

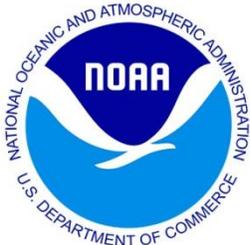
Tornado Warnings: Delivery, Economics, & Public Perception

Bibliography

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Background & Scope

The Weather Research and Forecasting Innovation Act of 2017 requires the National Oceanic and Atmospheric Administration (NOAA) to prioritize weather research to improve weather data, modeling, computing, forecasts, and warnings for the protection of life and property and the enhancement of the national economy. With this mandate NOAA is to establish a tornado warning improvement and extension program to reduce the loss of life and economic losses from tornadoes through the development and extension of accurate, effective, and timely tornado forecasts, predictions, and warnings, including the prediction of tornadoes beyond one hour in advance. This bibliography focuses on the economic impact of tornado warnings and how people behave with advanced warning. It is organized into four sections: Economic Impact, Risk & Mitigation; Public Perception & Behavior; Tornado Identification & Technology; Warning Process, Development, & Delivery.

Section 1 – Economic Impact, Risk & Mitigation

Section one is intended to provide an overview of research relating to the economic impact of tornadoes in terms of cost, risk, and mitigation. The research in this area ranges from the savings to be discovered through planning and building for tornadoes, to the various limitations of cost-loss models and the benefits found in early warning systems.

Section 2 – Public Perception & Behavior

Section two is intended to provide an overview of research relating to public reaction, behavior and perception of tornado risk and the driving factors considered when given advanced warning. Research in this area covers usage of forecast information, crowdsourcing, risk communication and decision-making among other factors like disaster education and past experience.

Section3 – Tornado Identification & Technology

Section three is intended to provide an overview of research relating to past and current tornado forecasting and advancements in technology. Research in this area includes false warnings, mobile apps, radar assessment and advances, and forecaster performance.

Section 4 – Warning Process, Development & Delivery

Section four is intended to provide an overview of research relating to the warning process, through development and delivery. Research in this area includes message effectiveness, emergency manager perspectives, modern information sourcing, and communication through various mediums i.e. using maps and visuals to communicate risk.

Sources Reviewed

Along with a web search for relevant reports from non-profits and other relevant materials the following databases were used to identify sources: Clarivate's Web of Science: Science Citation Index Expanded and Social Sciences Citation Index; Elsevier's Science Direct; ProQuest's Science and Technology, and EBSCO's PsycINFO. Only English language materials were included. There was no date range specification in order to cover any relevant research.

Section I: Economic Impact, Risk & Mitigation

Ashley, W. S., & Strader, S. M. (2016). Recipe for Disaster: How the Dynamic Ingredients of Risk and Exposure Are Changing the Tornado Disaster Landscape. *Bulletin of the American Meteorological Society*, 97(5), 767-786. <https://doi.org/10.1175/bams-d-15-00150.1>

Tornado disasters and their potential are a product of both hazard risk and underlying physical and social vulnerabilities. This investigation appraises exposure, which is an important component and driver of vulnerability, and its interrelationship with tornado risk in the United States since the mid-twentieth century. The research demonstrates how each of these dynamic variables have evolved individually and interacted collectively to produce differences in hazard impact and disaster potential at the national, regional, and local scales. Results reveal that escalating tornado impacts are driven fundamentally by growing built-environment exposure. The increasing tornado disaster probability is not uniform across the landscape, with the mid-South region containing the greatest threat based on the juxtaposition of an immense tornado footprint risk and elevated exposure/development rates, which manifests—at least for one important impact marker—in the area’s high mortality rate. Contemporary, high-impact tornado events are utilized to emphasize how national- and regional-level changes in exposure are also apparent at the scale of the tornado. The study reveals that the disaster ingredients of risk and exposure do vary markedly across scales, and where they have increasing and greater overlap, the probability of disaster surges. These findings have broad implications for all weather and climate hazards, with both short- and long-term mitigation strategies required to reduce future impacts and to build resilience in the face of continued and amplifying development in hazard-prone regions.

Coleman, T. A., Knupp, K. R., Spann, J., Elliott, J. B., & Peters, B. E. (2010). The History (and Future) of Tornado Warning Dissemination in the United States. *Bulletin of the American Meteorological Society*, 92(5), 567-582. <https://doi.org/10.1175/2010BAMS3062.1>

Since the successful tornado forecast at Tinker AFB in 1948 paved the way for the issuance of tornado warnings, the science of tornado detection and forecasting has advanced greatly. However, tornado warnings must be disseminated to the public to be of any use. The Texas tornado warning conferences in 1953 began to develop the framework for a modern tornado warning system and included radar detection of tornadoes, a spotter network, and improved communications between the U.S. Weather Bureau, spotters, and public officials, allowing more timely warnings and dissemination of those warnings to the public. Commercial radio and television are a main source of warnings for many, and the delivery methods on TV have changed much since 1960. NOAA Weather Radio (NWR) was launched after the 1974 Super Outbreak of tornadoes, with the most important feature being the tone alert that allowed receivers to alert people even when the radio broadcast was turned off. Today, NWR reaches most of the U.S. population, and Specific Area Message Encoding technology has improved its warning precision. Outdoor warning sirens, originally designed for use in enemy attack, were made available for use during tornado warnings around 1970. "Storm based" warnings, adopted by the National Weather Service in 2007, replaced countybased warnings and greatly reduce the warning area. As communications advances continue, tornado warnings will eventually be delivered to precise locations, using GPS and other location technology, through cellular telephones, outdoor sirens, e-mails, and digital television, in addition to NWR.

Donner, W. R. (2007). The Political Ecology of Disaster: An Analysis of Factors Influencing U.S. Tornado Fatalities and Injuries, 1998-2000. *Demography*, 44(3), 669-685. Retrieved from <https://link.springer.com/journal/volumesAndIssues/13524>

This study examines casualties from tornadoes in the United States between the years 1998 and 2000. A political model of human ecology (POET) was used to explore how the environment, technology, and social inequality influence rates of fatalities and injuries in two models. Data were drawn from four sources: John Hart's Severe Plot v2.0, National Weather Service (NWS) Warning Verification data, Storm Prediction Center (SPC) watch data, and tract-level census data. Negative binomial regression was used to analyze the causes of tornado fatalities and injuries. Independent variables (following POET) are classified in the following manner: population, organization, environment, and technology. Rural population, population density, and household size correspond to population; racial minorities and deprivation represent social organization; tornado area represents environment; and tornado watches and warnings, as well as mobile homes, correspond to technology. Findings suggest a strong relationship between the size of a tornado path and both fatalities and injuries, whereas other measures related to technology, population, and organization produce significant yet mixed results. Census tracts having larger populations of rural residents was, of the nonenvironmental factors, the most conclusive regarding its effects across the two models. The outcomes of analysis, although not entirely supportive of the model presented in this study, suggest to some degree that demographic and social factors play a role in vulnerability to tornadoes.

Gall, M., Borden, K. A., & Cutter, S. L. (2009). When Do Losses Count? *Bulletin of the American Meteorological Society*, 90(6), 799-810. <https://doi.org/10.1175/2008bams2721.1>

Current global and national databases that monitor losses from natural hazards suffer from a number of limitations, which in turn lead to misinterpretation and fallacies concerning the "truthfulness" of hazard loss data. These biases often go undetected by end users and are generally a product of the type of information stored in loss databases and how they are constructed. This paper highlights some common shortcomings and root causes for data misinterpretation by asking what biases are present in existing databases and how these then manifest themselves in actual loss figures. For illustrative purposes, four widely used, nonproprietary, Web-based hazard databases are examined: the international Emergency Events Database (EM-DAT), the international Natural Hazards Assessment Network (NATHAN), the Spatial Hazard Events and Losses Database for the United States (SHELDUS), and the National Weather Service's Storm Events. We identify six general biases: hazard bias, temporal bias, threshold bias, accounting bias, geographic bias, and systemic bias. To achieve resilient and sustainable communities, we need systematic and comprehensive inventories at the national as well as international level, and data that are temporally and geographically comparable.

Lave, L. B., & Apt, J. (2006). Planning for Natural Disasters in a Stochastic World. *Journal of Risk and Uncertainty*, 33(1-2), 117-130. <https://link.springer.com/journal/volumesAndIssues/11166>

We examine the risks and management of natural disasters. A benefit-cost framework focuses attention on (1) designing control structures, such as dams and levees, and mitigation policies, such as construction standards, to protect lives and property against small and medium, rather than large sized natural disasters; and (2) warning and evacuation to save lives for large natural disasters. Providing information rather than command solutions generally enhances social benefits, if people understand the

risks and bear the expected costs. Requiring actuarially fair insurance simultaneously provides information and has individuals bear the expected costs.

Lazo, J. K. (2010). The Costs and Losses of Integrating Social Sciences and Meteorology. *Weather Climate and Society*, 2(3), 171-173. <https://doi.org/10.1175/2010wcas1086.1>

Brief treatise on the cost-loss model and its use in reporting weather research to show economic impact and recommendations to move beyond this simplistic view, specifically in regard to publications in the journal *Weather, Climate and Society*.

Lim, J., Loveridge, S., Shupp, R., & Skidmore, M. (2017). Double Danger in the Double Wide: Dimensions of Poverty, Housing Quality and Tornado Impacts. *Regional Science and Urban Economics*, 65, 1-15. <https://doi.org/10.1016/j.regsciurbeco.2017.04.003>

Tornadoes are the most frequent of the natural hazards in the United States, causing significant yearly human and economic losses. Given the potential destructive power of tornado events and their largely unpredictable nature, it is important to identify the major determinants of vulnerability. To date, only a limited number of studies have empirically investigated the determinants of tornado-induced deaths. Based on a conceptual framework where risk is considered to be a function of physically defined natural hazards and socially constructed vulnerability, we extend previous empirical studies by examining a wider range of potential socioeconomic, governmental, and housing factors that determine tornado-induced fatalities. Using detailed county-level data for years 1980–2014, we find that counties with higher per capita income and per capita government spending on public safety and welfare have fewer deaths, whereas counties with greater income disparity are more vulnerable to tornadoes. We explore which aspects of poverty seem most associated with fatalities. Housing quality (measured by mobile homes as a proportion of housing units) is a critical factor in explaining tornado-induced fatalities.

Matthew, L. C., & Naim, K. (2008). Early warning systems and disaster preparedness and response in local government. *Disaster Prevention and Management: An International Journal*, 17(5), 587-600. <https://doi.org/10.1108/09653560810918621>

Purpose - The aim of this research is to better inform public policy makers and the disaster management community about the use of early warning systems. The central research question of this article is how local governments should provide early warning to the citizenry of impending tornado danger.
Design/methodology/approach - The main objectives of the paper were achieved by reviewing the literature on early warning systems for tornadoes and by conducting a content analysis of news reports, from the Orlando Sentinel newspaper, which identified the most cost-effective early warning system for tornadoes. The theoretical approach of the paper covered the responses, results, and recommendations themes from the disaster management early warning system literature.
Findings - The study concludes with a disaster management policy recommendation for an early warning system for tornadoes for local government. The paper's recommendation is to utilize the cost-effective NOAA weather radios to alert the citizenry of impending tornado danger. This recommendation is also generalizable to early warning systems for hurricanes, flash flooding, terrorist attacks, and other major natural and man-made disasters.
Research limitations/implications - A research limitation is that the paper focuses on Central Florida. Future research could begin with the paper's findings and generalize

these findings to other areas internationally. Practical implications - The paper will better inform governmental policy makers and members of the disaster management community about the early warning system alternatives available to warn the citizenry of impending tornado danger. It will hopefully begin a dialogue among disaster management practitioners and academics about early warning systems for tornadoes. Originality/value - The paper fills a gap in the tornado early warning system literature. Heretofore, there has been little writing, which this paper reviews, that compares early warning systems for tornadoes. However, the original value of the paper is that it specifically focuses on the instrument of warning the citizenry of tornadoes, the time of day of the tornado event, and the life-saving effects of tornado warnings. The value of the paper will be to public policy makers world-wide and to the growing disaster management community.

Merrell, D., Simmons, K. M., & Sutter, D. (2002). The Market for Tornado Safety: Analysis of Applications to the Oklahoma Saferoom Initiative. *Journal of Economic Insight (formerly the Journal of Economics (MVEA))*, 28(1), 35-50. Retrieved from <https://EconPapers.repec.org/RePEc:mve:journl:v:28:y:2002:i:1:p:35-50>

We examine applications to the Oklahoma Saferoom Initiative, which offered rebates to residents for construction of an in-home tornado shelter. Markets for risk mitigation are prone to market failure because consumers treat low probability, high consequence events as zero probability events. Tornado and tornado casualty rates vary across Oklahoma counties, and according to expected utility theory the application rate should vary accordingly. We confirm this prediction. Recent tornadoes and casualties, not surprisingly, predict application rates better than fifty year totals.

Miller, B. M. (2018). The Not-So-Marginal Value of Weather Warning Systems. *Weather, Climate, and Society*, 10(1), 89-101. <https://doi.org/10.1175/wcas-d-16-0093.1>

Knowing the benefits of creating or expanding programs is important for determining optimal levels of investment. Yet estimates of the benefits of weather warning systems are sparse, perhaps because there is often no clear counterfactual of how individuals would have fared without a particular warning system. This paper enriches the literature and informs policy decisions by using conditional variation in the initial broadcast dates of the National Oceanic and Atmospheric Administration's Weather Radio All Hazards (NWR) transmitters to produce both cross-sectional and fixed effects estimates of the causal impact of expanding the NWR transmitter network. Results suggest that from 1970 to 2014, expanding NWR coverage to a previously untreated county was associated with an almost 40% reduction in injuries and as much as a 50% reduction in fatalities. The benefits associated with further expansion of this system have likely declined over time.

National Institute of Building Sciences (2005). *Natural hazard mitigation saves: an independent study to assess the future savings from mitigation activities*. Retrieved from <https://www.preventionweb.net/publications/view/1087>

This report presents the results of an independent study to assess the future savings from hazard mitigation activities. The study shows that money spent on reducing the risk of natural hazards is a sound investment. On average, a dollar spent by FEMA on hazard mitigation (actions to reduce disaster losses) saves the nation about \$4 in future benefits. In addition, FEMA grants to mitigate the effects of

floods, hurricanes, tornados, and earthquakes between 1993 and 2003 are expected to save more than 220 lives and prevent almost 4,700 injuries over approximately 50 years. Hurricane Katrina painfully demonstrates the extent to which catastrophic damage affects all Americans and the federal treasury.

Scott, P., & Liang, D. (2016). What Is the Economics of Wind Hazard Mitigation? *Journal of Business Valuation and Economic Loss Analysis*, 11(1), 25-29. <https://doi.org/10.1515/jbvela-2015-0012>

Tornadoes, hurricanes, and other extreme winds cause deaths, injuries, and millions, if not billions, of dollars in damages every year in the United States. Mitigation is necessary to reduce the loss of life, anxiety and suffering, and economic losses. But how much are people willing to invest in their peace of mind? Policy makers typically use the range of \$1 million to \$10 million per life saved to determine whether a policy that would save lives should be implemented. Individuals have shown that they are willing to pay more for homes with upgrades for mitigation and safety even though they would have no insurance incentive and it is likely that the added cost only affords them peace of mind.

Shen, G., & Hwang, S. N. (2015). A spatial risk analysis of tornado-induced human injuries and fatalities in the USA. *Natural Hazards*, 77(2), 1223-1242. <https://doi.org/10.1007/s11069-015-1654-5>

Tornadoes are the most violent atmospheric hazards in the world in terms of human fatalities, injuries, and economic damages. The USA, especially the south and central states, faces numerous tornado disasters. However, there is a lack of good models for reliable tornado risk analysis. This research develops two spatial risk analysis models, base model and location quotient model, for the forty-eight continental US states, using a database for all tornadoes reported during 1950–2012. The models are based on state-level expected losses, standard deviations, and their corresponding state-level percentages, ranges, and ranks of tornado-induced human injuries and fatalities. The models are validated using Pearson's and Spearman's correlations and scatter plots for samples and population of the tornado database. The results show that the models perform well in terms of yielding consistent expected tornado risks and related measures at the state level. The models serve as good alternatives to existing models for spatial tornado risks and ranks in the USA.

Simmons, K., & Sutter, D. (2011). *Economic and Societal Impacts of Tornadoes*.

For almost a decade, economists Kevin M. Simmons and Daniel Sutter have been studying the economic effects and social consequences of the approximately 1,200 tornadoes that touch down across the United States annually. During this time, they have compiled information from sources such as NOAA and the U.S. Census Bureau to examine the casualties caused by tornadoes and to evaluate the National Weather Service (NWS)'s efforts to reduce these casualties. Their unique database has enabled this fascinating and game-changing study for meteorologists, social scientists, emergency managers, and everyone studying severe weather, policy, disaster management, or applied economics.

