might also prove fruitful.

Project Duration. Three years

Project Staffing and Budget. This project will require at least a PI and a GRA. The interviews and survey will be a significant cost, but travel expenses should be comparable to that of a typical research grant. The budget required for this study will be approximately $350,000.

Probability of Near-term Payoff. This project has a low probability of near-term payoff (within approximately five years after project completion) because almost all of its results will require action by emergency managers, news media, and the American Red Cross. However, the payoffs can be accelerated by incorporating the results of this research into the *StormReady* and *TsunamiReady* community programs.

Project I. Pre-Impact Planning for Post-Impact Community Recovery

Project Rationale. It has long been recognized that communities need to develop emergency response plans before disasters strike because there is often enough time to respond to an emergency but not enough time to plan and respond. In recent years, it has become increasingly obvious that this principle applies to disaster recovery as much as to emergency response. The value of pre-impact recovery planning seems obvious and there is anecdotal evidence to support this conclusion (e.g., Wu & Lindell, 2004), but the research base is extremely thin (Tierney & Oliver-Smith, 2012). Thus, research is needed to confirm this limited evidence and to systematically examine the process of developing pre-impact recovery plans as well as to evaluate their effectiveness in producing a faster and more complete recovery from disasters.

Expected Benefits. This research would benefit local emergency managers and land use planners by identifying the most effective strategies and the critical resources needed to develop a community's pre-impact disaster recovery plan. This would benefit disaster-stricken households and businesses by accelerating their progress toward psychological adjustment and the re-establishment of normal patterns of social, economic, and political interaction.

Project Scope. Project staff could begin by conducting a qualitative study of four communities struck by tornadoes, two of which had pre-impact recovery plans and two comparison communities that lacked pre-impact recovery plans. Interviews could be conducted to examine variables that might distinguish between those communities that did, and those that did not, develop pre-impact recovery plans. Such variables are likely to include the capacity and commitment of the local emergency management and land use planning agencies. Later, project staff could identify a broader set of communities and conduct a survey to determine the degree to which findings from the qualitative study generalized to this broader set of communities.

Project Duration. Three years

Project Staffing and Budget. This project will require at least a PI and a GRA. The interviews and survey will be a significant cost, but travel expenses should be comparable to that of a typical research grant. The budget required for this study will be approximately $350,000.

Probability of Near-term Payoff. This project has a low probability of near-term payoff (within approximately five years after project completion) because almost all of its results will require action by emergency managers, land use planners, and senior elected and appointed officials of local jurisdictions. However, the payoffs can be accelerated by incorporating the results of this research into the *StormReady* and *TsunamiReady* community programs.

Project J. Tornado Mitigation Adoption

Project Rationale. The fundamental effect of tornado wind on structures is relatively well understood. Wind speed is the dominant meteorological variable, but there are other characteristics such as the vertical velocity profile, gust structure, and intensity of updrafts whose impacts are less well understood. In addition, tornado impacts are determined by a building's design and the materials from which it is constructed (see www.spc.noaa.gov/faq/tornado/ef-scale.html). Communities can reduce tornado impacts if building owners to adopt mitigation measures voluntarily (either by effective risk communication or through economic incentives) or by passing building codes that require increased wind resistant designs and materials. Two major problems for both voluntary and code-required wind hazard mitigation are that tornadoes are relatively rare in many jurisdictions and that there is a significant cost of mitigation. Consequently, the extent to which tornado hazard mitigation has been implemented lags substantially behind the engineering state of the art. Research could improve the implementation of wind hazard mitigation in two ways. First, research on building owners' decisions whether or not to upgrade their structures voluntarily or in response to incentives could guide engineers in the development of designs that are more likely to achieve widespread adoption. Second, research on the processes by which communities adopt more stringent building code requirements would be valuable in identifying and overcoming social, psychological, economic, and political impediments to code upgrades.

Expected Benefits. Very high levels of wind hazard mitigation would strengthen the entire building envelope and, thus, would directly reduce damage to building structures and indirectly reduce casualties and damage to building contents. More limited levels of wind hazard mitigation would strengthen only parts of a building and, thus, would focus on the reduction of casualties for virtually all tornadoes (i.e., a FEMA 320 safe room or an ICC 500 shelter) or some tornadoes (a hardened area)—see Levitan's White Paper 8. Research on mitigation for mobile homes would be particularly important because such structures can be expected to be completely demolished at 127 mph, whereas single family structures would not be expected to experience this degree of damage until the wind speed reached 200 mph (WSAC, 2004). A study of decisions to install community shelters in mobile home parks would be particularly beneficial because approximately 40% of all mobile homes are located in these areas.

Project Scope. Researchers should conduct a multidisciplinary (e.g., economists, planners, engineers) study of the factors affecting implementation of tornado mitigation for two types of structures—mobile homes and single-family dwellings. The project team could contact mobile home park operators to identify mobile home parks that have installed community shelters and another group that has not. In addition, the researchers could contact tornado storm shelter vendors to identify owners of single-family dwellings that have installed safe rooms/shelters and a randomly selected comparison group of single-family dwelling owners that has not installed safe rooms/shelters. In-person interviews and standardized mail or telephone surveys could be conducted to identify characteristics of those who have, and those who have not, installed safe rooms/shelters. These *revealed preference* surveys (surveys of actual behavior) could be supplemented by *stated preference* surveys (surveys of expected or intended behavior—see Project K) to further examine safe room/shelter installation decisions. In addition, the research team could conduct a study of local land use planners' experiences with jurisdictional requirements for installing mobile home community safe rooms/shelters. They could also conduct a survey of local land use planners' perceptions of the benefits and costs of increasing safe room/shelter installation by means of risk communication, economic and other incentives, and regulatory requirements. This survey could also address planners' expectations about the degree of support and opposition for these measures that could be expected from different stakeholders in their communities. This study should be conducted in at least two states that differ in their political cultures (i.e., their general support for government involvement in the marketplace).

Project Duration. Three years

Project Staffing and Budget. This project will require a senior-level PI, Co-PI, and GRA. The interviews and surveys will be significant costs and travel expenses will be somewhat higher than on a typical research grant. The budget required for this study would be approximately $450,000.

Probability of Near-term Payoff. This project has a low probability of near-term payoff (within approximately five years after project completion) because most of its results must be implemented by local jurisdictions that adopt risk communication programs, incentives, or regulations.

Project K. Contingent Valuation of Tornado Warning Parameters

Project Rationale. When designing or revising public programs such as tornado forecast and warning systems, it is extremely valuable to conduct needs assessments that evaluate the potential cost-effectiveness of alternative program designs. Indeed, market research such as this is quite commonly used in the private sector to determine the designs of products ranging from automobiles to tablet computers. It would be extremely valuable to conduct contingent valuation ("stated preference") studies that examine risk area residents' economic valuation of improvements in the accuracy of estimated tornado forecast parameters such as lead time, probability of detection, false alarm rate, path forecasts, tornado intensity, forward movement speed, and area warned. Although contingent valuation studies need to be designed and executed quite carefully (see Arrow et al., 1993), they can provide extremely useful information.

Expected Benefits. Contingent valuation studies could provide NWS with useful information about how risk residents value different warning message parameters. In turn, this could guide agency research priorities regarding the allocation of research funds to different areas of meteorological research. Combining contingent valuation data with an assessment of likely technological advances (assessed, perhaps, though a Delphi study of experts—see Dombroski, Fischhoff & Fischbeck, 2006, for an example) could assist NWS administrators in making funding decisions that would be more effective in delivering higher value warning information at an earlier date. Even greater impact could be obtained if the technology assessment and contingent valuation were to be coordinated with Project D (*Effects of False Alarms on Warning Recipients*), Project E (*Effects of Warning Message Content and Warning Context on Population Response*), and Project F (*Laboratory and Web Experiments on Warning Messages*) because these three studies will be examining the ways in which people *actually use* warning message information.

Project Scope. Although a wide range of different contingent valuation studies could be conducted, it would be extremely valuable to conduct a stated preference study that examines the economic valuation of some subset of the following warning parameters—lead time, probability of detection, reduced false alarm rate, path forecast, tornado intensity, forward movement speed, and area warned. It would be inadvisable to try to study all of these variables in a single study but consultation with NWS staff could identify the best subset based upon the probability of near term major improvements in forecasts of each of the warning parameters. A contingent valuation study might involve two communities—one in a high tornado hazard area and the other in a medium tornado hazard area—whose residents provide a wide range of demographic characteristics, especially age, education, income, ethnicity, homeownership, and tenure in the community (see Lindell & Prater, 2000, for a similar study design addressing earthquake mitigation and preparedness).

Project Duration. Three years

Project Staffing and Budget. This project will require at least a PI and a GRA. The post-impact surveys will be a significant cost, but travel expenses should be comparable to that of a typical research grant. The budget required for this study will be approximately $450,000.

Probability of Near-term Payoff. This project has a very high probability of near-term payoff (within approximately five years after project completion) because its results can be implemented completely within NWS.

Project L. Develop a Social Science Short Course for Weather Forecasters

Project Rationale. Weather forecasters need to understand how people's interpretation of weather hazard information affects their hazard mitigation, emergency preparedness and response, and disaster recovery actions. Benjamin McLuckie's (1974) *Warning–A Call to Action* provided an excellent first step in this direction and many of the principles he identified are still valid. Nonetheless, there has been a significant amount of social science research conducted in the past 40 years that should be disseminated to weather forecasters. More recently, NRC (2006, p. 99) Recommendation 3 stated "ongoing training of forecasters should expose them to the latest tools in [communication of risk and uncertainty]". Specifically, that report advocates initial training in uncertainty for students in hydrometeorological sciences and continuing education of current practitioners in the public and private sectors. Such training should also prepare meteorologists for the heterogeneity in people's levels of numeracy.

Expected Benefits. Weather forecasters would benefit from a more complete understanding of the ways in which people interpret and act on meteorological information to protect themselves from the impacts of severe weather.

Project Scope. The exploratory mini-workshop regarding the integration of social science research began with a brief orientation to social science research relevant to meteorological operations and services (OFCM, 2010). This effort can be expanded in two ways. First, the audience should be expanded from senior managers of meteorological services in federal agencies to operational forecast personnel in NWS WFOs. Second, the content of the short course should be expanded to address a wide range of issues that are relevant to public response to warnings of severe weather.

This course would update the content, and provide additional material, on warning response by households, businesses and local governments that has been generated in the past four decades. The course could also rely on the potential contributions of the different social sciences (see SAB/SSWG, 2009, pp. 10-11) to add relevant material on other aspects of emergency response and emergency preparedness, as well as information about hazard mitigation and disaster recovery. The course content should be developed through systematic procedures for instructional system design as identified by Goldstein and Ford (2002). First, similar to McLuckie's two summers as a warning procedures consultant in the NWS Southern Region headquarters, some social scientists should observe forecast operations and conduct qualitative interviews with a range of staff in different geographical regions and at different levels of NWS. These preliminary activities should be followed by conducting a job/task analysis (JTA) of weather forecasters' jobs that can identify the knowledge, skills, and abilities that are needed on the job (KSAs). Next, a diverse panel of weather forecasters, academic meteorologists, and social scientists should review the list of tasks and KSAs to identify the training content that is needed and ways to deliver this content during initial training for new hires and continuing training for current job incumbents.

Project Duration. Three years.

Project Staffing and Budget. This project will require at least a PI and a GRA. The observations and JTA will be significant costs, but travel expenses should be comparable to that of a typical research grant. The budget required for this study will be approximately $350,000.

Probability of Near-term Payoff. This project has a relatively high probability of near-term payoff (within approximately five years after project completion) because most of its results can be implemented within NWS. In addition, incorporation of cognitive task analysis procedures into the JTA can identify improved training procedures and job performance aids that will assist meteorologists in making their weather forecasts.

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

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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 (e.g., Ziegler & Rasmussen, 1998; Johns & Doswell, 1992). [Convective Available Potential Energy (CAPE) is a measure of the total positive buoyancy integrated with height; larger values of CAPE indicate greater buoyant forcing for the upward motion, hereafter the *updraft*, in the storm.] Interestingly, the layer of negative parcel buoyancy is important for suppressing early, weak convection and allowing CAPE to continue to increase until stronger convection forms. However, if this layer is too deep or too 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. Flow along rising terrain can help provide the upward motion needed to reach this level. Storms also 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 locally more favorable environment through which the parcels travel (e.g., Wilson et al., 1992). 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 (Wilson & Roberts, 2006). 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 (e.g., Wilson et al., 1992; Marquis et al., 2007; Buban et al., 2012)

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 (Ziegler & Rasmussen, 1998). 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, the layers of negative buoyancy for lifted parcels, as well as near-surface parcel properties and the effects of entrainment 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 (e.g., Klemp & Wilhelmson, 1978; Weisman & Klemp, 1982, 1984; Rotunno & Klemp, 1982, 1985; Wicker & Wilhelmson, 1995), observations (e.g., Brandes, 1977; Lemon & Doswell, 1979; Bluestein, 1999; Markowski et al., 2002), and theories based on our understanding of the equations governing atmospheric motion (e.g., Lilly 1986; Davies-Jones, 1984; Davies-Jones & Brooks, 1993). We know that most strong and nearly all violent tornadoes are associated with a class of storms known as *supercells* (Browning, 1964) 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 storm-relative winds (i.e., the vorticity has a *streamwise* component), then the updraft will rotate (Davies-Jones, 1984). 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 (Trapp et al., 2005). 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 (Davies-Jones, 1982). 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 (Rotunno & Klemp, 1985). For example, as precipitation falls from the base of a cloud, 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 (Davies-Jones & Brooks, 1993). Once this rotation reaches low levels, the main updraft of the storm can contract it 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 (Wakimoto et al., 2004; Markowski et al., 2011), likely owing to similar processes occurring in their cold pools. This similarity 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, significantly tornadic storms have been found to contain outflow near the tornado that is *warmer* than in their nontornadic counterparts (Markowski et al., 2002; Gryzch et al., 2007; Hirth et al., 2008), implying weaker buoyancy variations in the tornadic storms. Weaker buoyancy variations would make it more difficult to generate the vorticity that is tilted into the tornado, but contracting the rotation in the final step would be easier. 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 active area of research, but observational climatologies show that significantly tornadic storms generally occur in environments characterized by high relative humidity (Thompson et al., 2003), 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 (Thompson et al., 2003), even though the vorticity associated with this shear does not appear to be directly tilted into near-surface vertical vorticity. Instead, it may have an indirect effect by increasing the strength of the rotation aloft which leads to a pressure field that supports better lifting and stretching of the outflow air (Markowski et al., 2010). 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 microphysical processes (i.e., the formation of precipitation and subsequent evaporation or melting) accurately in numerical models (Dawson et al., 2010). These processes are essential to producing realistic cold pools and realistic vorticity generation in our computer simulations, so improving their treatment in the models is an essential research step.

Although 0-1 km vertical shear and cloud base height (related to the low-level relative humidity) are helpful in distinguishing tornadic and nontornadic supercells (Rasmussen & Blanchard, 1998; Rasmussen, 2003; Thompson et al., 2003), they do not discriminate perfectly between the two types and, thus, both misses and false alarms still occur frequently, suggesting we still are missing pieces of the puzzle in relating tornado development to features of the environment. For tornado watches, the skill is lowest in the portion of the parameter space characterized by fairly low CAPE and moderate shear. Unfortunately, despite the lower probability of tornado formation in this regime compared to the high-CAPE and high-shear regime, this environment occurs frequently, leading to a large overall tornado count.