Simmons Kevin, M., & Sutter, D. (2006). Direct Estimation of the Cost Effectiveness of Tornado Shelters. *Risk Analysis*, 26(4), 945-954. <https://doi.org/10.1111/j.1539-6924.2006.00790.x>

This article estimates the cost effectiveness of tornado shelters using the annual probability of a tornado and new data on fatalities per building struck by a tornado. This approach differs from recent estimates

of the cost effectiveness of tornado shelters in Reference 1 that use historical casualties. Historical casualties combine both tornado risk and resident action. If residents of tornado-prone states take greater precautions, observed fatalities might not be much higher than in states with lower risk. Estimation using the tornado probability avoids this potential bias. Despite the very different method used, the estimates are \$68 million in permanent homes and \$6.0 in mobile homes in Oklahoma using a 3% real discount rate, within about 10% of estimates based on historical fatalities. The findings suggest that shelters provide cost-effective protection for mobile homes in the most tornado-prone states but not for permanent homes.

Simmons, K. M., & Sutter, D. (2007). Tornado shelters and the housing market. *Construction Management and Economics*, 25(11), 1119-1126. <https://doi.org/10.1080/01446190701618299>

Mitigation against natural hazards often involves long-lived, immobile investments. Home owners must be able to capture the present value of future benefits to equate the private and societal return on mitigation. The capitalization of mitigation into home prices thus is crucial for home owners to have a proper incentive for mitigation. We investigate the existence of a premium for tornado shelters using home sales in Oklahoma City, where the deadly tornado outbreak of 3 May 1999 and the Oklahoma Saferoom Initiative increased public awareness of tornado shelters. We find that a shelter increases the sale price of a home by 3.5% to 4% or approximately \$4200 given the mean price of homes sold in 2005. The magnitude of the premium is plausible given that shelters retail for \$2500-\$3000 installed.

Smith, A. B., & Katz, R. W. (2013). US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases. *Natural Hazards*, 67(2), 387-410. <https://doi.org/10.1007/s11069-013-0566-5>

This paper focuses on the US Billion-dollar Weather/Climate Disaster report by the National Oceanic and Atmospheric Administration's National Climatic Data Center. The current methodology for the production of this loss dataset is described, highlighting its strengths and limitations including sources of uncertainty and bias. The Insurance Services Office/Property Claims Service, the US Federal Emergency Management Agency's National Flood Insurance Program and the US Department of Agriculture's crop insurance program are key sources of quantified disaster loss data, among others. The methodology uses a factor approach to convert from insured losses to total direct losses, one potential limitation. An increasing trend in annual aggregate losses is shown to be primarily attributable to a statistically significant increasing trend of about 5 % per year in the frequency of billion-dollar disasters. So the question arises of how such trend estimates are affected by uncertainties and biases in the billion-dollar disaster data. The net effect of all biases appears to be an underestimation of average loss. In particular, it is shown that the factor approach can result in a considerable underestimation of average loss of roughly 10–15 %. Because this bias is systematic, any trends in losses from tropical cyclones appear to be robust to variations in insurance participation rates. Any attribution of the marked increasing trends in crop losses is complicated by a major expansion of the federally subsidized crop insurance program, as a consequence encompassing more marginal land. Recommendations concerning how the current methodology can be improved to increase the quality of the billion-dollar disaster dataset include refining the factor approach to more realistically take into account spatial and temporal variations in insurance participation rates.

Sutter, D., & Erickson, S. (2010). The Time Cost of Tornado Warnings and the Savings with Storm-Based Warnings. *Weather, Climate, and Society*, 2(2), 103-112.
<https://doi.org/10.1175/2009wcas1011.1>

The authors examine the cost of time spent under tornado warnings issued annually by the National Weather Service (NWS). County-based tornado warnings imposed substantial costs on the nation: an average of 234 million person-hours spent under warnings annually between 1996 and 2004, with a value of \$2.7 billion (U.S. dollars) per year. Counties are large relative to tornado damage areas; therefore, county-based warnings overwarned for tornadoes, warning many persons a safe distance from the storm and not in immediate danger. In October 2007 the NWS introduced storm-based warnings (SBW) for tornadoes, which are expected to reduce the area warned by 70%–75%. SBW consequently will reduce the time spent under warnings by over 160 million person-hours per year, with a value of \$1.9 billion. The time spent under warnings does not measure the full cost to society because many people do not respond to the warnings. Adjusting for warning response, this study estimates that SBW might save 66 million person-hours actually spent sheltering a year with a value of \$750 million. Sensitivity analysis indicates that the value of time spent sheltering saved by SBW exceeds \$100 million per year with a probability of 0.95.

Sutter, D., & Poitras, M. (2010). Do people respond to low probability risks? Evidence from tornado risk and manufactured homes. *Journal of Risk and Uncertainty*, 40(2), 181-196.
<https://doi.org/10.1007/s11166-010-9087-8>

Whether people perceive and respond to low-probability natural hazards is a research question of considerable policy relevance. We obtain evidence by considering the response of housing choice to tornado risk for manufactured homes. The vulnerability of manufactured housing, combined with its growing share of the U.S. housing market, has led to proposed mandates for community shelters in mobile home parks. Expected utility theory, however, predicts that households should account for tornado risk in their housing choice. We test for an effect of tornado risk on manufactured housing demand using cross-sectional state data, as well as counties in three tornado prone states. We find that people do respond to tornado risk; our estimates indicate that each expected annual state tornado death per million residents reduces demand for manufactured homes by about 3%. The estimated quantity effect is consistent with the market studies of the price elasticity of manufactured homes.

Sutter, D., & Simmons Kevin, M. (2014). Preparing for Danger: On the Impact of Tornado Watches on Tornado Casualties. *International Journal of Mass Emergencies and Disasters*, 32(1), 1-25.
Retrieved from <http://www.ijmed.org/articles/647/>

We explore the impact of tornado watches on tornado casualties. The time needed to take shelter for a tornado can be as little as a few minutes, but because warning lead times averaged less than 15 minutes in 2004, a watch could alert residents to be ready to receive and respond to a later warning. We find that casualties per tornado are greater for tornadoes occurring within a tornado watch, although this difference vanishes when controlling for tornado, warning, and path characteristics in a regression analysis. We find no evidence that watches reduce casualties, either directly or by increasing the effectiveness of tornado warnings. Tornadoes occurring within watches are more often warned for and warnings reduce casualties, so watches do contribute to lives saved through the warning process.

Sutter, D., & Stephenson, E. (2008). Political Economy and Natural Hazards Mitigation: State Incentives for Tornado Shelters. *Journal of Public Finance and Public Choice/Economia delle Scelte Pubbliche*, 26(2-3), 77-92. Retrieved from http://www.gangemeditore.com/categoria.php?id_categoria=33

Hurricane Katrina has spurred public choice economists' interest in the political economy of natural hazards. We provide a case study in the political economy of hazards mitigation from tornado shelters in Oklahoma. We analyze the determinants of support for a referendum for a tax exemption for tornado shelters, and then the number of shelters enrolled for the exemption. Generally the determinants of support for the referendum are consistent with the determinants of subsequent shelter installation. Particularly, greater tornado risk increase both support for the referendum and installation, which suggests that individuals do not ignore a low probability natural hazard risk either as voters or consumers.

World Meteorological Organization (2014). *The atlas of mortality and economic losses from weather, climate and water extremes 1970-2012.pdf*. Retrieved from <https://public.wmo.int/en/resources/library/atlas-mortality-and-economic-losses-weather-and-climate-extremes-1970-2012>

The Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2012) seeks to raise awareness of these and other challenges to collecting and analyzing disaster risk information. It presents a worldwide analysis of extreme weather, climate and water events, drawing on the Emergency Events Database (EM-DAT), compiled by the Centre for Research on the Epidemiology of Disasters (CRED). The Atlas compares the reported impacts of meteorological, climatic and hydrological extremes (as categorized by CRED) on people and economies at both global and regional levels.

Section II: Public Perception & Behavior

Allan, J. N., Ripberger, J. T., Ybarra, V. T., & Cokely, E. T. (2017). The Oklahoma Warning Awareness Scale: A Psychometric Analysis of a Brief Self-Report Survey Instrument. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 61(1), 1203-1207. <https://doi.org/10.1177/1541931213601783>

Natural hazards (e.g., earthquakes, tornadoes, floods) pose many risk communication challenges for emergency managers and policy makers. Critical obstacles to risk readiness are often attributed to differences in (a) warning awareness, (b) risk understanding, and (c) behavioral responses. Although a considerable body of research has focused on risk understanding (see www.RiskLiteracy.org) there is relatively less research mapping individual differences in warning awareness and related vulnerabilities. Here, we present a psychometric study (n=254) with cross-validation, testing a two parameter polytomous logistic model of subjective warning awareness (i.e., people's assessment of how likely they are to receive risk and hazard warnings from trusted sources). The final instrument included four items and one criterion that may be related to other important natural hazard response behaviors, providing a foundation for continuing exploration of warning awareness. Discussion focuses on potential

applications of the Oklahoma Warning Awareness Scale as it pertains to natural hazards and other risks more broadly.

Ash, K. D. (2017). A qualitative study of mobile home resident perspectives on tornadoes and tornado protective actions in South Carolina, USA. *GeoJournal*, 82(3), 533-552.
<https://doi.org/10.1007/s10708-016-9700-8>

Occupants of mobile or manufactured homes in the United States of America (USA) are highly exposed and susceptible to injury or death from tornado hazards. This problem is most pronounced in the southern and eastern USA, where tornadoes are frequent and mobile homes comprise upwards of 15 % of the housing stock. Recognizing this vulnerability, emergency management entities and the USA National Weather Service often recommend that mobile home residents evacuate to a nearby sturdy building or a specially-built tornado shelter when tornadoes threaten their communities. Previous research suggests, however, that only 30 % of residents follow this recommendation. In this research I aim to provide insight as to why many mobile home residents seldom undertake the suggested course of action for tornadoes. Using excerpts from twenty semi-structured interviews conducted during 2013 in South Carolina, I show that some individuals understand physical characteristics of tornadoes very differently than experts do. In addition, mobile home residents may also hold views that differ from experts about the ability of their homes to withstand tornadic winds and debris. Even if mobile home occupants pay close attention to thunderstorm hazards and might be willing to evacuate, they may prioritize protective actions for lightning or flash flooding over those recommended for tornadoes. Finally, the interviews reveal that there is much confusion over where to go, when to leave, and which route to take to arrive safely at a sheltering place for tornado hazards. I discuss some of the potential ramifications of the findings for theory and practice and suggest how future research might build on this work.

Ash, K. D., Schumann, R. L., & Bowser, G. C. (2014). Tornado Warning Trade-Offs: Evaluating Choices for Visually Communicating Risk. *Weather Climate and Society*, 6(1), 104-118.
<https://doi.org/10.1175/wcas-d-13-00021.1>

Recent improvements in weather observation and monitoring have increased the precision of tornado warnings. The National Weather Service currently issues storm-based tornado warnings, and even more geographically specific warnings that include probability information are under development. At the same time, the widespread proliferation of smartphone and mobile computing technology supports the rapid dissemination of graphical weather warning information. Some broadcasters and private companies have already begun using probabilistic-style tornado warning graphics. However, the development of these new types of warnings has occurred with limited research on how users interpret probabilistic visualizations. This study begins filling this void by examining responses to color scheme and relative position using probabilistic tornado warning designs. A survey of university students is used to measure the level of perceived fear and likelihood of protective action for a series of hypothetical warning scenarios. Central research questions investigate 1) differences in responses across warning designs, 2) clustering of extreme responses in each design, 3) trends in responses with respect to probability levels, 4) differences in responses inside versus outside the warnings, and 5) differences in responses near the edges of the warning designs. Results suggest a variety of trade-offs in viewer responses to tornado warnings based on visual design choices. These findings underscore the need for more comprehensive research on visualizations in weather hazard communication that can aid

meteorologists in effectively warning the public and spur appropriate tornado protection behaviors in a timely manner.

Balluz, L., Schieve, L., Holmes, T., Kiezak, S., & Malilay, J. (2002). Predictors for People's Response to a Tornado Warning: Arkansas, 1 March 1997. *Disasters*, 24(1), 71-77.
<https://doi.org/10.1111/1467-7717.00132>

On 1 March 1997, powerful tornadoes touched down in Arkansas (USA) on a Saturday afternoon. Twenty-six fatalities and 400 non-fatal injuries were reported. We performed a population-based cross-sectional study to determine factors associated with appropriate responses to tornado warnings. Of 146 survey participants, 140 (96 per cent) knew the difference between -tornado watch- and -tornado warning- and were aware of when the warning was announced. Of those 140 participants, 64 (45.7 per cent) responded to the warning by seeking shelter, and 58 (90.6 per cent) of those 64 acted within five minutes of hearing the warning. Four factors were positively associated with those seeking shelter: having graduated from high school (OR = 4.2, 95 per cent CI =1.1-15.5); having a basement in one's house (OR = 3.8, 95 per cent exact CI=1.1-17.1); hearing a siren (OR = 4.4, 95 per cent CI = 1.3-18.9); and having prepared a household plan of response when tornadoes occur (OR=2.6, 95 per cent CI = 1.1->6.3). On the basis of these findings, we recommend: first, that people who live in tornado-prone areas have a personal plan of action to help them respond immediately to warnings; second, public-health education officials in areas with frequent tornadic activity should do more to educate the public about what they can do to protect themselves from a tornado; and third, that emergency-management officials planning protection measures for vulnerable communities should consider that most people have limited time (our study documented five minutes) in which to respond to a tornado warning. Thus, shelters in tornado-prone areas should be quickly accessible by residents.

Barry, D., Baruch, F., Alexander, D., & Stephen, B. B. (2015). Environmental risk perception from visual cues: the psychophysics of tornado risk perception. *Environmental Research Letters*, 10(12), 124009. <https://doi.org/10.1088/1748-9326/10/12/124009>

Lay judgments of environmental risks are central to both immediate decisions (e.g., taking shelter from a storm) and long-term ones (e.g., building in locations subject to storm surges). Using methods from quantitative psychology, we provide a general approach to studying lay perceptions of environmental risks. As a first application of these methods, we investigate a setting where lay decisions have not taken full advantage of advances in natural science understanding: tornado forecasts in the US and Canada. Because official forecasts are imperfect, members of the public must often evaluate the risks on their own, by checking environmental cues (such as cloud formations) before deciding whether to take protective action. We study lay perceptions of cloud formations, demonstrating an approach that could be applied to other environmental judgments. We use signal detection theory to analyse how well people can distinguish tornadic from non-tornadic clouds, and multidimensional scaling to determine how people make these judgments. We find that participants (N = 400 recruited from Amazon Mechanical Turk) have heuristics that generally serve them well, helping participants to separate tornadic from non-tornadic clouds, but which also lead them to misjudge the tornado risk of certain cloud types. The signal detection task revealed confusion regarding shelf clouds, mammatus clouds, and clouds with upper- and mid-level tornadic features, which the multidimensional scaling task suggested was the result of participants focusing on the darkness of the weather scene and the ease of discerning its features. We recommend procedures for training (e.g., for storm spotters) and communications (e.g.,

tornado warnings) that will reduce systematic misclassifications of tornadicity arising from observers' reliance on otherwise useful heuristics.

Blanchard-Boehm, R. D., & Cook, M. J. (2004). Risk Communication and Public Education in Edmonton, Alberta, Canada on the 10th Anniversary of the 'Black Friday' Tornado. *International Research in Geographical and Environmental Education*, 13(1), 38-54.
<https://doi.org/10.1080/10382040408668791>

In July 1997, on the 10th anniversary of the great 'Black Friday' Tornado, city officials of Edmonton, the print and broadcast media, agencies dealing in emergency management, and the national weather organisation recounted stories of the 1987, F5 tornado that struck Edmonton on a holiday weekend. The information campaign also presented environmental and educational information regarding a range of protective measures that should be adopted in the event of another tornado strike. A unique opportunity arose to study the effects of the 1997 risk communication campaign, and to assess the extent to which a random sample from the population of Edmonton heard, understood, believed, confirmed, and responded to the low-key, non-urgent, environmental and educational warning messages. These behaviours comprise the General Hazards Risk Communication Model that guided this study, as developed by Mileti, Sorensen, Haas, Blanchard-Boehm and others. We found the following explanatory variables to be statistically significant in predicting whether our survey respondents adopted protective measures towards future occurrences of tornadoes following the information campaign: (1) levels of perceived vulnerability to future occurrences; (2) past experiences with the 1987 tornado event; (3) presentation of new environmental and educational information in the 1997 campaign; and, (4) levels of formal education.