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 (Lee et al., 2006; Wurman et al., 2007), while other studies noted tornado occurrence as a supercell encountered an air mass boundary (Markowski et al., 1998). Interestingly, these types of interactions sometimes 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. A recent climatological study suggests that 18% of tornadoes occur in quasi-linear convective systems (QLCSs) (Trapp et al., 2005). Unlike supercell tornadoes, these tornadoes often are not accompanied by a rotating updraft aloft, and the mechanism(s) by which their parent circulations (mesovortices) form is an area of ongoing research (Trapp & Weisman, 2003; Atkins & St. Laurent, 2009). 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 (Wakimoto & Wilson, 1989; Lee & Wilhelmson, 1997). Such boundaries may already contain significant vertical vorticity due to the contrast in the horizontal winds across the boundary. This pre-existing vorticity is simply contracted (stretched) by the developing updraft. This formation mechanism is entirely different than that for supercell tornadoes. Finally, tornadoes often develop in land-falling hurricanes (McCaul, 1991); and although they are generally weak and brief, numerous F3 tornadoes have been observed in these conditions (McCaul et al., 2004).

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 (e.g., Marquis et al., 2012). 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 (e.g., Ward, 1972; Church & Snow, 1985), theory (e.g., Davies-Jones, 1973; Fiedler & Rotunno, 1986), 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) (e.g., Lewellen & Lewellen, 2007). 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 and only a handful of studies have been able to compare radar-observed winds to tornado damage (Wurman & Alexander, 2005).

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.

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White Paper 2:
Current Challenges in Tornado Forecast and Warning

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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.

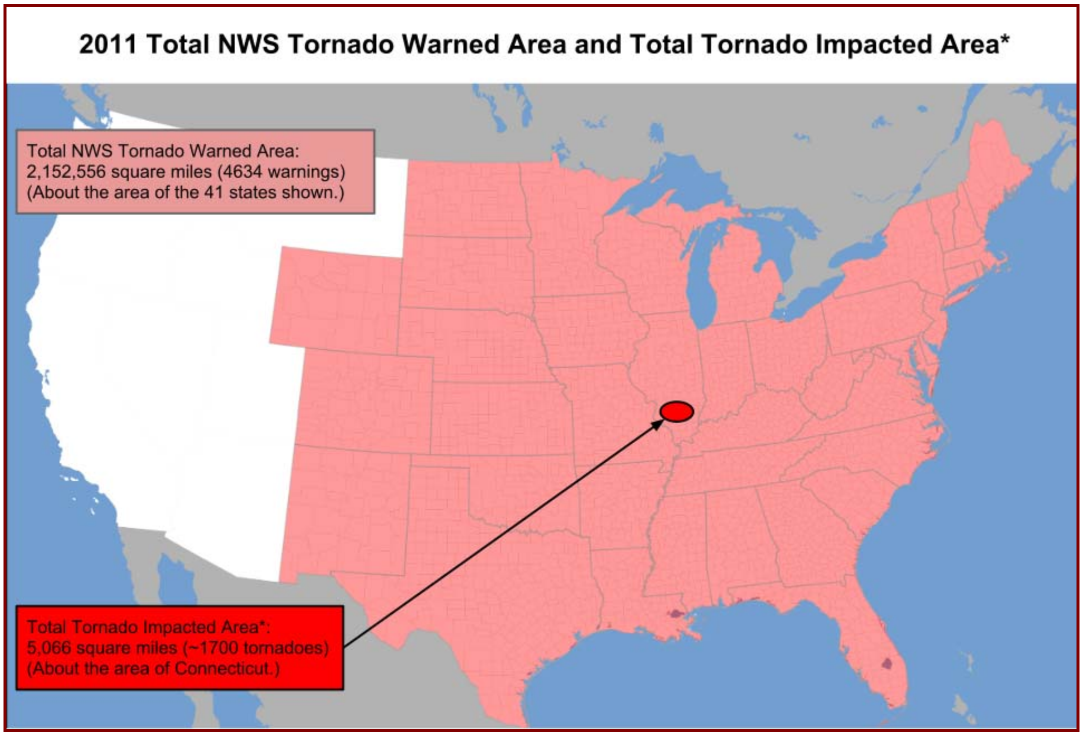
Spatial uncertainty in tornado prediction also poses a formidable forecast and warning challenge and is another component used to resolve the boundaries that contain the risk. It is especially challenging to define a risk area prior to tornado-producing thunderstorms appearing on radar, and the subsequent 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.

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).

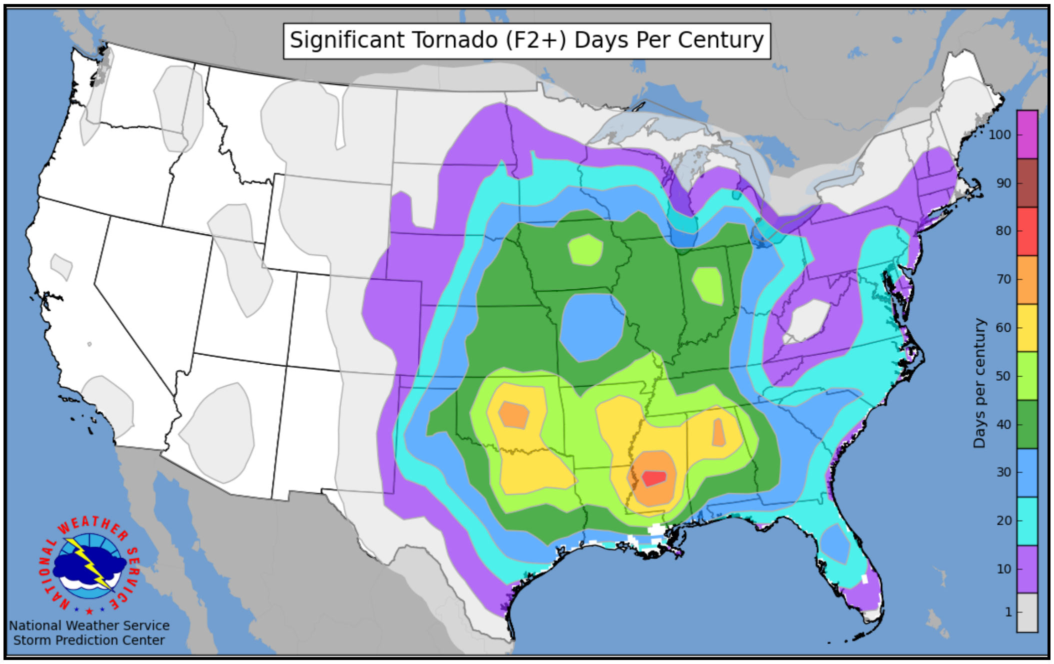
Figure 1. Total Tornado Warned Area in 2011 Compared to Total Area "Impacted"



Note: 2011 was one of the most prolific years for tornadoes in United States history, with nearly 1700 individual tornadoes reported. The total impacted area (in red) is calculated by multiplying each tornado path length by its width and then doubling the resulting area to account for the possible peripheral impacts and public perception of being "hit". Source: (NWS and SPC data)

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 NWS'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.

Figure 2. The Estimated Return Frequency of a Significant Tornado to Within 25 Miles of Any Point



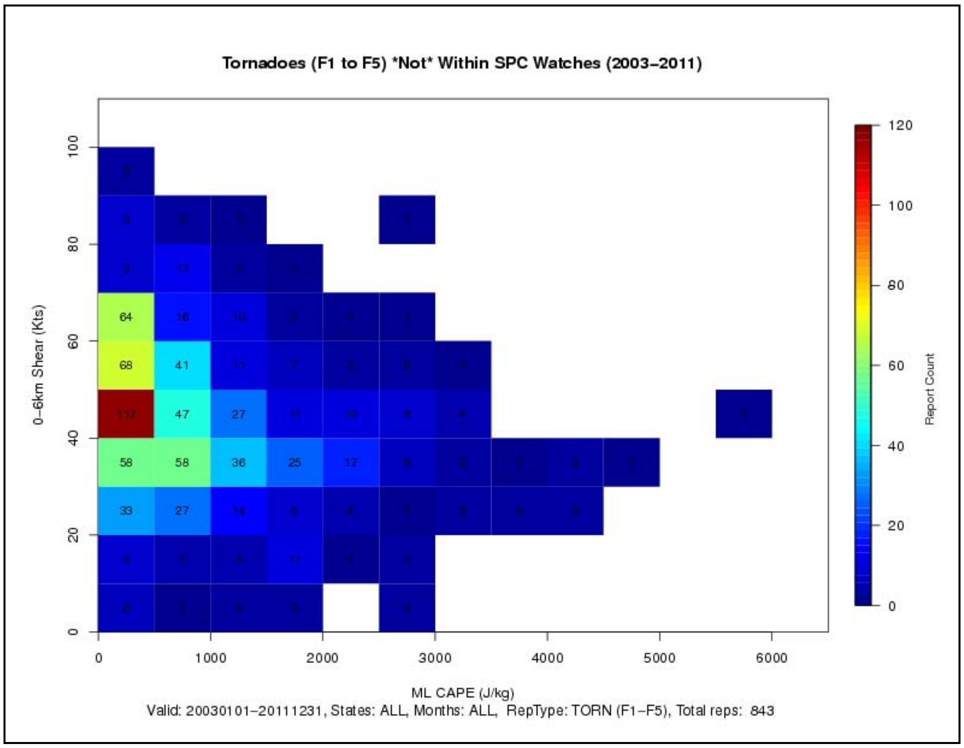
Source: SPC Data 1961-2010

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 NWS 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).

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 3."Phase-Space" Diagram Showing Those Atmospheric Conditions Most Likely to Have "Missed" Tornado Events That Were Not Contained in an NWS/SPC Watch

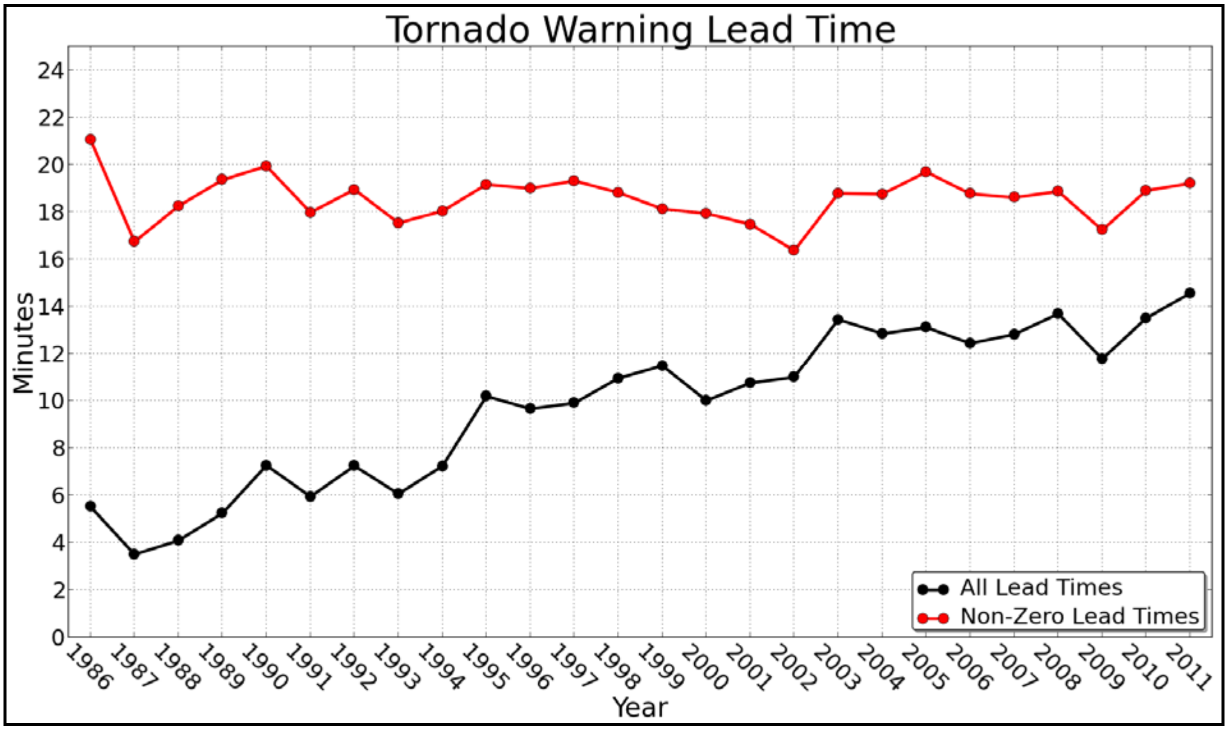


Note: The environments where tornadoes are difficult to forecast are those characterized by low instability (x-axis) and high vertical wind shear (y-axis). These environments are also not uncommon and usually do not result in tornadoes.

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.

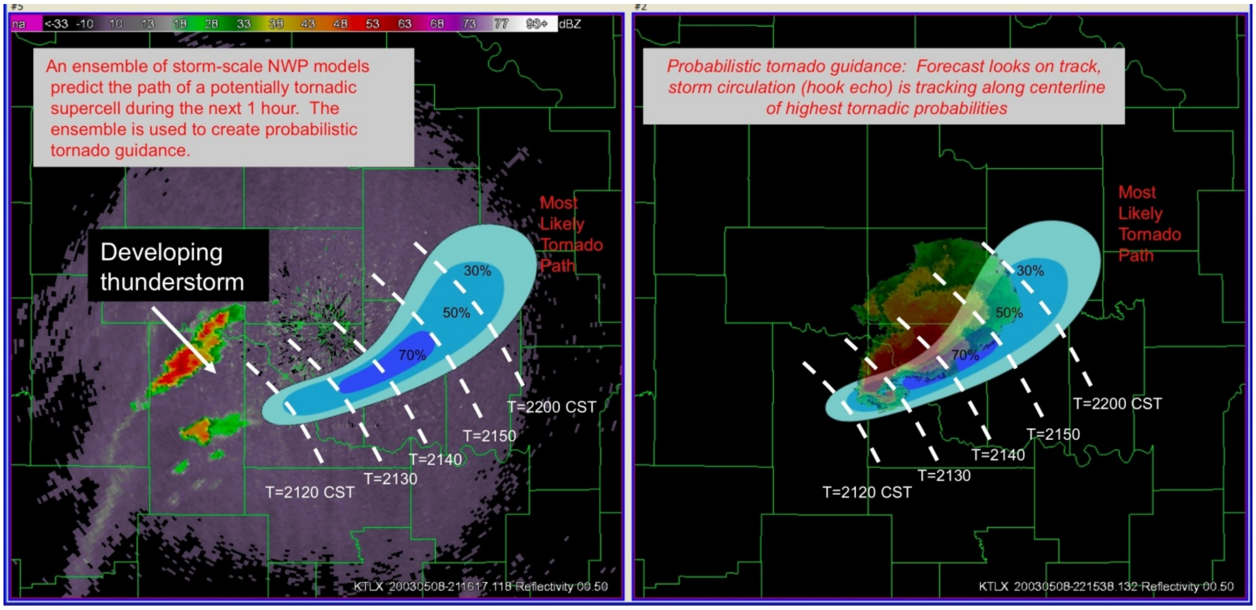
Figure 4. Annual Mean National Tornado Warning Lead Times According to NWS Definition



Note: Data points 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. Source: Harold Brooks and Patrick Marsh.

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 NWS forecasters and hence to the public.

Figure 5. Conceptual Illustration of a Convective-Scale Warn-On-Forecast System.