Casteel, M. A. (2018). An empirical assessment of impact based tornado warnings on shelter in place decisions. *International Journal of Disaster Risk Reduction*.
<https://doi.org/10.1016/j.ijdrr.2018.01.036>

In the spring of 2012, the United States' National Weather Service implemented new impact based tornado warnings (IBWs) that include information about predicted storm impacts to improve the likelihood of one taking protective action. In addition to including more extreme language, IBWs for especially intense tornadoes include threat tags labeling the impact as "considerable" or "catastrophic." Research by the author Casteel (2016) [3] showed that, when compared to non-IBWs, IBWs for low intensity tornadoes produced higher intentions of sheltering in place. The research reported here builds upon that earlier work. In four experiments, IBWs for stronger tornadoes are compared to those for weaker tornadoes, to assess whether the severe language used in the higher impact IBWs motivates higher sheltering intentions. Participants adopted the role of a plant manager tasked with keeping employees safe and read IBWs containing differing impact and severity language. At three decision points, the participants stated their likelihood of having employees shelter in place. In three of four experiments, the results show that any warning containing impact language stronger than a low intensity IBW, regardless of the presence of threat tags or extreme language, produced higher sheltering intentions. Additionally, sheltering decisions to "considerable" or "catastrophic" warnings did not differ in two experiments involving adult samples. These results suggest that the heightened risk transmitted by the stronger impact statements does communicate increased risk and that extreme language is not necessary to craft an effective tornado warning.

Chatfield, A. T., & Brajawidagda, U. (2014). Crowdsourcing Hazardous Weather Reports from Citizens via Twittersphere under the Short Warning Lead Times of EF5 Intensity Tornado Conditions. In R. H. Sprague (Ed.), *2014 47th Hawaii International Conference on System Sciences* (pp. 2231-2241). <https://doi.org/10.1109/hicss.2014.281>

The May 20 2013 tornado in Oklahoma has demonstrated the short warning lead times of EF5 intensity tornadoes, even with the integrated Next Generation Weather Surveillance Doppler Radar network, remain a challenge both for governments responsible for early warnings and citizens who need to respond appropriately. Although research on government use of social media for adaptable disaster response is emerging, little is known about social media-mediated early tornado warnings and crowdsourcing in the e-government literature. This research, therefore, aims to reduce this gap in the literature through a case study of the National Weather Service's experimental use of Twitter for crowdsourcing hazardous weather reports from citizens during and in the immediate aftermath of the May 20 tornado. Our social network analysis and content analysis results found evidence for value of the #okwx Twittersphere to tie closely the government and volunteer citizen tornado watchers and enable multidirectional interactive conversations and crowdsourcing.

Dash, N., & Gladwin, H. (2007). Evacuation Decision Making and Behavioral Responses: Individual and Household. *Natural Hazards Review*, 8(3), 69-77. [https://doi.org/10.1061/\(ASCE\)1527-6988\(2007\)8:3\(69\)](https://doi.org/10.1061/(ASCE)1527-6988(2007)8:3(69))

Researchers have examined a wide range of factors that affect evacuation decisions after people hear hurricane forecasts and other information. This review of the literature focuses on three broad areas of research that often overlap: warning, risk perception, and evacuation research. Whereas it is challenging to demarcate the literature along these lines, we believe each of these areas represents important dimensions of evacuation decision making. The literature on warning focuses to varying degrees on warning as a social process, rather than a simple result of hearing official warnings. Warnings by themselves do not motivate evacuation—people must perceive risk. The extensive literature on objective and subjective processes in risk perception has to be evaluated. The review concludes with a focus on some important work in modeling evacuation and evacuation decision-making. Finally, we present recommendations for future research that draws on the strength of earlier work while focusing more directly on risk, the information included in hurricane forecasts, and the timing of those forecasts.

Demuth, J. L. (2018). Explicating Experience: Development of a Valid Scale of Past Hazard Experience for Tornadoes. *Risk Anal*, 0(0). <https://doi.org/10.1111/risa.12983>

People's past experiences with a hazard theoretically influence how they approach future risks. Yet, past hazard experience has been conceptualized and measured in wide-ranging, often simplistic, ways, resulting in mixed findings about its relationship with risk perception. This study develops a scale of past hazard experiences, in the context of tornadoes, that is content and construct valid. A conceptual definition was developed, a set of items were created to measure one's most memorable and multiple tornado experiences, and the measures were evaluated through two surveys of the public who reside in tornado-prone areas. Four dimensions emerged of people's most memorable experience, reflecting their awareness of the tornado risk that day, their personalization of the risk, the intrusive impacts on them personally, and impacts experienced vicariously through others. Two dimensions emerged of

people's multiple experiences, reflecting common types of communication received and negative emotional responses. These six dimensions are novel in that they capture people's experience across the timeline of a hazard as well as intangible experiences that are both direct and indirect. The six tornado experience dimensions were correlated with tornado risk perceptions measured as cognitive-affective and as perceived probability of consequences. The varied experience-risk perception results suggest that it is important to understand the nuances of these concepts and their relationships. This study provides a foundation for future work to continue explicating past hazard experience, across different risk contexts, and for understanding its effect on risk assessment and responses.

Demuth, J. L., Lazo, J. K., & Morss, R. E. (2011). Exploring Variations in People's Sources, Uses, and Perceptions of Weather Forecasts. *Weather, Climate, and Society*, 3(3), 177-192. <https://doi.org/10.1175/2011WCAS1061.1>

Past research has shown that individuals vary in their attitudes and behaviors regarding weather forecast information. To deepen knowledge about these variations, this article explores 1) patterns in people's sources, uses, and perceptions of everyday weather forecasts; and 2) relationships among people's sources, uses, and perceptions of forecasts, their personal characteristics, and their experiences with weather and weather forecasts. It does so by performing factor and regression analysis on data from a nationwide survey of the U.S. public, combined with other data. Forecast uses factored into planning for leisure activities and for work/school-related activities, while knowing what the weather will be like and planning how to dress remained separate. Forecast parameters factored into importance of precipitation parameters and of temperature-related parameters, suggesting that these represent conceptually different constructs. Regression analysis showed that the primary drivers for how often people obtain forecasts are what they use forecasts for and their perceived importance of and confidence in forecast information. People's forecast uses are explained in large part by their frequency of obtaining forecasts and their perceived importance of temperature-related and precipitation forecast information. This suggests that that individual's frequency of obtaining forecasts, forecast use, and importance of forecast parameters are closely interrelated. Sociodemographic characteristics and, to a lesser extent, weather-related experience also influence some aspects of people's forecast sources, uses, and perceptions. These findings continue to build understanding of variations among weather forecast users, which can help weather information providers improve communication of forecasts to better meet users' needs.

Drost, R. (2013). Memory and Decision Making: Determining Action when the Sirens Sound. *Weather Climate and Society*, 5(1), 43-54. <https://doi.org/10.1175/wcas-d-11-00042.1>

Memories, both semantic, or learned knowledge, and episodic, or personal experiences, play an important role in an individual's decision making under risk. In addition, varying levels of knowledge and experience exist in each individual. These memories enable individuals to make informed decisions based on previous knowledge or experience, and ultimately influence one's behavior under risk. In this study, 49 undergraduate students participated in a 1-h, classroom-based experiment focusing on decision making. The sample contained n = 23 "episodic" participants, referred to as "high episodic," who reported having personally experienced a tornado and n = 24 participants, referred to as "low episodic," who had no reported tornado experience. Incomplete data reported by the remaining participants were not included in this study. All participants completed a decision-making task both before and after viewing a 5-min slideshow stimulus related to tornadoes and associated damage. This

decision-making task prompted participants to describe the actions they would anticipate taking during an actual tornado warning. Prior to the stimulus, high episodic participants exhibited a marginally higher tendency to ignore a tornado warning than those participants without episodic (low episodic) memories. After the tornado stimulus, all participants reported a greater likelihood to engage in precautionary action than reported prior to the stimulus. It is also found that 1) those participants with low episodic memory showed greater precaution than the high episodic memory group, and 2) participants with greater knowledge of tornadoes showed the greatest gains in anticipated precautionary behavior. This study suggests that increasing a population's general knowledge of tornadoes could result in greater individual precaution and overall safety during a tornadic event.

Durage, S. W., Kattan, L., Wirasinghe, S. C., & Ruwanpura, J. Y. (2014). Evacuation behaviour of households and drivers during a tornado. *Natural Hazards*, 71(3), 1495-1517. <https://doi.org/10.1007/s11069-013-0958-6>

With increasing concerns over the possibility of tornadoes in highly populated areas in Canada, emergency managers are looking into ways to mitigate the impacts of tornadoes. Given that tornadoes can cause enormous destruction, early warnings and proper evacuation actions are critically important in helping save lives. In this paper, a survey was conducted to analyse the evacuation behaviour of households and drivers during a hypothetical tornado warning situation in the city of Calgary, Alberta. Nearly 500 Calgarians took part in the online survey and provided information on how they would respond to tornado warnings after receiving them. This paper presents the results of the survey. Using probit models, the factors influencing these evacuation decisions are identified and discussed in detail. The results of the household evacuation model show the importance of improving awareness about the safest locations during a tornado. It further highlights the need for targeting the population under the age of 30, who are more likely to take unsafe evacuation actions. The model for evacuation of drivers shows that several factors, such as knowing the difference between a watch and a warning, awareness of safe cover, receipt of warnings through natural environmental cues and the level of education, trigger evacuation actions in avoiding a tornado threat.

Durage, S. W., Wirasinghe, S. C., & Ruwanpura, J. Y. (2016). Decision Analysis for Tornado Warning and Evacuation. *Natural Hazards Review*, 17(1), 04015014. [https://doi.org/10.1061/\(ASCE\)NH.1527-6996.0000195](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000195)

Uncertainties associated with decision making regarding tornado warnings can lead to false warnings and missed events. A false warning is a situation when the public is warned about a tornado and one does not actually occur. A missed event is a catastrophic situation where a tornado touchdown occurs without an advance warning. This paper mainly focuses on how false warnings and missed events influence the decision-making process of households and forecasters. The underlying factors for false warnings and missed events are analyzed in detail. Forecasters' decision making about tornado warnings and the public's decision to respond to a warning are analyzed using a probabilistic decision-tree approach. A logical basis for decision making is developed, and a fundamental inequality for decisions regarding tornado warnings is identified. This logical basis is applicable to other disasters as well. False warning and missed event probabilities are analyzed using the data from the Canadian Prairies. The overall analysis is applicable to improve the tornado-warning performance in the Canadian Prairies.

Hoekstra, S., Klockow, K., Riley, R., Brotzge, J., Brooks, H., & Erickson, S. (2011). A Preliminary Look at the Social Perspective of Warn-on-Forecast: Preferred Tornado Warning Lead Time and the General Public's Perceptions of Weather Risks. *Weather Climate and Society*, 3(2), 128-140. <https://doi.org/10.1175/2011wcas1076.1>

Tornado warnings are currently issued an average of 13 min in advance of a tornado and are based on a warn-on-detection paradigm. However, computer model improvements may allow for a new warning paradigm, warn-on-forecast, to be established in the future. This would mean that tornado warnings could be issued one to two hours in advance, prior to storm initiation. In anticipation of the technological innovation, this study inquires whether the warn-on-forecast paradigm for tornado warnings may be preferred by the public (i.e., individuals and households). The authors sample is drawn from visitors to the National Weather Center in Norman, Oklahoma. During the summer and fall of 2009, surveys were distributed to 320 participants to assess their understanding and perception of weather risks and preferred tornado warning lead time. Responses were analyzed according to several different parameters including age, region of residency, educational level, number of children, and prior tornado experience. A majority of the respondents answered many of the weather risk questions correctly. They seemed to be familiar with tornado seasons; however, they were unaware of the relative number of fatalities caused by tornadoes and several additional weather phenomena each year in the United States. The preferred lead time was 34.3 min according to average survey responses. This suggests that while the general public may currently prefer a longer average lead time than the present system offers, the preference does not extend to the 1–2-h time frame theoretically offered by the warn-on-forecast system. When asked what they would do if given a 1-h lead time, respondents reported that taking shelter was a lesser priority than when given a 15-min lead time, and fleeing the area became a slightly more popular alternative. A majority of respondents also reported the situation would feel less life threatening if given a 1-h lead time. These results suggest that how the public responds to longer lead times may be complex and situationally dependent, and further study must be conducted to ascertain the users for whom the longer lead times would carry the most value. These results form the basis of an informative stated-preference approach to predicting public response to long (>1 h) warning lead times, using public understanding of the risks posed by severe weather events to contextualize lead-time demand.

Hoss, F., & Fischbeck, P. (2017). Use of Observational Weather Data and Forecasts in Emergency Management: An Application of the Theory of Planned Behavior. *Weather, Climate, and Society*, 10(2), 275-290. <https://doi.org/10.1175/WCAS-D-16-0088.1>

Many factors affect the extent to which forecasts inform emergency responses. In a survey based on the Theory of Planned Behavior (TPB), 207 U.S. emergency managers (EMs) were asked about 1) their past and intended future use of short-term weather forecasts and recorded weather data, 2) the perceived limitations and 3a) their attitude toward the usefulness of such weather information, 3b) their attitude toward their job and toward uncertainty, 4) perceived social norms, and 5) self-assessed numeracy. Work experience was found to be the best predictor of whether an emergency manager relied on recorded weather data and short-term weather forecasts in the past or intends to do so in the future. Among TPB variables, mainly social expectations and data attitude drive the reliance on recorded weather data and short-term forecasts. The EMs' perception of the weather information's limitations is related to their perceptions of what their social surroundings think. In sum, this article sheds light on when and why EMs use weather data and forecasts and how training can be improved.

Jauernic, S. T., & Van Den Broeke, M. S. (2016). Perceptions of tornadoes, tornado risk, and tornado safety actions and their effects on warning response among Nebraska undergraduates. *Natural Hazards*, 80(1), 329-350. <https://doi.org/10.1007/s11069-015-1970-9>

A survey of 613 undergraduates at a large public university in Nebraska was used to study how participants perceive tornadoes, tornado risk, and appropriate safety actions. Questions were asked to gauge participants' overall tornado knowledge and response to tornado threat. Many students sought more information before responding to warnings and reported this additional confirmatory information would be necessary for them to respond to future warnings. Some variables were found to be positively or negatively associated with having safety plans and sheltering decisions. Those who responded to the highest proportion of warnings were from the Great Plains, perceived the local city as equally likely to be affected by a tornado compared to the surrounding region, and reported learning tornado-related information primarily from their parents. International students and those gaining most of their tornado-related knowledge from school responded to fewer warnings and took less safe actions overall. Many myths about tornado behavior and tornado safety were found to be prevalent.

Jon, I., Huang, S.-K., & Lindell, M. K. (2018). Perceptions and reactions to tornado warning polygons: Would a gradient polygon be useful? *International Journal of Disaster Risk Reduction*. <https://doi.org/10.1016/j.ijdr.2018.01.035>

The National Weather Service has adopted warning polygons that more specifically indicate the risk area than its previous county-wide warnings. However, these polygons are not defined in terms of numerical strike probabilities (ps). To better understand people's interpretations of warning polygons, 167 participants were shown 23 hypothetical scenarios in one of three information conditions—polygon-only (Condition A), polygon + tornadic storm cell (Condition B), and polygon + tornadic storm cell + flanking nontornadic storm cells (Condition C). Participants judged each polygon's ps and reported the likelihood of taking nine different response actions. The polygon-only condition replicated the results of previous studies; ps was highest at the polygon's centroid and declined in all directions from there. The two conditions displaying storm cells differed from the polygon-only condition only in having ps just as high at the polygon's edge nearest the storm cell as at its centroid. Overall, ps values were positively correlated with expectations of continuing normal activities, seeking information from social sources, seeking shelter, and evacuating by car. These results indicate that participants make more appropriate ps judgments when polygons are presented in their natural context of radar displays than when they are presented in isolation. However, the fact that ps judgments had moderately positive correlations with both sheltering (a generally appropriate response) and evacuation (a generally inappropriate response) suggests that experiment participants experience the same ambivalence about these two protective actions as people threatened by actual tornadoes.

Jon, I., Huang, S. K., & Lindell, M. K. (2017). Perceptions and Expected Immediate Reactions to Severe Storm Displays. *Risk Analysis*. <https://doi.org/10.1111/risa.12896>

To better understand people's interpretations of National Weather Service's tornado warning polygons, 145 participants were shown 22 hypothetical scenarios in one of four displays—deterministic polygon, deterministic polygon + radar image, gradient polygon, and gradient polygon + radar image. Participants judged each polygon's numerical strike probability (ps) and reported the likelihood of taking seven

different response actions. The deterministic polygon display produced ps that were highest at the polygon's centroid and declined in all directions from there. The deterministic polygon + radar display, the gradient polygon display, and the gradient polygon + radar display produced ps that were high at the polygon's centroid and also at its edge nearest the tornadic storm cell. Overall, ps values were negatively related to resuming normal activities, but positively correlated with expectations of resuming normal activities, seeking information from social sources, seeking shelter, and evacuating by car. These results replicate the finding that participants make more appropriate ps judgments when polygons are presented in their natural context of radar images than when the polygons are presented in isolation and that gradient displays appear to provide no appreciable benefit. The fact that ps judgments had moderately positive correlations with both sheltering (a generally appropriate response) and evacuation (a generally inappropriate response) provides experimental confirmation that people threatened by actual tornadoes are conflicted about which protective action to take.