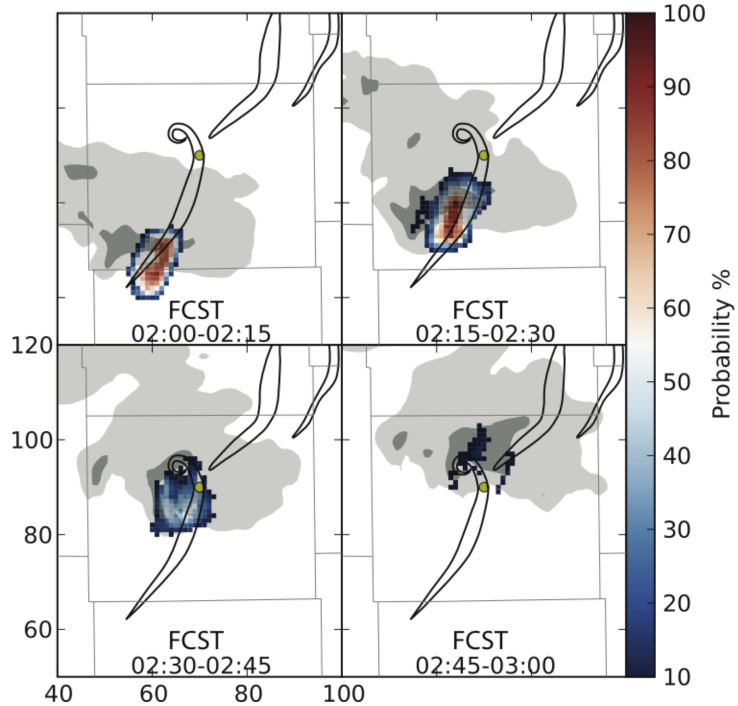


Note: Developing thunderstorms are observed by radar (left) and assimilated into a convection-resolving numerical weather prediction model ensemble forecast system. Probabilistic predictions of the future evolution of these storms are produced, yielding a tornado probability field valid over the following 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. Source: 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.

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.

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.



Note: 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. Source: Stensrud et al. (2012).

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White Paper 3:
Household Preparedness and Mitigation

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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 (Kelley, Wood, Kano, & Bourque, 2012). But research has also examined what increases preparedness and mitigation for a variety of different natural, technological and human-made hazards including floods (Grothmann & Reusswig, 2006; Lin, Shaw & Ho, 2008; Mishra & Suar, 2007; Terpstra, 2011), hurricanes (Basolo, Steinberg, Burby, Levine, Cruz & Huang, 2009; Kim & Kang, 2010), wildfires (Martin, Bender & Raish, 2007), landslides (Lin et al., 2008), volcanoes (Kim & Kang, 2010), heat (Mishra & Suar, 2007), toxic chemical releases (Lindell & Hwang, 2008), technological disasters (Steinberg, Basolo, Burby, Levine & Cruz, 2004), terrorism (Bourque, Mileti, Kano & Wood, in press, a; Bourque, Regan, Kelley, Wood, Kano & Mileti, in press, b; Eisenman, Glik, Ong, Zhou, Tseng, Long, Fielding & Asch, 2009; Eisenman, Wold, Fielding, Long, Setodji, Hickey & Gelberg, 2006; Kano, Wood, Bourque & Mileti, in press; Lee & Lemyre, 2009; Torabi & Seo, 2004; Wood, Mileti, Kano & Bourque, in press), 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 (Lindell & Prater, 2000; Nguyen, Shen, Ershoff, Afifi & Bourque, 2006). Many characteristics of households and individuals have been examined in the attempt to understand the circumstances under which households prepare and mitigate (Lindell, in press).

After briefly reviewing how antecedent variables (gender, race/ethnicity, socioeconomic status, and risk perception) affect household preparedness and mitigation, this paper focuses on the following questions. First, how do different methods of measuring preparedness and mitigation influence findings? Second, how does past exposure to disasters affect preparedness and mitigation? Third, what is the role of information seeking in increasing preparedness and mitigation?

Antecedent Variables

Gender

When gender is examined in studies of preparedness, results are mixed. Lindell and Prater (2000) reported that women were less likely to make hazard adjustments. In Los Angeles (Eisenman et al., 2006), men were less likely to have emergency supplies and plans than women, but these differences disappeared in multivariate models. Fothergill (1996, 1998) suggested that men and women might differ in the kinds of preparedness activities that they do. Mileti and colleagues (Mileti & Darlington, 1997; Mileti & Fitzpatrick, 1993) reported mixed results as regards gender, whereas others reported that gender was unrelated to taking preparedness actions (Eisenman et al., 2006; Nguyen et al., 2006; Lindell & Hwang, 2008; Spittal, McClure, Siegert & Walkey, 2008).

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 (Kelley et al., 2012).

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 (Edwards, 1993; Faupel & Styles, 1993; Turner, Nigg, Heller-Paz, 1986). Lindell and Hwang (2008) reported that Whites were more like to have flood insurance, but non-whites were more likely to have made flood adjustments. Peacock (2003) 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 (Lindell & Prater, 2000; Nguyen et al., 2006).

Studies focused on terrorism conducted after September 11, 2001, report similarly mixed results. Torabi and Seo (2004) reported that more African Americans than Whites organized supplies as a consequence of the attacks. Eisenman et al. (2006) 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 (2004) 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." (Eisenman et al., 2006, p. 169).

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 (Bourque et al., in press, a). In multivariate models gender (female) and race/ethnicity (non-white) had modest indirect effects on preparedness (Bourque et al., in press, b). In California, Kano, Wood, Kelley & Bourque (2009) reported that Hispanic respondents consistently reported doing fewer preparedness and mitigation activities than other race/ethnic groups, while White respondents reported more earthquake preparedness and mitigation (Bourque et al., in press, b). Race/ethnicity did not have a significant main effect on preparedness in multivariate models (Kelley et al., 2012).

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 there was a positive association between education and individual preparedness behavior for terrorism but no association with avoidance behavior (Lee & Lemyre, 2009).

A positive association between education and preparedness for earthquake was reported in Istanbul (Tekeli-Yeşil, Dedeoğlu, Braun-Fahrlaender & Tanner, 2010). Lindell and Hwang (2008) 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 (2000) 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 (Grothmann & Reusswig, 2006).

Nationally, Bourque et al. (in press, a) found that 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 (Kelley et al., in press).

Risk Perception

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 (Ablah, Konda & Kelley, 2009; Basolo et al., 2009; Kim & Kang, 2010; Lee & Lemyre, 2009; Lin et al., 2008; Martin et al., 2007; Ozdemir & Yilmaz, 2011) and had no effect on preparedness in others (Eisenman et al., 2006; Lindell & Prater, 2000; Lindell & Whitney, 2000; Mileti & Fitzpatrick, 1993; Mileti & Darlington, 1997; Mishra & Suar, 2007; Spittal et al., 2008; Steinberg et al., 2004; Tekeli-Yeşil, et al., 2010). Martin, Martin and Kent (2009) reported that risk perception slightly mediated the influence of knowledge and self-efficacy on preparedness for wildfires. Lindell and Hwang (2008) 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 (Bourque et al., in press, b).

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 (Heller, Alexander, Gatz, Knight & Rose, 2005; Lindell, Arlikatti & Prater, 2009; Mileti & Darlington, 1997; Nguyen et al., 2006; Russell, Goltz & Bourque, 1995; Spittal et al., 2008; Turner et al., 1986). In some cases, included within the set of items are questions more appropriately considered as measures of milling behavior (Grothmann & Reusswig, 2006) or self-efficacy (Lindell et al., 2009). Individual questions are used (Basolo et al., 2009; Grothmann & Reusswig, 2006; Wood, Kano, Mileti &

Bourque, 2009) as well as one or more indexes (Lindell & Hwang, 2008; Nguyen et al., 2006; Russell et al., 1995). Some measures focus on intentions to prepare (Terpstra, 2011), attitudes toward preparedness (Siegrist & Gutscher, 2006; Tekeli-Yeşil et al, 2010), or anticipated reactions to warnings (Knocke & Kolivras, 2007).

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 (1986) asked whether 16 activities had been done or were planned for either earthquakes or other reasons. 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 (Russell et al., 1995; Nguyen et al., 2006). 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 (Bourque et al., in press, a; Bourque et al., in press, b; Kano et al., in press; Wood et al., in press). Consistent with findings for earthquakes (Nguyen et al., 2006; Russell et al., 1995), 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)—see Wood et al. (2009). 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. (1995), Lindell and colleagues (Lindell et al., 2009; Lindell & Perry, 2000; Lindell & Prater, 2002; Lindell & Whitney, 2000) 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. 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. (2006) and Heller et al. (2005) 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 (Cooley, Catalano, Mishra & Serxner, 1992; Jackson, 1977, 1981; Lindell & Perry, 2000; Russell et al., 1995; Sato, 2011).

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 (1991) and Lindell and Perry (2000) 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. (1995) reported that high levels of fear during and frequent thoughts about earthquakes were weakly correlated with increased preparedness. Lindell and Perry (2000) similarly reported that hazard intrusiveness (frequency of thought and discussion about a hazard) modestly increases preparedness. Siegel, Shoaf, Afifi and Bourque (2003) 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 (Ozdemir & Yilmaz, 2011; Tekeli-Yeşil et al., 2010), past exposure to a disaster (Bourque et al., in press; Mishra & Suar, 2007; Paul & Bhuiyan, 2010; Perry & Lindell, 2008; Siegrist & Gutscher, 2008) and experiencing damage in a past disaster (Grothmann & Reusswig, 2006; Mileti & Fitzpatrick, 1993; Paul & Bhuiyan, 2010; Siegrist & Gutscher, 2008) 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 such as terrorism, natural disasters, other reasons (Bourque et al., in press, a). 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 (Bourque et al., in press, b).

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 Seeking 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 (Bourque et al., in press, b; Kelley et al., 2012; Mileti & Fitzpatrick, 1993; Mileti & Darlington, 1997; Paton, Smith & Johnson, 2005; Perry & Lindell, 2008). Mileti and colleagues (Mileti & Darlington, 1997; Mileti & Fitzpatrick, 1993), Perry and Lindell (2008) and Paton et al. (2005) 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 (Basolo et al., 2009; Kelley et al., 2012; Lindell & Hwang, 2008; Wood et al., in press), the number of channels over which information is received (Kelley et al., 2012; Wood et al., in press), the number of types of information received (Kelley et al., 2012; Wood et al., in press), cues or seeing others prepare (Kelley et al., 2012; Mileti & Fitzpatrick, 1993; Wood et al., in press), being embedded in a neighborhood information system (Kim & Kang, 2010), and being active in a social network (Heller et al., 2005). 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.

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 (Wood et al., in press). 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 (Kelley et al., 2012). 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

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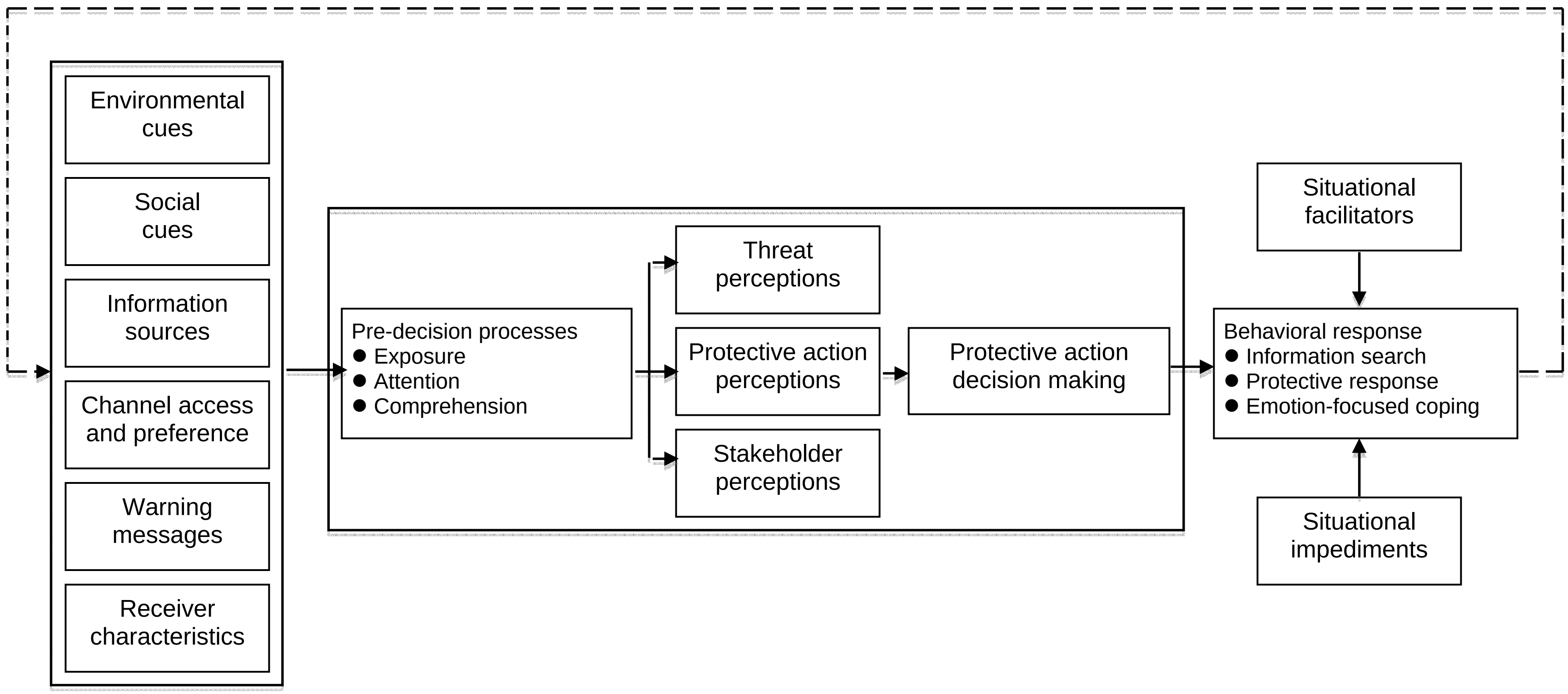
Researchers have conducted many studies of the process by which people respond to environmental cues or socially transmitted warnings about environmental hazards (Drabek, 1986; Mileti & Sorenson 1990; Sorensen, 2000; Tierney et al., 2001). Lindell and Perry (1992, 2004, in press) have integrated findings 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 and Perry (2012)

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 NWS 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

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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 that 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 and 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 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 forewarning, 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 hurricanes (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 rapid onset 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 protection 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 characteristic. 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 the category of *mobility impairments*, for example, does not distinguish what proportion of those in this category require the use of a cane or the use of a wheelchair.
- Similarly, there is a need for large-scale epidemiological research that distinguishes between different types of elderly populations, specifically elderly adults who have disabilities of different types. Some elderly adults are easily able to take protective action whereas 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

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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

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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 & Lazo, 2011). Tornado forecasts are not free, and establishing their value helps public officials determine if investing in forecast improvements is worthwhile. In speaking of *value*, 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. 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 NWS 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 & Lellyett, 1996; Johnson & Holt 1997; Freebairn & 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 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 & 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 exist (NOAA warning verification records date to 1986) 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.[1] Sufficient variation in contemporary warning performance exists to allow estimation of an econometric model.[2] 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.[3] 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 & Sutter, 2012a).

[1] 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.

[2] "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.

[3] 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 & Cutter, 1998)

The tornado warning process might also produce several other types of societal and economic[4] 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.

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.[5]

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 & 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 & 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 straightforward 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.

[4] Although 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.

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

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

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 & Sutter 2007a,b), and stated preference methods (Ozdemir, 2005, Ewing & 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 & 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 & 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 & 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[6], would rank as the fourth-costliest disaster for insured losses in U.S. history. That has clearly put tornado losses 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? [7]. 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

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

[7] 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 & Kunreuther, 2011).