Kanti, P. B., Mitchel, S., & Marcellus, C. (2015). Predictors of compliance with tornado warnings issued in Joplin, Missouri, in 2011. *Disasters*, 39(1), 108-124. <https://doi.org/10.1111/disa.12087>

Joplin, a city in the southwest corner of Missouri, United States, suffered an EF-5 tornado in the late afternoon of 22 May 2011. This event, which claimed the lives of 162 people, represents the deadliest single tornado to strike the US since modern record-keeping began in 1950. This study examines the factors associated with responses to tornado warnings. Based on a post-tornado survey of survivors in Joplin, it reveals that tornado warnings were adequate and timely. Multivariate logistic regression identified four statistically significant determinants of compliance with tornado warnings: number of warning sources, whether respondents were at home when the tornado struck, past tornado experience, and gender. The findings suggest several recommendations, the implementation of which will further improve responses to tornado warnings.

Kathleen, S. M. (2013). The Public Response to Hazardous Weather Events: 25 Years of Research. *Geography Compass*, 7(10), 669-685. <https://doi.org/10.1111/gec3.12076>

Recent disasters with high numbers of fatalities such as Hurricane Katrina or the 2011 southeastern tornado outbreak demonstrate the need to understand the public's response in extreme weather events. Much of what we know about how an individual responds to a weather hazard comes from case study research on behaviors and perceptions following single events. Because many of the actions are context specific, it is important to periodically review these case studies as a group to identify any trends that cut across hazards or locations. This paper examines research on individual-level response to weather hazards from 1988 to 2012 and identifies similarities among the events. In conducting the review, the author also identified those areas in the response to hazardous weather events that are least frequently studied, including response to extreme heat and winter storms and to a lesser extent the response to flood events in the USA. Subjects covered in many of the papers included how one becomes aware of the hazard, how one responds, and what factors influence the response. Each of these subjects is discussed for each type of event, followed by a summary of the generalizations that may be made from these case studies.

Kellens, W., Terpstra, T., & De Maeyer, P. (2013). Perception and communication of flood risks: a systematic review of empirical research. *Risk Anal*, 33(1), 24-49. <https://doi.org/10.1111/j.1539-6924.2012.01844.x>

Flood hazards are the most common and destructive of all natural disasters. For decades, experts have been examining how flood losses can be mitigated. Just as in other risk domains, the study of risk perception and risk communication has gained increasing interest in flood risk management. Because of this research growth, a review of the state of the art in this domain is believed necessary. The review comprises 57 empirically based peer-reviewed articles on flood risk perception and communication from the Web of Science and Scopus databases. The characteristics of these articles are listed in a comprehensive table, presenting research design, research variables, and key findings. From this review, it follows that the majority of studies are of exploratory nature and have not applied any of the theoretical frameworks that are available in social science research. Consequently, a methodological standardization in measuring and analyzing people's flood risk perceptions and their adaptive behaviors is hardly present. This heterogeneity leads to difficulties in comparing results among studies. It is also shown that theoretical and empirical studies on flood risk communication are nearly nonexistent. The article concludes with a summary on methodological issues in the fields of flood-risk perception and flood-risk communication and proposes an agenda for future research.

Klockow, K. E. (2013). *Spatializing tornado warning lead-time: Risk perception and response in a spatio-temporal framework* (doctoral dissertation). University of Oklahoma, Norman, OK. Retrieved from ProQuest Database.

The present research borrows from theory in cartography, spatial cognition, and risk decision science to examine the perception of risk in a geospatial context. These perspectives can be applied to understand the ways people interpret representations of uncertainty and perceive risk from hazards that vary over a spatial domain. The studies presented in this dissertation use multiple complementary methods to understand, from different perspectives, how people form judgments about their risk from tornado hazards. In the first study, results from a case study of a widespread tornado outbreak reveal the many layers of subjectivity involved in perceiving risk in a geospatial context. Specifically, this study identifies and describes two general types of geospatial risk perception factors: (1) a priori expectations of hazard behavior and (2) properties of hazard development as framed by various mediums of communication. In the second study, the same case is examined to understand the protective action decision process over space and time, and to specify how new technologies might influence risk decision-making in that context. Finally, in a third study, a microworld decision experiment systematically manipulated various representations of uncertainty in a spatial domain to investigate their effects on subjective estimates of risk. Specifically, this study proposes and finds evidence for three geospatial risk framing effects: warning boundary inclusion, distance, and symbolic color coding. This work concludes with a summary of findings and recommendations for warning practice and further research.

Kox, T., & Thielen, A. H. (2017). To Act or Not To Act? Factors Influencing the General Public's Decision about Whether to Take Protective Action against Severe Weather. *Weather, Climate, and Society*, 9(2), 299-315. <https://doi.org/10.1175/wcas-d-15-0078.1>

Research suggests that providing weather forecast end users with additional information about the forecast uncertainty of a possible event can enhance the preparation of mitigation measures. But not all

users have the same threshold for taking action. This paper focuses on the question of whether there are influencing factors that determine decision thresholds for numerical weather forecast information beginning at which the general public would start to take protective action. In spring 2014, 1342 residents of Berlin, Germany participated in a survey. Questions related to the following topics: perception of and prior experience with severe weather, trustworthiness of forecasters and confidence in weather forecasts, and sociodemographic and socioeconomic characteristics. Within the questionnaire a scenario was created in order to determine individual decision thresholds and see whether subgroups of the sample lead to different thresholds. Results show that people's willingness to act tends to be higher and decision thresholds tend to be lower if the expected weather event is more severe or the property at risk is of higher value. Several influencing factors of risk perception have significant effects such as education, housing status, and ability to act, whereas classic sociodemographic determinants alone are often not sufficient to fully grasp risk perception and protection behavior.

Luo, J., Cong, Z., & Liang, D. (2015). Number of warning information sources and decision making during tornadoes. *American Journal of Preventive Medicine*, 48(3), 334-337. <http://dx.doi.org/10.1016/j.amepre.2014.09.007>

Background: Taking proper protective action upon receiving tornado warnings is critical to reducing casualties. With more warning information sources becoming available, how the number of such information sources affects decision making should be quantitatively investigated. Purpose: To examine how the number of warning information sources affected individuals' decisions to take protective action during tornadoes. Methods: A telephone survey using random sampling was conducted in 2012 with residents in Tuscaloosa AL and Joplin MO, resulting in a working sample of 782 respondents. Both cities were struck by violent tornadoes (Enhanced Fujita Scale [EF]4 and EF5) in 2011. The analysis was conducted in 2013. Results: Logistic regression analysis showed that relative to having only one warning information source, having two and three or more warning information sources significantly increased the odds of taking protective action in Joplin but not in Tuscaloosa; having three or more sources had a significantly stronger effect on taking protective action in Joplin than in Tuscaloosa. Having an emergency preparation plan in both cities and being white in Tuscaloosa significantly increased the odds of taking protective action, whereas being divorced in Joplin reduced these odds. Conclusions: Receiving warnings from more warning information sources might be more beneficial in places with less previous exposure to tornadoes and for populations with lower awareness of a potential tornado and higher probability of receiving no warnings. Emergency management agencies and public health officials should give priority to these places and populations when formulating disaster mitigation decisions and policies. (PsycINFO Database Record (c) 2016 APA, all rights reserved) (Source: journal abstract)

Miran, S. M., Ling, C., James, J. J., Gerard, A., & Rothfus, L. (2017). User perception and interpretation of tornado probabilistic hazard information: Comparison of four graphical designs. *Applied Ergonomics*, 65, 277-285. <http://dx.doi.org/10.1016/j.apergo.2017.06.016>

Effective design for presenting severe weather information is important to reduce devastating consequences of severe weather. The Probabilistic Hazard Information (PHI) system for severe weather is being developed by NOAA National Severe Storms Laboratory (NSSL) to communicate probabilistic hazardous weather information. This study investigates the effects of four PHI graphical designs for tornado threat, namely, "four-color", "red-scale", "grayscale" and "contour", on users' perception,

interpretation, and reaction to threat information. PHI is presented on either a map background or a radar background. Analysis showed that the accuracy was significantly higher and response time faster when PHI was displayed on map background as compared to radar background due to better contrast. When displayed on a radar background, "grayscale" design resulted in a higher accuracy of responses. Possibly due to familiarity, participants reported four-color design as their favorite design, which also resulted in the fastest recognition of probability levels on both backgrounds. Our study shows the importance of using intuitive color-coding and sufficient contrast in conveying probabilistic threat information via graphical design. We also found that users follow a rational-perceiving-judging-feeling-acting approach in processing probabilistic hazard information for tornado.

Miran, S. M., Ling, C., & Rothfusz, L. (2018). Factors influencing people's decision-making during three consecutive tornado events. *International Journal of Disaster Risk Reduction*, 28, 150-157.
<https://doi.org/10.1016/j.ijdrr.2018.02.034>

On May 19th, 20th, and 31st 2013, three tornadoes with different intensities struck the Oklahoma City metropolitan area. A set of survey data was collected from residents in the area two months after the events. This study aims to explore the effects of different factors, the environmental context factor (proximity to the tornado's path), the information factor (number of weather information sources) as well as personal factors (age, marital status, gender, education, prior experience with tornadoes, type of geographical area- rural vs. urban-, and income), on people's protective action. For each of three tornado events, a multiple logistic regression model was built to identify the statistically significant factors on taking protective action by people. The results showed that only the factors of "proximity to the tornado" and "number of weather information sources" in all three models had significant effects on the odds of taking protective action. The likelihood of taking protective action when people were on the tornado's path was significantly higher than that of scenarios in which people were outside 5 miles of the tornado. Holding the other variables constant, adding one unit to the number of information sources increases the odds of taking protective action by 2.27 on average for the three events.

Mishra, S., & Suar, D. (2012). Effects of Anxiety, Disaster Education, and Resources on Disaster Preparedness Behavior. *Journal of Applied Social Psychology*, 42(5), 1069-1087.
<https://doi.org/10.1111/j.1559-1816.2011.00853.x>

The thrust of this study is to understand the responses of anxiety-prone people to threats like natural disasters. It examines whether anxiety influences disaster preparedness, and whether disaster education and resources mediate between anxiety and disaster preparedness. Data were collected from 300 people, each from flood-prone and heat-wave-affected areas in Orissa, India. Controlling for the influence of age and family type, the results revealed that trait anxiety decreased flood and heat-wave preparedness. Further, it was found that disaster education and resources are partial mediators between anxiety and flood preparedness and full mediators between anxiety and heat-wave preparedness. Implications of the findings are discussed within the socioeconomic and cultural contexts of India.

Morss, R. E., Demuth, J. L., & Lazo, J. K. (2008). Communicating Uncertainty in Weather Forecasts: A Survey of the U.S. Public. *Weather and Forecasting*, 23(5), 974-991.
<https://doi.org/10.1175/2008WAF2007088.1>

Weather forecasts are inherently uncertain, and meteorologists have information about weather forecast uncertainty that is not readily available to most forecast users. Yet effectively communicating forecast uncertainty to non-meteorologists remains challenging. Improving forecast uncertainty communication requires research-based knowledge that can inform decisions on what uncertainty information to communicate, when, and how to do so. To help build such knowledge, this article explores the public's perspectives on everyday weather forecast uncertainty and uncertainty information using results from a nationwide survey. By contributing to the fundamental understanding of laypeople's views on forecast uncertainty, the findings can inform both uncertainty communication and related research. The article uses empirical data from a nationwide survey of the U.S. public to investigate beliefs commonly held among meteorologists and to explore new topics. The results show that when given a deterministic temperature forecast, most respondents expected the temperature to fall within a range around the predicted value. In other words, most people inferred uncertainty into the deterministic forecast. People's preferences for deterministic versus nondeterministic forecasts were examined in two situations; in both, a significant majority of respondents liked weather forecasts that expressed uncertainty, and many preferred such forecasts to single-valued forecasts. The article also discusses people's confidence in different types of forecasts, their interpretations of the probability of precipitation forecasts, and their preferences for how forecast uncertainty is conveyed. Further empirical research is needed to study the article's findings in other contexts and to continue exploring perception, interpretation, communication, and use of weather forecast uncertainty.

Morss Rebecca, E., Lazo Jeffrey, K., & Demuth Julie, L. (2010). Examining the use of weather forecasts in decision scenarios: results from a US survey with implications for uncertainty communication. *Meteorological Applications*, 17(2), 149-162. <https://doi.org/10.1002/met.196>

The hydrometeorological community has limited understanding of how people interpret forecast information and use it in decision making, hampering effective forecast communication. This article addresses these issues in the context of weather prediction, focusing especially on forecast uncertainty. It does so using empirical data from decision scenario questions asked in a nationwide US survey. Respondents were asked their probabilistic threshold for taking action to protect against potential rain or frost. They were then asked to make yes/no protective decisions in a potential reservoir flooding or fruit frost scenario given different forecasts. The results indicate that people have different probabilistic thresholds for taking protective action and that context and presentation influence forecast use. The results also suggest that many people infer uncertainty into deterministic forecasts, and that many respondents were able to interpret probabilistic forecasts of the type presented well enough to use them in the decision questions. Further, the analysis suggests that most respondents did not make decisions according to the simplest form of the cost-loss decision model. The analysis also examines relationships between respondents' information use and other aspects of their perceptions and interpretations of forecast uncertainty, including their interpretations of probability of precipitation. The findings add to fundamental knowledge about people's interpretations and use of weather forecasts, especially forecasts that explicitly convey uncertainty, and provide a starting point for future related work using survey and experimental approaches.

Nagarajan, M., Shaw, D., & Albores, P. (2012). Disseminating a warning message to evacuate: A simulation study of the behaviour of neighbours. *European Journal of Operational Research*, 220(3), 810-819. <https://doi.org/10.1016/j.ejor.2012.02.026>

Large-scale evacuations are a recurring theme on news channels, whether in response to major natural or manmade disasters. The role of warning dissemination is a key part in the success of such large-scale evacuations and its inadequacy in certain cases has been a 'primary contribution to deaths and injuries' (Hayden et al., 2007). Along with technology-driven 'official warning channels' (e.g. sirens, mass media), the role of unofficial channel (e.g. neighbours, personal contacts, volunteer wardens) has proven to be significant in warning the public of the need to evacuate. Although post-evacuation studies identify the behaviours of evacuees as disseminators of the warning message, there has not been a detailed study that quantifies the effects of such behaviour on the warning message dissemination. This paper develops an Agent-Based Simulation (ABS) model of multiple agents (evacuee households) in a hypothetical community to investigate the impact of behaviour as an unofficial channel on the overall warning dissemination. Parameters studied include the percentage of people who warn their neighbours, the efficiency of different official warning channels, and delay time to warn neighbours. Even with a low proportion of people willing to warn their neighbour, the results showed considerable impact on the overall warning dissemination.

Ripberger, J. T., Silva, C. L., Jenkins-Smith, H. C., Carlson, D. E., James, M., & Herron, K. G. (2015). False Alarms and Missed Events: The Impact and Origins of Perceived Inaccuracy in Tornado Warning Systems. *Risk Analysis*, 35(1), 44-56. <https://doi.org/10.1111/risa.12262>

Theory and conventional wisdom suggest that errors undermine the credibility of tornado warning systems and thus decrease the probability that individuals will comply (i.e., engage in protective action) when future warnings are issued. Unfortunately, empirical research on the influence of warning system accuracy on public responses to tornado warnings is incomplete and inconclusive. This study adds to existing research by analyzing two sets of relationships. First, we assess the relationship between perceptions of accuracy, credibility, and warning response. Using data collected via a large regional survey, we find that trust in the National Weather Service (NWS; the agency responsible for issuing tornado warnings) increases the likelihood that an individual will opt for protective action when responding to a hypothetical warning. More importantly, we find that subjective perceptions of warning system accuracy are, as theory suggests, systematically related to trust in the NWS and (by extension) stated responses to future warnings. The second half of the study matches survey data against NWS warning and event archives to investigate a critical follow-up question Why do some people perceive that their warning system is accurate, whereas others perceive that their system is error prone? We find that subjective perceptions are in part a function of objective experience, knowledge, and demographic characteristics. When considered in tandem, these findings support the proposition that errors influence perceptions about the accuracy of warning systems, which in turn impact the credibility that people assign to information provided by systems and, ultimately, public decisions about how to respond when warnings are issued.

Schultz, D. M., Grunfest, E. C., Hayden, M. H., Benight, C. C., Drobot, S., & Barnes, L. R. (2010). Decision Making by Austin, Texas, Residents in Hypothetical Tornado Scenarios. *Weather, Climate, and Society*, 2(3), 249-254. <https://doi.org/10.1175/2010wcas1067.1>

One of the goals of the Warning Project is to understand how people receive warnings of hazardous weather and subsequently use this information to make decisions. As part of the project, 519 surveys from Austin, Texas, floodplain residents were collected and analyzed. About 90% of respondents

understood that a tornado warning represented a more serious and more likely threat than a tornado watch. Most respondents (86%) were not concerned about a limited number of false alarms or close calls reducing their confidence in future warnings, suggesting no cry-wolf effect. Most respondents reported safe decisions in two hypothetical scenarios: a tornado warning issued while the respondent was home and a tornado visible by the respondent while driving. However, nearly half the respondents indicated that they would seek shelter from a tornado under a highway overpass if they were driving. Despite the limitations of this study, these results suggest that more education is needed on the dangers of highway overpasses as shelter from severe weather.

Sherman-Morris, K. (2005). Tornadoes, television and trust—A closer look at the influence of the local weathercaster during severe weather. *Global Environmental Change Part B: Environmental Hazards*, 6(4), 201-210. <https://doi.org/10.1016/j.hazards.2006.10.002>

Previous research has acknowledged the importance of mass media in shaping risk perception and as the channel through which people get information during and after disasters. There is still much more to know about the role mass media (but especially the television medium) plays in people's precautionary hazard behaviors. Close to 400 people were surveyed in the Memphis, TN television market about their knowledge and perception of the severe weather threat, and their past experiences with tornadoes and severe thunderstorms. The survey results show that respondents do develop a relationship with their local television weathercaster and also trust their weathercaster during severe weather. This relationship and trust can then predict the likelihood of taking shelter during severe weather. Ultimately, the case will be made that the findings may be useful to future hazards research in other locations.

Silver, A. (2015). Watch or warning? Perceptions, preferences, and usage of forecast information by members of the Canadian public. *Meteorological Applications*, 22(2), 248-255. <https://doi.org/10.1002/met.1452>

Environment Canada is responsible for monitoring weather conditions and developing associated forecast products for millions of Canadians. Although it is clear that these forecasts are reaching many different end-users, it is less certain how these products are perceived or used by the Canadian public. This research investigated the way(s) in which individual end-users in southern Ontario obtained, interpreted, and used weather forecasts in their every-day decision-making. Semi-structured interviews (n = 35) and close-ended questionnaires (n = 268) were conducted with residents from Huron and Perth Counties in Ontario, Canada, between October 2011 and March 2012 as part of a larger research project. It was found that most respondents used weather products for pragmatic reasons (e.g. deciding appropriate clothing or planning a trip). These individuals typically did not pay attention to ambient weather conditions unless they were inconvenient or threatening. Despite this, many respondents displayed relatively high levels of weather salience, in terms of familiarity with and awareness of local weather patterns. While most participants had a general understanding of the difference between a weather watch and a weather warning, a substantial portion of the sample were unable to differentiate between the two products. Lastly, many respondents also indicated that they trusted and valued Environment Canada weather forecasts, and they sought this information actively to help in their decision-making.

Silver, A., & Andrey, J. (2014). The Influence of Previous Disaster Experience and Sociodemographics on Protective Behaviors during Two Successive Tornado Events. *Weather Climate and Society*, 6(1), 91-103. <https://doi.org/10.1175/wcas-d-13-00026.1>

The role of previous disaster experience as a motivating factor for protective action during high-risk events is still a matter of considerable discussion and inconsistent findings in the hazards literature. In this paper, two events that occurred in August 2011 in Goderich, Ontario, Canada, are examined: an F3 tornado that impacted the community on 21 August 2011 and a tornado warning that was posted for the region 3 days later on 24 August 2011. This case study provided the opportunity to examine the roles of previous disaster experience and sociodemographics on the decision-making process during two successive potentially tornadic events. The results of this research are based on close-ended questionnaires completed by individuals who experienced both storms or who experienced only the subsequent storm on 24 August 2011 (n = 177). Physical cues were found to be the primary motivator during the 21 August 2011 tornado, while the tornado warning was the primary motivator during the subsequent storm. Additionally, there was an increase in the percentage of individuals who took protective action on 24 August 2011 regardless of the respondents' presence or absence during the 21 August 2011 tornado. Finally, none of the tested sociodemographic variables was found to be statistically significant for the 21 August 2011 tornado, while only gender (female) was found to be positively correlated with protective behaviors on 24 August 2011. These findings suggest that previous disaster experience (either direct or indirect) and sociodemographics intersect in a variety of complex ways.

Stokoe, R. M. (2016). Putting people at the centre of tornado warnings: How perception analysis can cut fatalities. *International Journal of Disaster Risk Reduction*, 17, 137-153. <https://doi.org/10.1016/j.ijdrr.2016.04.004>

Despite improvements in tornado Disaster Risk Reduction (DRR), since the 1990s the number, and proportion, of people dying in tornadoes in America has increased. This paper examines how people rely, understand and trust tornado alerts and the Early Warning Systems (EWS) that disseminate them, if socio-demographics cause specific groups to experience greater risk, whether these factors have affected the rise in fatalities and what mitigation measures could reverse this. Ford County, Kansas, was selected as a case study. Interviews were conducted with officials and an online survey marketed through Facebook was undertaken, receiving 547 responses. Results showed white men were particularly vulnerable to tornadoes as they were more likely to ignore warnings. Hispanics, older people and those with tornado experience were also at higher risk if they heard an alert from an EWS they distrusted or did not understand. Population growth in these groups and technology changes have helped cause the recent fatality rise and, unless changes are made to the EWS, the continued increase in size of these groups will lead to more people becoming at risk from, or perishing in, tornadoes. Recommendations to prevent this include federal regulation and improved education materials for sirens, alerts translated into Spanish, discontinuing NOAA radio and developing an official forecast and alerting app.

Sutter, D., & Poitras, M. (2010). Do people respond to low probability risks? Evidence from tornado risk and manufactured homes. *Journal of Risk and Uncertainty*, 40(2), 181-196. <http://dx.doi.org/10.1007/s11166-010-9087-8>

Whether people perceive and respond to low-probability natural hazards is a research question of considerable policy relevance. We obtain evidence by considering the response of housing choice to tornado risk for manufactured homes. The vulnerability of manufactured housing, combined with its growing share of the U.S. housing market, has led to proposed mandates for community shelters in mobile home parks. Expected utility theory, however, predicts that households should account for tornado risk in their housing choice. We test for an effect of tornado risk on manufactured housing demand using cross-sectional state data, as well as counties in three tornado prone states. We find that people do respond to tornado risk; our estimates indicate that each expected annual state tornado death per million residents reduces demand for manufactured homes by about 3%. The estimated quantity effect is consistent with the market studies of the price elasticity of manufactured homes.

Trainor, J. E., Nagele, D., Philips, B., & Scott, B. (2015). Tornadoes, Social Science, and the False Alarm Effect. *Weather, Climate, and Society*, 7(4), 333-352. <https://doi.org/10.1175/wcas-d-14-00052.1>

Despite considerable interest in the weather enterprise, there is little focused research on the “false alarm effect.” Within the body of research that does exist, findings are mixed. Some studies suggest that the false alarm effect is overstated, while several recent efforts have provided evidence that FAR may be a significant determinate of behavior. This effort contributes to the understanding of FAR through a sociological analysis of public perceptions and behavioral responses to tornadoes. This analysis begins by addressing public definitions of FAR and then provides two statistical models, one focused on perception of FAR and one focused on behavioral response to tornado warnings. The authors’ approach incorporates a number of sociological and other social science concepts as predictors in both of these models. Findings provide a number of important insights. Most notably, it is found that 1) there is a wide degree of variation in public definitions of false alarm, 2) actual county FAR rates do not predict perception of FAR, 3) actual county FAR rates do predict behavioral response, and 4) planning and family characteristics are also influential. Another major contribution is to illustrate the significant complexity associated with analysis of false alarms. Conclusions discuss the limits of this analysis and future direction for this type of research.

Whitmer, D. E., Schroeder, B. L., Bailey, S. K. T., & Sims, V. K. (2017). Reconsidering the “Conventional Wisdom” of the Relationship between False Alarms and Risk Beliefs. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 61(1), 1419-1423. <https://doi.org/10.1177/1541931213601838>

The purpose of this research was to examine how false alarm experience of weather-related emergencies affects the relationship between perceived danger and desire for warnings. Participants reported how dangerous they perceived each event to be, whether they believed warnings should be distributed, whether they had experienced the event, and whether they had experienced a false alarm of the event. Participants indicated strong agreement for the desire for weather warnings. Although the literature implies that people who have experienced many false alarms may perceive that danger as less severe in the future due to the “crywolf effect,” our data suggest that people have a heightened risk perception and desire for warnings of those events. Because memories inform mental representations that guide decision-making in uncertain situations, it is imperative that future research continue to examine what people have stored in memory of false alarm experiences to settle debates in the contentious literature of false alarms and risk perception.

Whitmer, D. E., Sims, V. K., & Torres, M. E. (2017). Assessing Mental Models of Emergencies Through Two Knowledge Elicitation Tasks. *Human Factors*, 59(3), 357-376.
<https://doi.org/10.1177/0018720816672117>

Objective: The goals of this study were to assess the risk identification aspect of mental models using standard elicitation methods and how university campus alerts were related to these mental models. Background: People fail to follow protective action recommendations in emergency warnings. Past research has yet to examine cognitive processes that influence emergency decision-making. Method: Study 1 examined 2 years of emergency alerts distributed by a large southeastern university. In Study 2, participants listed emergencies in a thought-listing task. Study 3 measured participants' time to decide if a situation was an emergency. Results: The university distributed the most alerts about an armed person, theft, and fire. In Study 2, participants most frequently listed fire, car accident, heart attack, and theft. In Study 3, participants quickly decided a bomb, murder, fire, tornado, and rape were emergencies. They most slowly decided that a suspicious package and identify theft were emergencies. Conclusion: Recent interaction with warnings was only somewhat related to participants' mental models of emergencies. Risk identification precedes decision-making and applying protective actions. Examining these characteristics of people's mental representations of emergencies is fundamental to further understand why some emergency warnings go ignored. Application: Someone must believe a situation is serious to categorize it as an emergency before taking the protective action recommendations in an emergency warning. Present-day research must continue to examine the problem of people ignoring warning communication, as there are important cognitive factors that have not yet been explored until the present research.

Zahran, S., Tavani, D., & Weiler, S. (2013). Daily variation in natural disaster casualties: Information flows, safety, and opportunity costs in tornado versus hurricane strikes. *Risk Analysis*, 33(7), 1265-1280. <http://dx.doi.org/10.1111/j.1539-6924.2012.01920.x>

Casualties from natural disasters may depend on the day of the week they strike. With data from the Spatial Hazard Events and Losses Database for the United States (SHELDUS), daily variation in hurricane and tornado casualties from 5,043 tornado and 2,455 hurricane time/place events is analyzed. Hurricane forecasts provide at-risk populations with considerable lead time. Such lead time allows strategic behavior in choosing protective measures under hurricane threat; opportunity costs in terms of lost income are higher during weekdays than during weekends. On the other hand, the lead time provided by tornadoes is near zero; hence tornadoes generate no opportunity costs. Tornado casualties are related to risk information flows, which are higher during workdays than during leisure periods, and are related to sheltering-in-place opportunities, which are better in permanent buildings like businesses and schools. Consistent with theoretical expectations, random effects negative binomial regression results indicate that tornado events occurring on the workdays of Monday through Thursday are significantly less lethal than tornadoes that occur on weekends. In direct contrast, and also consistent with theory, the expected count of hurricane casualties increases significantly with weekday occurrences. The policy implications of observed daily variation in tornado and hurricane events are considered.

Section III: Tornado Identification & Technology

Anderson-Frey, A. K., Richardson, Y. P., Dean, A. R., Thompson, R. L., & Smith, B. T. (2016). Investigation of Near-Storm Environments for Tornado Events and Warnings. *Weather and Forecasting*, 31(6), 1771-1790. <https://doi.org/10.1175/waf-d-16-0046.1>

In this study, a 13-yr climatology of tornado event and warning environments, including metrics of tornado intensity and storm morphology, is investigated with particular focus on the environments of tornadoes associated with quasi-linear convective systems and right-moving supercells. The regions of the environmental parameter space having poor warning performance in various geographical locations, as well as during different times of the day and year, are highlighted. Kernel density estimations of the tornado report and warning environments are produced for two parameter spaces: mixed-layer convective available potential energy (MLCAPE) versus 0–6-km vector shear magnitude (SHR6), and mixed-layer lifting condensation level (MLLCL) versus 0–1-km storm-relative helicity (SRH1). The warning performance is best in environments characteristic of severe convection (i.e., environments featuring large values of MLCAPE and SHR6). For tornadoes occurring during the early evening transition period, MLCAPE is maximized, MLLCL heights decrease, SHR6 and SRH1 increase, tornadoes rated as 2 or greater on the enhanced Fujita scale (EF2+) are most common, the probability of detection is relatively high, and false alarm ratios are relatively low. Overall, the parameter-space distributions of warnings and events are similar; at least in a broad sense, there is no systematic problem with forecasting that explains the high overall false alarm ratio, which instead seems to stem from the inability to know which storms in a given environment will be tornadic.

Barnes, L. R., Grunfest, E. C., Hayden, M. H., Schultz, D. M., & Benight, C. (2007). False Alarms and Close Calls: A Conceptual Model of Warning Accuracy. *Weather and Forecasting*, 22(5), 1140-1147. <https://doi.org/10.1175/waf1031.1>

The false alarm rate (FAR) measures the fraction of forecasted events that did not occur, and it remains one of the key metrics for verifying National Weather Service (NWS) weather warnings. The national FAR for tornado warnings in 2003 was 0.76, indicating that only one in four tornado warnings was verified. The NWS's goal for 2010 is to reduce this value to 0.70. Conventional wisdom is that false alarms reduce the public's willingness to respond to future events. This paper questions this conventional wisdom. In addition, this paper argues that the metrics used to evaluate false alarms do not accurately represent the numbers of actual false alarms or the forecasters' abilities because current metrics categorize events as either a hit or a miss and do not give forecasters credit for close calls. Aspects discussed in this paper include how the NWS FAR is measured, how humans respond to warnings, and what are alternative approaches to measure FAR. A conceptual model is presented as a framework for a new perspective on false alarms that includes close calls, providing a more balanced view of forecast verification.

Best, E. (2017). Development of Hybrid Notification Systems for Use in Storm-Based Warnings in Rural Communities. *Natural Hazards Review*, 18(4), 05017001. [https://doi.org/10.1061/\(ASCE\)NH.1527-6996.0000250](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000250)

This case study compares capabilities of existing emergency alert sirens and the wireless emergency alert (WEA) system in Calhoun County, Alabama, using storm-based warning polygons. Using siren ground cover, mobile phone tower ground cover, building data, and census population data, it is possible to compare and contrast the reach of these emergency warning systems within a real-world

environment for localized emergency test cases. This paper concludes by suggesting the addition of a hybrid warning system using only existing technology that could minimize both false-negative and false-positive warnings in low-density areas, maximizing both safety and efficiency of warning systems

Blair, S. F., & Leighton, J. W. (2014). Assessing Real-Time Tornado Information Disseminated through NWS Products. *Weather and Forecasting*, 29(3), 591-600. <https://doi.org/10.1175/waf-d-13-00126.1>

Real-time confirmation of a tornado specified in National Weather Service (NWS) warnings and statements is believed to increase the credibility and urgency of these critical warning messages for the end user, because it represents the greatest degree of certainty that the hazard exists. This timely tornado information disseminated in official NWS products and relayed through multiple sources by private and public partners may help the public believe, personalize, confirm, and respond to the warning message. This is the first study to explicitly assess the frequency of real-time confirmation of ongoing tornadoes within NWS products and explore what unique conditions may facilitate or hinder this process. Tornado reports and their respective NWS warnings and statements during a 5-yr period from 2007 to 2011 across the central contiguous United States were compiled and examined. Overall, 40% of tornadoes were confirmed in NWS products in real time. Increasing tornado pathlength, duration, and intensity subsequently resulted in an increasing likelihood of real-time confirmation prior to the tornado dissipating. The time of day was a factor; nighttime tornadoes were 20% less likely to receive real-time confirmation than daytime events. Additionally, increasing tornado forecast risk in products issued by the Storm Prediction Center corresponded to an increasing likelihood of real-time confirmation. Analysis of these data reveals specific scenarios when tornadoes are more or less likely to be reported in real time, providing some guidance for when timely ground-truth information may or may not be available.

Bodine, D. J., & Kurdzo, J. M. (2018). Ground-Based Radar Technologies for Tornado Observations. In *Remote Sensing of Clouds and Precipitation*: Springer.