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).

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

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Protection from tornadoes is often sought in storm cellars and basements, although these options are not available to many. Post-tornado investigations conducted by wind engineering researchers at Texas Tech University beginning in the 1970s identified that certain core parts of buildings often remained standing even when the rest of the structure was destroyed. These locations were typically small interior rooms such as bathrooms or closets, areas underneath stairways, small hallways and other areas with multiple wall intersections. This led to the idea of purposefully strengthening interior windowless rooms to provide occupant protection, which became known as "in-residence shelters", first reported by Kiesling and Goolsby (1974). In-residence shelters provided accessibility advantages over outdoor storm cellars or community shelters, reducing the time to get in the shelter and eliminating the danger of being struck by flying debris while attempting to reach an outdoor cellar or community shelter (WiSE, 2012). This concept was developed and refined over the next few decades through a combination of analysis, experiments, and post-tornado investigations.

The Defense Civil Preparedness Agency (DCPA) produced interim guidance for design of buildings and protection of occupants from tornado winds in the mid-1970s and DCPA's successor, the Federal Emergency Management Agency (FEMA), updated that interim guidance in the 1980s. An F5 tornado that was part of the 1997 Central Texas Tornado Outbreak struck the small town of Jarrell, Texas, destroying many homes and killing over two dozen people. A documentary aired on the National Broadcasting Company (NBC) about the Jarrell tornado also included a segment describing the above ground shelter concepts being developed at Texas Tech University (TTU). Local broadcasters filmed similar stories. The attention by the press helped gain national visibility for the concept and generated public interest (Kiesling et al., 2009). Building on the experience and expertise at TTU, federal guidelines for design and construction of residential safe rooms were published the following year in FEMA 320, *Taking Shelter From the Storm: Building a Safe Room Inside Your House* (FEMA, 1998).

After the tornado that devastated Oklahoma City in 1999, a grant program provided funding for residents who were rebuilding to include a shelter conforming to the requirements of FEMA 320. This led to a large increase in the number of both site-built and manufactured shelters being constructed. Design and construction guidance for community shelters was addressed the following year in FEMA 361 (FEMA, 2000). The growth of the storm shelter industry led to the creation of the National Storm Shelter Association (NSSA), which developed industry standards and quality assurance procedures. A joint effort between the International Code Council (ICC) and the NSSA culminated in development of national consensus ICC 500, *Standard for the Design and Construction of Storm Shelters* (ICC/NSSA, 2008). FEMA 320 and 361 guidance documents for residential and community safe rooms respectively were updated to incorporate the requirements of the new ICC 500 standard (FEMA, 2008a, 2008b). It is interesting to note that FEMA 320 is the most requested FEMA document in history, with over a million copies having been printed (Kiesling et al., 2009).

The 2009 editions of the most widely used national model building codes, the International Building Code (IBC) and International Residential Code (IRC), both incorporated the ICC 500 standard by reference. These model codes did not, however, include any requirement that buildings or facilities must provide shelters. The codes do require that shelters, if provided, must be constructed in accordance with

ICC 500. Even this limited requirement is only very slowly being implemented. Adoption and enforcement of building codes is a function of state and local governments. Some jurisdictions do not have building codes. Even in those jurisdictions that do have building codes, many have not yet updated their laws and ordinances to adopt the 2009 editions of the IBC and IRC. One location where progress has been made is Alabama, although as it often does, it took a disaster to get there. In response to the 2007 tornado in Enterprise that severely damaged the high school and several other schools and killed eight students, the Alabama Building Commission began requiring that all new K-12 public schools must provide tornado shelters built in accordance to the ICC 500 standard.

Differing Terminology and Levels of Protection

Design guidance/requirements for tornado safe rooms and shelters (FEMA 320, FEMA 361, ICC 500) address structural engineering requirements of loads and resistance of the building and its cladding for the primary hazards of extreme wind pressures, windborne debris, and atmospheric pressure change. Additional criteria are provided for fire safety and flood safety (related to siting and elevation), as well as architectural, mechanical, and electrical considerations including ventilation, lighting, signage, means of egress, and minimum required floor space for occupants. Other types of tornado protection beyond safe rooms and shelters do exist, but their focus is almost exclusively on protection from extreme winds and windborne debris

A number of different terms are used to identify buildings or areas within buildings that provide at least some relative level of protection from tornadoes.

Safe Room: The FEMA term for building or portion thereof designed and constructed to meet the requirements of FEMA 320 (for home or small business) or FEMA 361 (for community safe room).

Shelter: A building or portion thereof designed and constructed to meet the requirements of the ICC 500 standard.

Hardened Area: A building or portion thereof specifically designed and constructed to provide some increased level of protection above building code minimums, but not meeting ICC or FEMA criteria.

Best Available Refuge Area: An area of existing building that has been evaluated by a qualified architect or engineer as likely offer the greatest safety for building occupants during a tornado, using procedures such as those in FEMA P-431 (FEMA, 2009) and FEMA 361.

Other terms are used as well. Some facilities may identify spaces as *high wind shelter areas*, *tornado refuge areas*, or similar names. These areas may or may not be constructed or evaluated to provide better protection from tornadoes than any other parts of the building. They may be chosen by facility owners or managers without any knowledge or training regarding building performance in tornadoes. For example, it is not uncommon for school administrators to be responsible for developing the tornado sheltering plans for their schools or school campuses. Gymnasiums, cafeterias, and auditoriums have sometimes been identified as shelter or refuge areas despite their typically poorer performance than interior classrooms, hallways, and bathrooms.

In terms of the expected level of tornado protection offered, both FEMA guidance documents are provide explicit performance expectations. FEMA 361, *Design and Construction Guidance for Community Safe Rooms*, offers the somewhat remarkable statement:

> *A safe room designed according to the guidance presented in this manual provides near-absolute protection from death and injury, even though the building itself may be damaged during a design event.* (FEMA, 2008a). [underscore added for emphasis]

The requirements of the ICC 500 standard are identical to those of FEMA 361 in most instances, although where differences occur, FEMA requirements are more stringent. ICC 500 does not identify expected performance levels. However, its stated purpose is

> *…to establish minimum requirements to safeguard the public health, safety and general welfare relative to the design, construction and installation of storm shelters constructed for protection from high winds associated with tornadoes and hurricanes.(ICC/NSSA 2008).*

Hardened areas may or may not be designed in accordance with specific guidance. One example that does include information on expected performance is the "strong area" in-residence shelter developed by the Blue Sky Foundation of North Carolina. "A Strong Area is a shelter that provides approximately 75% of the protection that a FEMA 320 Safe Room provides against impact from high winds and windborne debris." (Markle, Neal, & Reinhold, undated).

Since Best Available Refuge Areas are parts of existing buildings with a wide range of designs and construction types and qualities, as opposed to newly designed and constructed areas, it isn't possible to develop definitive performance expectations. However, the relative performance expectations of Best Available Refuge Areas area provided in FEMA P-431 as described below.

> *It is important to note that, because these areas were not specifically designed as tornado safe rooms, their occupants may be injured or killed during a tornado. However, people in the best available refuge areas are less likely to be injured or killed than people in other areas of a building."* (FEMA, 2009)

One challenge to advancing tornado hazard mitigation is the numerous terms used to describe various types of tornado shelters and refuge areas. The nuances of each term as described in this section are lost on the overwhelming majority of the population, save a small cadre of engineers, architects, manufacturers, emergency managers, and government officials.