Ground-based radar technologies have made a tremendous impact by revealing the three-dimensional structure of winds and precipitation in tornadic storms and tornadoes. In this chapter, a historical perspective on ground-based radar technology is presented, including the exciting technological evolution from early weather radars that observed the first hook echoes to modern-day polarimetric and phased array radar technology capable of scanning storms in less than 10 s. Early radar studies revealed the importance of Doppler radar capabilities, and led to implementation of a nationwide operational Doppler radar network that substantially improved tornado warning lead-time and accuracy. Scientists have used ground-based radars extensively in field studies of tornadoes and tornadic storms, including mobile radar systems that allow scientists to get very close to storms to obtain very high resolution data. These field studies include large-scale field experiments such as the first and second Verification of the Origins of Rotation in Tornadoes EXperiments (VORTEX), which deployed a network of mobile radars with a suite of other instruments. From the combined efforts of scientists and engineers to develop ground-based radars and conduct field experiments, new scientific discoveries have transformed our understanding of tornadoes and tornadic storms. By combining data from multiple radars, scientists have developed an understanding of the three-dimensional flows with supercells and tornadoes, and documented how changes in the storm-scale flow impact tornadoes and their formation. Rapid-scan radar data have shown that tornadoes can form or dissipate in less than 1 min, and that the

tornado's intensity and three-dimensional structure can drastically change in 10 s or less. Using dual-polarization radars, new capabilities have emerged to detect tornado debris remotely and infer tornado intensity and storm-scale processes. Exciting mobile radars and operational radar prototypes are under development that will provide both rapid-scanning and dual-polarization capabilities. These new radar systems will have a critical role in helping scientists discover the missing pieces in our understanding of tornadogenesis and tornado dynamics, and will continue to improve tornado warning performance to better protect society.

Brooks, H. E. (2004). Tornado Warning Performance in the Past and Future: A Perspective from Signal Detection Theory. *Bulletin of the American Meteorological Society*, 85(6), 837-844. <https://doi.org/10.1175/bams-85-6-837>

Changes over the years in tornado-warning performance in the United States can be modeled from the perspective of signal detection theory. From this view, it can be seen that there have been distinct periods of change in performance, most likely associated with deployment of radars, and changes in scientific understanding and training. The model also makes it clear that improvements in the false alarm ratio can only occur at the cost of large decreases in the probability of detection, or with large improvements in the overall quality of the warning system.

Brotzge, J., & Erickson, S. (2010). Tornadoes without NWS Warning. *Weather and Forecasting*, 25(1), 159-172. <https://doi.org/10.1175/2009waf2222270.1>

During a 5-yr period of study from 2000 to 2004, slightly more than 26% of all reported tornadoes across the United States occurred without an NWS warning being issued. This study examines some of the reasons behind why no warnings were issued with these tornadoes, and what climatological, storm classification, and sociological factors may have played a role in the lack of warnings. This dataset of tornado records was sorted by F scale, geographically by region and weather forecast office (WFO), hour of the day, month of the year, tornado pathlength, tornado-to-radar distance, county population density, and number of tornadoes by day and order of occurrence. Results show that the tornadoes most likely to strike when the public is least likely to be aware were also those tornadoes with the greatest chance of not being warned. Singular tornado events (one tornado report per day within a WFO county warning area) and the first tornado report of the day were the most difficult scenarios on which to warn, with over half of all solitary tornado events not warned. Geographic areas that experienced a significant proportion of weak, solitary, and/or nocturnal tornadoes had a much higher ratio of missed warnings. In general, the stronger the tornado, as estimated from its F-scale rating and/or track length, the greater chance it was warned. However, the tornado distance from radar had a significant impact on tornado warning statistics. In addition, many weak tornadoes were not warned, and the overall ratio of missed tornado warnings to reported tornadoes actually increased over more densely populated regions, likely due to more complete postevent verification.

Brotzge, J., Erickson, S., & Brooks, H. (2011). A 5-yr Climatology of Tornado False Alarms. *Weather and Forecasting*, 26(4), 534-544. <https://doi.org/10.1175/waf-d-10-05004.1>

During 2008 approximately 75% of tornado warnings issued by the National Weather Service (NWS) were false alarms. This study investigates some of the climatological trends in the issuance of false alarms and highlights several factors that impact false-alarm ratio (FAR) statistics. All tornadoes and tornado warnings issued across the continental United States between 2000 and 2004 were analyzed,

and the data were sorted by hour of the day, month of the year, geographical region and weather forecast office (WFO), the number of tornadoes observed on a day in which a false alarm was issued, distance of the warned area from the nearest NWS radar, county population density, and county area. Analysis of the tornado false-alarm data identified six specific trends. First, the FAR was highest during nonpeak storm periods, such as during the night and during the winter and late summer. Second, the FAR was strongly tied to the number of tornadoes warned per day. Nearly one-third of all false alarms were issued on days when no tornadoes were confirmed within the WFO's county warning area. Third, the FAR varied with distance from radar, with significantly lower estimates found beyond 150 km from radar. Fourth, the FAR varied with population density. For warnings within 50 km of an NWS radar, FAR increased with population density; however, for warnings beyond 150 km from radar, FAR decreased regardless of population density. Fifth, the FAR also varied as a function of county size. The FAR was generally highest for the smallest counties; the FAR was ~80% for all counties less than 1000 km² regardless of distance from radar. Finally, the combined effects of distance from radar, population density, and county size led to significant variability across geographic regions.

Brotzge, J. A., Nelson, S. E., Thompson, R. L., & Smith, B. T. (2013). Tornado Probability of Detection and Lead Time as a Function of Convective Mode and Environmental Parameters. *Weather and Forecasting*, 28(5), 1261-1276. <https://doi.org/10.1175/waf-d-12-00119.1>

The ability to provide advanced warning on tornadoes can be impacted by variations in storm mode. This research evaluates 2 yr of National Weather Service (NWS) tornado warnings, verification reports, and radar-derived convective modes to appraise the ability of the NWS to warn across a variety of convective modes and environmental conditions. Several specific hypotheses are considered: (i) supercell morphologies are the easiest convective modes to warn for tornadoes and yield the greatest lead times, while tornadoes from more linear, nonsupercell convective modes, such as quasi-linear convective systems, are more difficult to warn for; (ii) parameters such as tornado distance from radar, population density, and tornado intensity (F scale) introduce significant and complex variability into warning statistics as a function of storm mode; and (iii) tornadoes from stronger storms, as measured by their mesocyclone strength (when present), convective available potential energy (CAPE), vertical wind shear, and significant tornado parameter (STP) are easier to warn for than tornadoes from weaker systems. Results confirmed these hypotheses. Supercell morphologies caused 97% of tornado fatalities, 96% of injuries, and 92% of damage during the study period. Tornado warnings for supercells had a statistically higher probability of detection (POD) and lead time than tornado warnings for nonsupercells; among supercell storms, tornadoes from supercells in lines were slightly more difficult to warn for than tornadoes from discrete or clusters of supercells. F-scale intensity and distance from radar had some impact on POD, with less impact on lead times. Higher mesocyclone strength (when applicable), CAPE, wind shear, and STP values were associated with greater tornado POD and lead times.

Calhoun, K. M., Smith, T. M., Kingfield, D. M., Gao, J. D., & Stensrud, D. J. (2014). Forecaster Use and Evaluation of Real-Time 3D VAR Analyses during Severe Thunderstorm and Tornado Warning Operations in the Hazardous Weather Testbed. *Weather and Forecasting*, 29(3), 601-613. <https://doi.org/10.1175/waf-d-13-00107.1>

A weather-adaptive three-dimensional variational data assimilation (3DVAR) system was included in the NOAA Hazardous Weather Testbed as a first step toward introducing warn-on-forecast initiatives into operations. NWS forecasters were asked to incorporate the data in conjunction with single-radar and

multisensor products in the Advanced Weather Interactive Processing System (AWIPS) as part of their warning decision process for real-time events across the United States. During the 2011 and 2012 experiments, forecasters examined more than 36 events, including tornadic supercells, severe squall lines, and multicell storms. Products from the 3DVAR analyses were available to forecasters at 1-km horizontal resolution every 5 min, with a 4–6-min latency, incorporating data from the national Weather Surveillance Radar-1988 Doppler (WSR-88D) network and the North American Mesoscale model. Forecasters found the updraft, vertical vorticity, and storm-top divergence products the most useful for storm interrogation and quickly visualizing storm trends, often using these tools to increase the confidence in a warning decision and/or issue the warning slightly earlier. The 3DVAR analyses were most consistent and reliable when the storm of interest was in close proximity to one of the assimilated WSR-88D, or data from multiple radars were incorporated into the analysis. The latter was extremely useful to forecasters in blending data rather than having to analyze multiple radars separately, especially when range folding obscured the data from one or more radars. The largest hurdle for the real-time use of 3DVAR or similar data assimilation products by forecasters is the data latency, as even 4–6 min reduces the utility of the products when new radar scans are available.

Federica, Z. (2016). Mobile weather apps or the illusion of certainty. *Meteorological Applications*, 23(4), 663-670. <https://doi.org/10.1002/met.1589>

A huge change has occurred in the way people obtain weather information in the last few years and a large percentage of the population now get weather forecasts on their mobile phones. There is currently a wide range of smartphone weather apps available: in 2014, iTunes App Store alone offered 5043 active applications in the weather category. The rapid penetration of new broadcasting technologies strongly affects the way weather forecasts are communicated to, and used by, people. Portability, permanent connectivity and geolocalization allow location-specific and time-sensitive weather forecasts to be provided. This paper explores the main features emerging in the 39 most popular weather apps in the United States, United Kingdom and Italy, and focuses on the implications in the communication of uncertainty. The results show that even if the advances in mobile communication technologies could, in principle, improve the effectiveness of weather communication enormously, the expectations created around weather forecasts appear to be inconsistent with current forecasting capabilities, particularly with their inherent uncertainties in space and time, as well as in the nature of the predicted weather events.

Heinselman, P. L., LaDue, D. S., & Lazrus, H. (2012). Exploring Impacts of Rapid-Scan Radar Data on NWS Warning Decisions. *Weather and Forecasting*, 27(4), 1031-1044. <https://doi.org/10.1175/waf-d-11-00145.1>

Rapid-scan weather radars, such as the S-band phased array radar at the National Weather Radar Testbed in Norman, Oklahoma, improve precision in the depiction of severe storm processes. To explore potential impacts of such data on forecaster warning decision making, 12 National Weather Service forecasters participated in a preliminary study with two control conditions: 1) when radar scan time was similar to volume coverage pattern 12 (4.5 min) and 2) when radar scan time was faster (43 s). Under these control conditions, forecasters were paired and worked a tropical tornadic supercell case. Their decision processes were observed and audio was recorded, interactions with data displays were video recorded, and the products were archived. A debriefing was conducted with each of the six teams independently and jointly, to ascertain the forecaster decision-making process. Analysis of these data

revealed that teams examining the same data sometimes came to different conclusions about whether and when to warn. Six factors contributing toward these differences were identified: 1) experience, 2) conceptual models, 3) confidence, 4) tolerance of possibly missing a tornado occurrence, 5) perceived threats, and 6) software issues. The three 43-s teams issued six warnings: three verified, two did not verify, and one event was missed. Warning lead times were the following: tornado, 18.6 and 11.5 min, and severe, 6 min. The three tornado warnings issued by the three 4.5-min teams verified, though warning lead times were shorter: 4.6 and 0 min (two teams). In this case, use of rapid-scan data showed the potential to extend warning lead time and improve forecasters' confidence, compared to standard operations.

Paulikas, M. J., & Schmidlin, T. W. (2017). US tornado fatalities in motor vehicles (1991–2015). *Natural Hazards*, 87(1), 121-143. <https://doi.org/10.1007/s11069-017-2756-z>

Motor vehicles historically have been dangerous locations to shelter in during tornado events. Throughout the twentieth century, motor vehicle design has become safer while tornado forecasting has become better understood. Despite such advances, tornado fatalities in motor vehicles still occur today, and some events periodically result in high numbers of deaths (e.g., ten motor vehicle occupants were killed by a single tornado in Garland, Texas, in 2015). We seek to examine all US tornado-induced motor vehicle fatalities documented between 1991 and 2015. Our findings indicate that motor vehicle fatalities have not significantly changed during this study period. We attribute annual fatality totals to persons lacking awareness of impending dangers coupled with numbers of significant tornado events for a given year. We find most fatalities result when vehicles are lofted or passengers are ejected, and this most typically occurs at the EF3–EF5 intensity thresholds. Fatalities that occur at weaker tornado winds (EF0–EF2) are most often attributed to collapsing debris (mostly trees) on vehicles. Spatially, motor vehicle fatalities are greatest in the Deep South and southern Great Plains regions where overall tornado and nighttime tornado frequencies are greatest. Some of the largest motor vehicle fatality events have resulted from tornadoes not being distinctly visible to motorists; such events have been characterized by tornadoes occurring at night or by tornadoes not appearing as “classic funnels.”

Simmons, K. M., & Sutter, D. (2005). WSR-88D Radar, Tornado Warnings, and Tornado Casualties. *Weather and Forecasting*, 20(3), 301-310. <https://doi.org/10.1175/waf857.1>

The impact of the installation of Weather Surveillance Radar-1988 Doppler (WSR-88D) radars in the 1990s on the quality of tornado warnings and occurrence of tornado casualties is examined. This analysis employs a dataset of tornadoes in the contiguous United States between 1986 and 1999. The date of WSR-88D radar installation in each National Weather Service Weather Forecast Office is used to divide the sample. Tornado warnings improved after the installation of Doppler radar; the percentage of tornadoes warned for increased from 35% before WSR-88D installation to 60% after installation while the mean lead time on warnings increased from 5.3 to 9.5 min and the false alarm ratio fell slightly. A regression analysis of tornado casualties, which controls for the characteristics of a tornado and its path, reveals that expected fatalities and expected injuries were 45% and 40% lower for tornadoes occurring after WSR-88D radar was installed in the NWS Weather Forecast Office. This analysis also finds that expected casualties are significantly lower for tornadoes occurring during the day or evening than late at night throughout the sample, which provides indirect evidence of the life-saving effects of tornado warnings.

Wilson, K. A., Heinselman, P. L., Kuster, C. M., Kingfield, D. M., & Kang, Z. H. (2017). Forecaster Performance and Workload: Does Radar Update Time Matter? *Weather and Forecasting*, 32(1), 253-274. <https://doi.org/10.1175/waf-d-16-0157.1>

Impacts of radar update time on forecasters warning decision processes were analyzed in the 2015 Phased Array Radar Innovative Sensing Experiment. Thirty National Weather Service forecasters worked nine archived phased-array radar (PAR) cases in simulated real time. These cases presented nonsevere, severe hail and/or wind, and tornadic events. Forecasters worked each type of event with approximately 5-min (quarter speed), 2-min (half speed), and 1-min (full speed) PAR updates. Warning performance was analyzed with respect to lead time and verification. Combining all cases, forecasters' Median warning lead times when using full-, half-, and quarter-speed PAR updates were 17, 14.5, and 13.6 min, respectively. The use of faster PAR updates also resulted in higher probability of detection and lower false alarm ratio scores. Radar update speed did not impact warning duration or size. Analysis of forecaster performance on a case-by-case basis showed that the impact of PAR update speed varied depending on the situation. This impact was most noticeable during the tornadic cases, where radar update speed positively impacted tornado warning lead time during two supercell events, but not for a short-lived tornado occurring within a bowing line segment. Forecasters improved ability to correctly discriminate the severe weather threat during a nontornadic supercell event with faster PAR updates was also demonstrated. Forecasters provided subjective assessments of their cognitive workload in all nine cases. On average, forecasters were not cognitively overloaded, but some participants did experience higher levels of cognitive workload at times. A qualitative explanation of these particular instances is provided.

Section IV: Warning Process, Development, & Delivery

Basher, R. (2006). Global early warning systems for natural hazards: systematic and people-centred. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 364(1845), 2167-2182. <https://doi.org/10.1098/rsta.2006.1819>

To be effective, early warning systems for natural hazards need to have not only a sound scientific and technical basis, but also a strong focus on the people exposed to risk, and with a systems approach that incorporates all of the relevant factors in that risk, whether arising from the natural hazards or social vulnerabilities, and from short-term or long-term processes. Disasters are increasing in number and severity and international institutional frameworks to reduce disasters are being strengthened under United Nations oversight. Since the Indian Ocean tsunami of 26 December 2004, there has been a surge of interest in developing early warning systems to cater to the needs of all countries and all hazards.

Bostrom, A., Morss, R. E., Lazo, J. K., Demuth, J. L., Lazrus, H., & Hudson, R. (2015). A Mental Models Study of Hurricane Forecast and Warning Production, Communication, and Decision-Making. *Weather, Climate, and Society*, 8(2), 111-129. <https://doi.org/10.1175/WCAS-D-15-0033.1>

AbstractThe study reported here explores how to enhance the public value of hurricane forecast and warning information by examining the entire warning process. A mental models research approach is applied to address three risk management tasks critical to warnings for extreme weather events: 1) understanding the risk decision and action context for hurricane warnings, 2) understanding the

commonalities and conflicts in interpretations of that context and associated risks, and 3) exploring the practical implications of these insights for hurricane risk communication and management. To understand the risk decision and action context, the study develops a decision-focused model of the hurricane forecast and warning system on the basis of results from individual mental models interviews with forecasters from the National Hurricane Center (n = 4) and the Miami-South Florida Weather Forecast Office (n = 4), media broadcasters (n = 5), and public officials (n = 6), as well as a group decision-modeling session with a subset of the forecasters. Comparisons across professionals reveal numerous shared perceptions, as well as some critical differences. Implications for improving extreme weather event forecast and warning systems and risk communication are threefold: 1) promote thinking about forecast and warning decisions as a system, with informal as well as formal elements; 2) evaluate, coordinate, and consider controlling the proliferation of forecast and warning information products; and 3) further examine the interpretation and representation of uncertainty within the hurricane forecast and warning system as well as for users.

Brotzge, J., & Donner, W. (2013). The Tornado Warning Process: A Review of Current Research, Challenges, and Opportunities. *Bulletin of the American Meteorological Society*, 94(11), 1715-1733. <https://doi.org/10.1175/BAMS-D-12-00147.1>

With the unusually violent tornado season of 2011, there has been a renewed national interest, through such programs as NOAA's Weather Ready Nation initiative, to reevaluate and improve our tornado warning process. This literature review provides an interdisciplinary, end-to-end examination of the tornado warning process. Following the steps outlined by the Integrated Warning System, current research in tornado prediction and detection, the warning decision process, warning dissemination, and public response are reviewed, and some of the major challenges for improving each stage are highlighted. The progress and challenges in multi-day to short-term tornado prediction are discussed, followed by an examination of tornado detection, focused primarily upon the contributions made by weather radar and storm spotters. Next is a review of the warning decision process and the challenges associated with dissemination of the warning, followed by a discussion of the complexities associated with understanding public response. Finally, several research opportunities are considered, with emphases on understanding acceptable risk, greater community and personal preparation, and personalization of the hazard risk.

Carr, R. H., Montz, B., Maxfield, K., Hoekstra, S., Semmens, K., & Goldman, E. (2016). Effectively Communicating Risk and Uncertainty to the Public: Assessing the National Weather Service's Flood Forecast and Warning Tools. *Bulletin of the American Meteorological Society*, 97(9), 1649-1665. <https://doi.org/10.1175/bams-d-14-00248.1>

The constant bombardment of weather information in different formats and time frames with different levels of certainty, how does an important message make an impact? For weather and river forecast offices, this is a pressing question given a likely future of increasing high-impact storm events. These offices need to quickly and effectively motivate public response to impending events such as flooding. Currently, communication of flood potential is accomplished through a suite of forecast and warning products, including river hydrographs, precipitation forecasts, and flood watches and warnings. Despite advances in forecast accuracy and lead time, people fail to respond to warnings and often suffer substantial damages and loss of property. To understand how the public uses and interprets National Weather Service (NWS) flood products, an extreme storm scenario was presented using NWS forecast

products in a series of focus groups in the Delaware River basin (Pennsylvania–New Jersey). Findings from the sessions informed revisions of the products to which participants reported increased understanding and motivation to take action. Participants demonstrated a strong preference for river-level information presented through the NWS hydrograph among all the NWS products shown depicting an approaching hurricane. Simplified graphics, explanations in general terms, intuitive colors, and geographic specificity are key recommendations to improve comprehension of risk and uncertainty. The National Oceanic and Atmospheric Administration (NOAA) and NWS are taking steps to operationalize some of these suggestions. This study's methods and results are applicable to other areas and hazard types.

Childs, S. J., & Schumacher, R. S. (2018). Cold-season Tornado Risk Communication: Case Studies from November 2016 to February 2017. *Weather, Climate, and Society*, 10(3), 419-433. <https://doi.org/10.1175/wcas-d-17-0073.1>

Abstract Cold-season tornadoes, defined here as those occurring during November–February (NDJF), pose many societal risks. Not only do they occur when tornadoes are least common in the United States, but NDJF tornadoes also tend to be nocturnal and are most prevalent in the Southeast, where complex terrain, limited resources, and a high mobile home density add social vulnerabilities. In the period 1953–2015, within the domain of 25°–42.5°N, 75°–100°W, over 900 people were killed as a result of NDJF tornadoes. Moreover, NDJF tornado frequency is increasing much faster than that of annual tornadoes. Given the enhanced societal risk, particularly in the Southeast, effective communication between professionals and the public is imperative during a cold-season tornado event. This study investigates communication strategies and barriers from the perspective of National Weather Service and broadcast meteorologists, as well as emergency managers, through a postevent survey of four major tornado events from November 2016 to February 2017. Barriers to tornado risk communication identified by the professionals included public “me-centeredness,” inconsistent messages, and timing and meteorological uncertainties, as well as case-specific factors. Meteorologists perceived their communities as vulnerable to tornadoes in general, yet also prepared and receptive to warnings. Factors influencing perceived barriers and vulnerability are incorporated into a conceptual model of tornado risk communication, which is applicable to tornadoes in general. Ideas for overcoming these barriers include consolidation of warning graphics, collaboration between the meteorological and social science communities, and improved education of tornado risks for the most vulnerable sectors of society.

Coleman, T. A., Knupp, K. R., Spann, J., Elliott, J. B., & Peters, B. E. (2011). The History (and Future) of Tornado Warning Dissemination in the United States. *Bulletin of the American Meteorological Society*, 92(5), 567-582. <https://doi.org/10.1175/2010BAMS3062.1>

Since the successful tornado forecast at Tinker AFB in 1948 paved the way for the issuance of tornado warnings, the science of tornado detection and forecasting has advanced greatly. However, tornado warnings must be disseminated to the public to be of any use. The Texas tornado warning conferences in 1953 began to develop the framework for a modern tornado warning system and included radar detection of tornadoes, a spotter network, and improved communications between the U.S. Weather Bureau, spotters, and public officials, allowing more timely warnings and dissemination of those warnings to the public. Commercial radio and television are a main source of warnings for many, and the delivery methods on TV have changed much since 1960. NOAA Weather Radio (NWR) was launched after the 1974 Super Outbreak of tornadoes, with the most important feature being the tone alert that

allowed receivers to alert people even when the radio broadcast was turned off. Today, NWR reaches most of the U.S. population, and Specific Area Message Encoding technology has improved its warning precision. Outdoor warning sirens, originally designed for use in enemy attack, were made available for use during tornado warnings around 1970. “Storm based” warnings, adopted by the National Weather Service in 2007, replaced countybased warnings and greatly reduce the warning area. As communications advances continue, tornado warnings will eventually be delivered to precise locations, using GPS and other location technology, through cellular telephones, outdoor sirens, e-mails, and digital television, in addition to NWR.

Demuth, J. L., Morss, R. E., Lazo, J. K., & Hilderbrand, D. C. (2013). Improving Effectiveness of Weather Risk Communication on the NWS Point-and-Click Web Page. *Weather and Forecasting*, 28(3), 711-726. <https://doi.org/10.1175/waf-d-12-00118.1>

The National Weather Service's (NWS) point-and-click (PnC) web page is a primary channel through which NWS directly provides routine and hazardous weather information to its users. The research presented here aims to improve risk communication of hazardous weather information on the PnC web page. The focus is on improving communication of threat existence and threat timing because this important information influences how individuals perceive and respond to a weather risk. Experimental presentations of PnC forecast information were designed for two weather scenarios: a severe thunderstorm warning and a flood watch. The experimental presentations were created by adding new textual and graphical pieces of information that were intended to better convey threat existence and timing, and they were evaluated through two rounds of nationwide surveys of PnC web page users. The survey results show that the default presentation of forecast information on the PnC web page was the least effective at conveying hazardous weather threat existence and timing. Adding start-time text and end-time text, when these information pieces were coupled, helped respondents understand the precise time that weather threats were in effect for the rapid-onset, short-duration severe thunderstorm warning and for the delayed-start, longer-duration flood watch. Adding a box graphic placed around the forecast icons further enhanced communication effectiveness by drawing respondents' attention to the weather threat. Other experimental forecast presentations were designed but were less effective at communicating hazardous weather threat existence and timing, illustrating the importance of empirically evaluating weather risk communication prior to providing it operationally.

Drost, R., Casteel, M., Libarkin, J., Thomas, S., & Meister, M. (2016). Severe Weather Warning Communication: Factors Impacting Audience Attention and Retention of Information during Tornado Warnings. *Weather Climate and Society*, 8(4), 361-372. <https://doi.org/10.1175/wcas-d-15-0035.1>

Weather hazards in the United States inflict both personal and economic tolls on the public. Communicating warnings about weather hazards is an important duty of TV weathercasters. Televised weather warnings are typically conveyed through live radar, live coverage, and warning scrolls. However, these traditional approaches may not be entirely effective given the limited attention some members of the public pay to these warnings. A study comparing individual responses to a traditional warning, an animated warning, and an audio warning was undertaken to evaluate the impact of delivery methods on viewer attention, retention, and preferences during viewing of severe weather warnings. A Tobii T60 eye tracker was used to document visual interactions with onscreen warnings and surveys were used to collect evidence of warning retention and preference. Demographic variables were also

collected to describe the study population. Results indicate that viewers of the animated warning retained more pertinent information about the tornado warning than viewers of the traditional warning, and retention during the traditional warning was equivalent to that of the audio warning. In addition, gaze patterns for the traditional warning were much more diffuse than for the animated warning, suggesting that attention was more focused on the animation than the live video. In addition, modifications to reduce visual complexity of traditional warnings may positively impact viewer attention to individual warning elements. Future studies will consider the effectiveness of a hybrid warning containing both traditional and animated components. The current research study can be used to advance current severe weather warning communication techniques and increase public awareness during severe weather events.

E., L. C., Walter, D., Brenda, P., J., B. E., Kevin, K., Eve, G., & Alex, G. (2010). Emergency manager decision-making and tornado warning communication. *Meteorological Applications*, 17(2), 163-172. <https://doi.org/10.1002/met.201>

Emergency managers (EMs) play a critical role in communicating severe weather and tornado warnings to the public, yet communicating the uncertainty of when, where or if a tornado may hit remains a great challenge for EMs. Focus group and survey data concerning weather product usage, weather observing spotter interaction, and decisions to warn the public were collected from Oklahoma EMs in order to characterize the communication processes EMs employ during severe weather outbreaks. These processes include: (1) acquiring weather information, (2) interpreting the information in order to make weather hazard threat assessments, (3) verifying the information, and (4) making time-sensitive warning decisions. The results indicate that while EMs use a variety of weather and radar products to acquire information, weather observing spotters are key sources of verification data. With respect to warning the public about tornado threats, sirens are the primary method. These findings are related to the development of a new radar system being developed by the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), so that this new technology can be designed to reduce uncertainty in the EM decision-making and warning communication processes. Copyright © 2010 Royal Meteorological Society

Ferris, J. S., & Newburn, D. A. (2017). Wireless alerts for extreme weather and the impact on hazard mitigating behavior. *Journal of Environmental Economics and Management*, 82, 239-255. <https://doi.org/10.1016/j.jeem.2016.11.002>

Wireless alerts delivered through mobile phones are a recent innovation in regulatory efforts toward preparation for extreme weather events including flash floods. In this article, we use difference-in-differences models of the number of car accidents from days with government issued alerts for flash flood events in Virginia. We find that wireless alert messages for flash flood warnings reduced car accidents by 15.9% relative to the counterfactual with non-wireless alert protocols. We also use a regression discontinuity model to analyze hourly traffic volume data immediately before and after a flash flood warning message is issued. We find that traffic volume is reduced by 3.1% immediately following the issuance of a wireless alert relative to before the alert. These results imply that wireless alert messages effectively reduce exposure to hazards associated with extreme weather.

Kuster, C. M., Heinselman, P. L., Snyder, J. C., Wilson, K. A., Speheger, D. A., & Hocker, J. E. (2017). An Evaluation of Radar-Based Tornado Track Estimation Products by Oklahoma Public Safety Officials. *Weather and Forecasting*, 32(5), 1711-1726. <https://doi.org/10.1175/WAF-D-17-0031.1>

Many public safety officials (e.g., emergency managers and first responders) use weather-radar data to inform many life-saving decisions, such as sounding outdoor warning sirens and directing storm spotters. Therefore, to include this important user group in ongoing radar applications research, a knowledge coproduction framework is used to interact with, learn from, and provide information to public safety officials. From these interactions, it became clear that radar-based products that estimate a tornado's location, intensity, or both could be valuable to public safety officials. Therefore, a survey was conducted and a focus group formed to 1) collect feedback on several of these products currently under development, 2) identify potential decisions that could be made with these products, and 3) examine the impact of radar update time on product usefulness. An analysis of the survey and focus group responses revealed that public safety officials preferred simple interactive products provided to them using multiple communication methods. Once received, any product that could clearly communicate where a tornado may have occurred would likely help public safety officials focus search and rescue efforts in the immediate aftermath of a tornado. Additionally, public safety officials preferred products created using rapid-update data (1-2-min volumetric updates) over conventional-update data (4-5-min volumetric updates) because it provided them with more complete information.

Liu, B. F., Wood, M. M., Egnoto, M., Bean, H., Sutton, J., Mileti, D., & Madden, S. (2017). Is a picture worth a thousand words? The effects of maps and warning messages on how publics respond to disaster information. *Public Relations Review*, 43(3), 493-506. <https://doi.org/10.1016/j.pubrev.2017.04.004>

Research examining whether visuals improve publics' crisis and disaster information comprehension is scarce despite the increasing popularity of infographics and visual-based social media in public relations practice. One disaster communication platform that is ideal for testing the potential effects of visuals on helping publics protect themselves during disasters is Wireless Emergency Alerts (WEAs). WEAs are 90-character warnings issued by governments and sent by wireless carriers to individuals (for free) facing an imminent threat such as a tornado or flood. The U.S. government is considering adding maps to future WEAs. Maps are one of the most relied-on tools for people to quickly gain knowledge about spatial tasks such as evacuating during disasters. Consequently, this paper empirically tests how at-risk publics respond to warning messages with and without maps. We do so through two experiments (N1=767, N2=550) of U.S. adults testing three disasters: a tsunami, an active shooter incident, and a radiological disaster.

Luo, J., Cong, Z., & Liang, D. (2015). Number of Warning Information Sources and Decision Making During Tornadoes. *American Journal of Preventive Medicine*, 48(3), 334-337. <https://doi.org/10.1016/j.amepre.2014.09.007>

Background Taking proper protective action upon receiving tornado warnings is critical to reducing casualties. With more warning information sources becoming available, how the number of such information sources affects decision making should be quantitatively investigated. Purpose To examine how the number of warning information sources affected individuals' decisions to take protective action during tornadoes. Methods A telephone survey using random sampling was conducted in 2012 with

residents in Tuscaloosa AL and Joplin MO, resulting in a working sample of 782 respondents. Both cities were struck by violent tornadoes (Enhanced Fujita Scale [EF]4 and EF5) in 2011. The analysis was conducted in 2013. Results Logistic regression analysis showed that relative to having only one warning information source, having two and three or more warning information sources significantly increased the odds of taking protective action in Joplin but not in Tuscaloosa; having three or more sources had a significantly stronger effect on taking protective action in Joplin than in Tuscaloosa. Having an emergency preparation plan in both cities and being white in Tuscaloosa significantly increased the odds of taking protective action, whereas being divorced in Joplin reduced these odds. Conclusions Receiving warnings from more warning information sources might be more beneficial in places with less previous exposure to tornadoes and for populations with lower awareness of a potential tornado and higher probability of receiving no warnings. Emergency management agencies and public health officials should give priority to these places and populations when formulating disaster mitigation decisions and policies.

Mason, J. B., & Senkbeil, J. C. (2014). Implications of the 2011 Tuscaloosa EF4 tornado for shelter and refuge decisions. *Natural Hazards*, 74(2), 1021-1041. <https://doi.org/10.1007/s11069-014-1230-4>

This research provides an overview and discussion of language used in tornado safety recommendations along with development of a rubric for scaled tornado safety recommendations. Residents living in affected areas and those temporarily housed at relief stations were surveyed to collect information on their experiences during a 2-week period following the April 27, 2011 Tuscaloosa, Alabama EF4 tornado. Respondents were asked about their refuge plans during the storm and about any future changes to those plans. A specific focus of this research evaluated the adequacy of each respondent's plan. Each refuge plan was compared using a tornado refuge rubric developed through the use of enhanced Fujita (EF) scale degree of damage ratings for available damage indicators. There was a significant difference in the counts of refuge adequacy for Tuscaloosa residents when holding the locations during the April 27 tornado constant and comparing adequacy ratings for weak (EF0–EF1), strong (EF2–EF3), and violent (EF4–EF5) tornadoes. There was also a significant difference when comparing the future tornado refuge plans of those same participants to the adequacy ratings for weak, strong, and violent tornadoes. This research introduces renewed discussion on proper refuge and shelter alternatives for days when violent tornadoes are forecasted.