Tornado Wind Characteristics for Safe Room and Shelter Design

The first step in developing design criteria for tornado resistance is to define the tornado hazard in engineering terms. Early attempts to estimate wind speeds in tornadoes included analysis of ground marks, analysis of flying debris from tornadoes caught on film. Minor and McDonald (1976) estimated tornadic windspeeds from the analyses of structural failures and concluded that surface level wind speeds were much lower than some previous estimates. Tornado climatology records using the Fujita Scale were used as the basis for developing a somewhat deterministic tornado design shelter design wind speed map for use in FEMA 320 and FEMA 361, which was later used in ICC 500 as well. The country was divided into one-degree grid squares and the total number of tornadoes of each F-scale category in each grid square was recorded. The areas of the country where F5 tornadoes were generally found to occur were bounded and assigned a wind speed of 250 mph as shown on Figure 1, and so on. Limitations in understanding of maximum surface level wind speeds in tornadoes, assignment of F-scale ratings to tornadoes, and completeness of the tornado historical record all impact the quality of the existing tornado shelter design speed map, and thus the safety and reliability of shelters designed to this map.

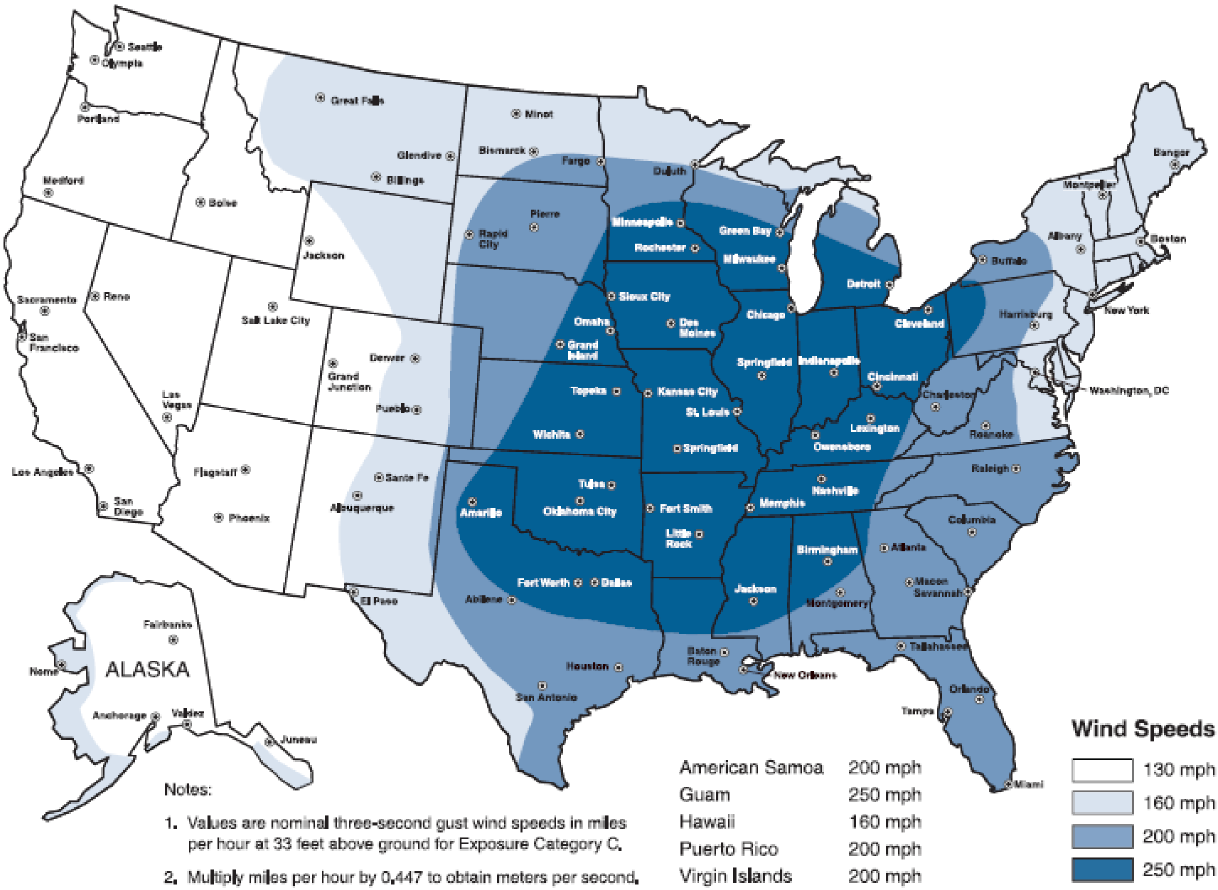
Understanding of other important characteristics of tornadic winds is still in its infancy, including the vertical velocity profile, gust structure, intensity of updrafts, and impacts of those features on the wind-structure interaction. Recently developed experimental facilities such as the Tornado/Microburst Simulator at Iowa State University and the Vortech Tornado Simulator at Texas Tech University are beginning to shed some light on these questions. For example, Haan, Balaramudu, and Sarkar (2010) reported peak lateral pressure coefficients on model of a gable-roofed house as much as 50% higher than those accepted for straight line winds. Vertical uplift coefficients on the roof were found to be two to three times larger than those in the current national wind loading standard (ASCE, 2010), due to large negative static pressures generated at the core of the vortex. If these results are ultimately confirmed, it may have significant impact on tornado design criteria, requiring design for much larger roof uplift loads in particular.

Societal Considerations/Challenges

FEMA safe rooms are intended to provide "near-absolute protection from death and injury,", but the number of facilities constructed is small. FEMA initiatives have contributed to construction of approximately 20,000 residential safe rooms, with tens of thousands more constructed with finds from private initiatives (FEMA, 2008b). The ICC 500 standard has only been available for a few years, so the number of shelters constructed to that document (providing similar level of performance) is likely much lower at this point. Cost is likely a significant factor. Construction costs average in the range of $6,300-$8,300 for an 8 ft x 8 ft safe room in a new home or building, and approximately 20% higher to retrofit an existing building (FEMA, 2008b). However, the mean willingness to pay (WTP) reported in a study of residents of Tulsa, Oklahoma was only $2,300 (Ewing & Kruse, 2006).

Part of the issue may be that consideration of cost and affordability were not as high priority as safety in the development of FEMA 320 and 361. Cost and affordability played a slightly larger role in the development of ICC 500, but even there these factors were not explicitly considered. In contrast, the In-Home Protection Against High Winds guidance was developed by the Blue Sky Foundation of North Carolina specifically considering the cost-benefit tradeoffs of different alternatives. One of their recommended designs "…offer(s) about 76% of the protection for about half the cost of a FEMA 320 structure." (Markle, Neal & Reinhold, 2003). Costs may also be a factor in the slow adoption of use of community safe rooms. The average increase in construction cost per square foot (of safe room) is 20-32% in most of the 250 mph design wind speed areas of the country shown in Figure 1 (FEMA, 2008a).

Figure 1. Tornado Design Wind Speeds
Used For ICC 500 Shelters And FEMA Safe Rooms



Source: FEMA (2008b)

Directions for Future Research

Perhaps the most basic question that needs to be asked and answered is "What are the optimal protective actions to help ensure life safety in tornadoes?" This question is relevant to both the present situation (i.e., current warning times and methods, building stock, etc.) and the future (i.e., likely increased warning time and accuracy, improved warning communications technologies, etc.). Considering the present, research questions include: Is the current guidance for where to take refuge in homes or businesses adequate? Does the population understand and appropriately act on the available guidance? What can be done to increase identification and usage of Best Available Refuge Areas in existing buildings (a relatively low cost improvement)?

Considering the future, much research is needed to better define the wind hazard and wind loading (wind-structure interaction). What are the tornado wind speeds just above the ground, which directly effects the buildings? What are the turbulence and velocity profiles? Are tornadic winds affected by surface roughness and topographic features like straight line and thunderstorm winds? What are appropriate pressure coefficients for building surfaces?

Regarding the design of safe rooms and shelters, how can many more be built so that most people would have access to a safe place to ride out the storm? Are current requirements too stringent, creating cost impediments? Can lower cost construction methods/materials be found, and/or should there be more alternatives to current guidelines and standards that improve the benefit/cost ratio? If warning times, accuracies, and warning delivery technologies significantly improve in the future, does this open new possibilities for neighborhood and community shelters and safe rooms?

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