Mason, J. B., & Senkbeil, J. C. (2015). A Tornado Watch Scale to Improve Public Response. *Weather Climate and Society*, 7(2), 146-158. <https://doi.org/10.1175/wcas-d-14-00035.1>

A tornado refuge rubric was revised into a six-level, hierarchical Tornado Watch Scale (TWS) from level 0 to level 5 based on the likelihood of high or low-impact tornadic events. Levels correspond to an estimate of the maximum potential tornado intensity for a given day and include refuge/shelter categories of “adequate,” “questionable,” or “inadequate,” which encompass a range of refuge/shelter locations taken from the Enhanced Fujita scale. Ratings are based on a conservative estimate of damage indicators in high winds and the safety of a person taking refuge inside buildings of varying structural design. Audio recordings similar to those used in current NOAA weather radio communications were developed for each TWS intensity level. Recordings representing an existing tornado watch, existing particularly dangerous situation (PDS) tornado watch, and three proposed levels from the TWS were then used in interviews with Alabama residents to determine how changes to the information contained

in the watch statements would affect each participant's tornado safety actions and risk perception. Participants were also questioned about their knowledge and past experience with tornado hazards and their preference between the existing NWS tornado watches and the TWS. Results indicate a strong preference for the TWS when compared to existing products. The TWS was favored for providing additional information, containing descriptions of expected severity, and being easy to understand. The TWS also elicits more adequate safety decisions and more appropriate risk perception when compared to existing products, and these increases in safety were statistically significant.

Miran, S. M., Ling, C., James, J. J., Gerard, A., & Rothfusz, L. (2017). User perception and interpretation of tornado probabilistic hazard information: Comparison of four graphical designs. *Applied Ergonomics*, 65, 277-285. <https://doi.org/10.1016/j.apergo.2017.06.016>

Effective design for presenting severe weather information is important to reduce devastating consequences of severe weather. The Probabilistic Hazard Information (PHI) system for severe weather is being developed by NOAA National Severe Storms Laboratory (NSSL) to communicate probabilistic hazardous weather information. This study investigates the effects of four PHI graphical designs for tornado threat, namely, "four-color", "red-scale", "grayscale" and "contour", on users' perception, interpretation, and reaction to threat information. PHI is presented on either a map background or a radar background. Analysis showed that the accuracy was significantly higher and response time faster when PHI was displayed on map background as compared to radar background due to better contrast. When displayed on a radar background, "grayscale" design resulted in a higher accuracy of responses. Possibly due to familiarity, participants reported four-color design as their favorite design, which also resulted in the fastest recognition of probability levels on both backgrounds. Our study shows the importance of using intuitive color-coding and sufficient contrast in conveying probabilistic threat information via graphical design. We also found that users follow a rational-perceiving-judging-feeling-and acting approach in processing probabilistic hazard information for tornado. (C) 2017 Elsevier Ltd. All rights reserved.

Morss, R. E., Cuite, C. L., Demuth, J. L., Hallman, W. K., & Shwom, R. L. (2018). Is storm surge scary? The influence of hazard, impact, and fear-based messages and individual differences on responses to hurricane risks in the USA. *International Journal of Disaster Risk Reduction*. <https://doi.org/10.1016/j.ijdr.2018.01.023>

This article uses data from an online survey-based experiment to investigate how risk communications and individual differences influence people's responses to approaching hurricane risks. Survey data were collected from 1716 residents of coastal areas of the USA affected by Hurricane Sandy. Respondents were randomly assigned to receive a combination of textual messages about a hypothetical approaching hurricane, including hazard-based, impact-based, and fear-based messages. The analysis examines how the experimental messages influenced respondents' evacuation intentions, risk perceptions, efficacy beliefs, and perceptions of the information and its source. The influence of non-message factors, including respondents' actual and perceived geographical exposure to hurricane-related risks, evacuation planning, and hurricane-related experiences, is also investigated. The results indicate that the high-impact and fear messages increased evacuation intentions, risk perceptions, and response efficacy, but the effects were small. The hazard message manipulations did not significantly influence most of the dependent variables examined; in particular, neither of the two storm surge messages

tested increased evacuation intentions or risk perceptions relative to the wind-only or flood message. There were also no significant differences in message effects among respondents who lived or thought they lived in areas at higher risk. Further, several individual difference variables examined influenced evacuation intentions more than the message variations. Overall, experience evacuating for Sandy was the strongest predictor of evacuation intentions. These results indicate the importance of designing and evaluating hazard risk communications in the context of the other messages people are receiving and the individual differences that influence protective decision making.

Morss, R. E., Demuth, J. L., Lazrus, H., Palen, L., Barton, C. M., Davis, C. A., . . . Watts, J. (2017). Hazardous Weather Prediction and Communication in the Modern Information Environment. *Bulletin of the American Meteorological Society*, 98(12), 2653-2674. <https://doi.org/10.1175/BAMS-D-16-0058.1>

During the last few decades, scientific capabilities for understanding and predicting weather and climate risks have advanced rapidly. At the same time, technological advances, such as the Internet, mobile devices, and social media, are transforming how people exchange and interact with information. In this modern information environment, risk communication, interpretation, and decision-making are rapidly evolving processes that intersect across space, time, and society. Instead of a linear or iterative process in which individual members of the public assess and respond to distinct pieces of weather forecast or warning information, this article conceives of weather prediction, communication, and decision-making as an interconnected dynamic system. In this expanded framework, information and uncertainty evolve in conjunction with people's risk perceptions, vulnerabilities, and decisions as a hazardous weather threat approaches; these processes are intertwined with evolving social interactions in the physical and digital worlds. Along with the framework, the article presents two interdisciplinary research approaches for advancing the understanding of this complex system and the processes within it: analysis of social media streams and computational natural-human system modeling. Examples from ongoing research are used to demonstrate these approaches and illustrate the types of new insights they can reveal. This expanded perspective together with research approaches, such as those introduced, can help researchers and practitioners understand and improve the creation and communication of information in atmospheric science and other fields.

O'Brien, M. A., & Peterson, C. (2017). Age Differences in Tornado Warning Responses and Emotions. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 61(1), 26-30. <https://doi.org/10.1177/1541931213601501>

Empowering tornado-prone community residents to effectively prepare for and respond to tornado warnings is a significant challenge for public safety. Although several studies have investigated participant knowledge, response intentions and behavior to different warnings, few studies have evaluated actual responses to tornado warnings from a sufficiently large sample to reveal the greatest challenges and opportunities for increasing compliance. This study examined warning knowledge and tornado experiences of 30 college students and 30 older community residents in two tornado-prone states. Findings corroborated prior research but also highlighted the need to understand how information gathering supports individual judgments of warning relevance at specific times and locations. We also found age differences in the type of information utilized to make these judgments, highlighting the need for focused community education and communication. Analysis of tornado

aftermath emotional experiences particularly supports the NWS's proposal to exploit disaster aftermath priming to increase compliance.

Perreault, M. F., Houston, J. B., & Wilkins, L. (2014). Does Scary Matter?: Testing the Effectiveness of New National Weather Service Tornado Warning Messages. *Communication Studies*, 65(5), 484-499. <https://doi.org/10.1080/10510974.2014.956942>

In Spring 2011, record-level tornadoes in the South and Midwest United States resulted in significant human injury and death. In response, the National Weather Service (NWS) developed new warning messages for the 2012 storm season, utilizing more frightening warning language and more specific directions. The current study tested the effectiveness of these new messages by showing participants four different experimental stimuli: regular TV warning messages, new scary TV warning messages, regular radio warning messages, and new scary radio warning messages. Results indicated that behavioral intentions were not affected by any of the experimental stimuli. However, regular warning messages were perceived as more credible than the new scary messages. We also examined characteristics of individuals in relation to severe-weather information use and found that women and those with more storm experience used more sources of severe-weather information.

Ripberger, J. T., Silva, C. L., Jenkins-Smith, H. C., & James, M. (2015). The Influence of Consequence-Based Messages on Public Responses to Tornado Warnings. *Bulletin of the American Meteorological Society*, 96(4), 577-590. <https://doi.org/10.1175/bams-d-13-00213.1>

The Central Region Headquarters of the National Weather Service (NWS) recently launched an experimental product that supplements traditional tornado and severe thunderstorm warning products with information about the potential impact of warned storms. As yet, however, we know relatively little about the influence of consequence-based messages on warning responsiveness. To address this gap, we fielded two surveys of U.S. residents that live in tornado-prone regions of the country. Both surveys contained an experiment wherein participants were randomly assigned a consequence-based tornado warning message and asked to indicate how they would respond if they were to receive such a warning. Respondents that were assigned to higher-impact categories were more likely choose protective action than respondents assigned to lower-impact categories. There was, however, a threshold beyond which escalating the projected consequences of the storm no longer increased the probability of protective action. To account for this, we show that the relationship between consequence-based messages and protective action depends on the type of action being considered. At lower levels of projected impact, increasing the expected consequences of the storm simultaneously increased the probability that respondents selected a “shelter in place” or “leave residence” option. At higher levels of projected impact, this relationship changed—increasing the projected consequences of the storm decreased the probability that respondents would shelter in place and increased the probability that they would leave their residence for what they perceived to be a safer location. In some severe storm situations, this behavior may increase rather than decrease the risks.

Schumann, R. L., Ash, K. D., & Bowser, G. C. (2018). Tornado Warning Perception and Response: Integrating the Roles of Visual Design, Demographics, and Hazard Experience. *Risk Analysis*, 38(2), 311-332. <https://doi.org/10.1111/risa.12837>

Recent advancements in severe weather detection and warning dissemination technologies have reduced, but not eliminated, large-casualty tornado hazards in the United States. Research on warning cognition and behavioral response by the public has the potential to further reduce tornado-related deaths and injuries; however, less research has been conducted in this area compared to tornado research in the physical sciences. Extant research in this vein tends to bifurcate. One branch of studies derives from classic risk perception, which investigates cognitive, affective, and sociocultural factors in relation to concern and preparation for uncertain risks. Another branch focuses on psychological, social, and cultural factors implicated in warning response for rapid onset hazards, with attention paid to previous experience and message design. Few studies link risk perceptions with cognition and response as elicited by specific examples of warnings. The present study unites risk perception, cognition, and response approaches by testing the contributions of hypothesized warning response drivers in one set of path models. Warning response is approximated by perceived fear and intended protective action as reported by survey respondents when exposed to hypothetical tornado warning scenarios. This study considers the roles of hazard knowledge acquisition, information-seeking behaviors, previous experience, and sociodemographic factors while controlling for the effects of the visual warning graphic. Findings from the study indicate the primacy of a user's visual interpretation of a warning graphic in shaping tornado warning response. Results also suggest that information-seeking habits, previous tornado experience, and local disaster culture play strong influencing roles in warning response.

Silver, A., & Conrad, C. (2010). Public perception of and response to severe weather warnings in Nova Scotia, Canada. *Meteorological Applications*, 17(2), 173-179. <https://doi.org/10.1002/met.198>

Hurricane Juan, which struck Atlantic Canada on 29 September, 2003, revealed the full extent of public vulnerability to severe weather events in Nova Scotia. In this study, 130 people were interviewed via a systematic sampling technique to examine their perception of severe weather warnings, and to determine what actions (if any) they are most likely to take when a warning has been posted. It was found that different target groups (e.g. the elderly, students) use different modes of media to obtain their severe weather information. It is recommended that forecast centres tailor their advisories for specific media sources so as best to reach various target groups. It was also found that respondents are generally satisfied with the weather warnings they receive, but there is a lack of awareness of the existence and extent of public vulnerability in Nova Scotia. The development of a comprehensive education campaign which will outline various facets of social vulnerability, while also offering recommendations on how best to lower existing social vulnerability, is critical. Copyright © 2010 Royal Meteorological Society

Simmons, K. M., & Sutter, D. (2008). Tornado Warnings, Lead Times, and Tornado Casualties: An Empirical Investigation. *Weather and Forecasting*, 23(2), 246-258. <https://doi.org/10.1175/2007waf2006027.1>

Abstract Conventional wisdom holds that improved tornado warnings will reduce tornado casualties, because longer lead times on warnings provide extra opportunities to alert residents who can then take precautions. The relationship between warnings and casualties is examined using a dataset of tornadoes in the contiguous United States between 1986 and 2002. Two questions are examined: Does a warning issued on a tornado reduce the resulting number of fatalities and injuries? Do longer lead times reduce casualties? It is found that warnings have had a significant and consistent effect on tornado injuries, with a reduction of over 40% at some lead time intervals. The results for fatalities are mixed. An increase

in lead time up to about 15 min reduces fatalities, while lead times longer than 15 min increase fatalities compared with no warning. The fatality results beyond 15 min, however, depend on five killer tornadoes and consequently are not robust.

Strawderman, L., Carruth, D. W., Sherman-Morris, K., Menard, P., Warkentin, M., & McNeal, K. S. (2018). Individual transportation decisions under conditions of risk and uncertainty. *Natural Hazards*, 92(2), 927-942. <https://doi.org/10.1007/s11069-018-3232-0>

This study explores the influence of three factors on a person's decision to drive in winter weather: destination, affected area, and caution level. Participants (n = 555) completed an online survey that included scenarios with text of a simulated radio message involving a character named Mike. After the scenario, participants answered Likert-scaled questions related to their intention to drive (what would you do) and their recommended behavior for others (what should Mike do). There was a significant effect of destination and caution level on the decision to drive. Participants were more likely to respond that they would drive if the destination was work rather than dinner, and if the caution statement was "exercise caution" rather than "do not drive." There were similar significant effects of destination and caution level on what the scenario character should do. It is recommended that a clear directive be included in warning messages to encourage drivers to stay off the roadways during hazardous weather.

Tinker, T. (2013). Communicating and managing change during extreme weather events - promising practices for responding to urgent and emergent climate threats. *Journal of Business Continuity & Emergency Planning*, 6(4).

Large-scale weather events in the USA such as hurricanes Sandy, Isaac and Katrina challenge traditional approaches to change communication and management (CCM) before during and after crises. A major challenge (as well as opportunity) is addressing change from the 'whole-community' perspective affecting a spectrum of people, policies, processes, behaviours and outcomes. When CCM is used effectively, one of its fundamental advantages is creating a sense of urgency. This paper looks at optimising communication during extreme weather events, engaging stakeholders, harnessing the power of social media and change, and correlating organisational and individual behaviours and actions. The strategic blend of change management and crisis communication strategies and tactics in CCM is a central feature in the response to the full range of extreme weather scenarios.

Wallace, Z. C., & Hill, A. A. (2017). Forecaster and Emergency Manager Perspectives on Coordination and Communication with the Weather-Warned Public. *Papers in Applied Geography*, 3(2), 157-170. <https://doi.org/10.1080/23754931.2017.1299036>

According to the National Weather Service, each year the United States experiences an average of 1,200 tornadoes that kill about sixty people and injure about 1,500. The goal of this work is to explore the warning communication process from the perspectives of the forecaster (National Weather Service) and the responder (emergency management agencies) and to identify variations and challenges in communication strategies. This research explores the priorities, perceptions, perspectives, and challenges these professionals face and identifies any variations among regions and between professions. Through two different national surveys, these professionals provide insight into the realities of disseminating warnings and meeting particular needs of the communities they serve. This work

further examines the perceptions professionals have of weather understanding by the public. Tornado risk and warnings are the primary focus of this work. Findings reveal that forecasters and emergency managers lack confidence that the public understands warnings and watches. This study also found consistency in the frequency and nature of interaction between National Weather Service Forecast Offices and the communities they serve and regional variations were observed in the interactions between emergency managers and the communities they serve.

Wu, D., & Cui, Y. (2018). Disaster early warning and damage assessment analysis using social media data and geo-location information. *Decision Support Systems*.
<https://doi.org/10.1016/j.dss.2018.04.005>

Societies are confronted with destructive natural disasters of increasing frequency. Social networks are playing an increasingly important role as early warning systems, aiding with rapid disaster assessment and post-disaster recovery. There is a need for both the public and disaster-relief agencies to better understand how social media can be utilized to assess and respond to natural disasters. However, existing research on the role of social media in society's response to natural disasters is neither holistic nor systematic. In this study, we conduct a hierarchical multiscale analysis based on multiple data resources, combining social media data, economic losses, and geo-information. We verify the role played by social media before, during, and after a natural disaster. We investigate whether the combination of social media and geo-location information can contribute to a more efficient early warning system and help with disaster assessment. This paper draws attention to the fact that during a disaster, citizens turn to social media and the majority of tweets contain information about the hurricane and/or its impact with negative sentiment. We demonstrate that the severity of damage in one area is positively correlated with the intensity of disaster-related activity. Meanwhile, the coastal areas and areas with close proximity to Hurricane center tend to suffer from higher losses during a disaster. Our findings explore the role played by social media from individuals in affected populations and how they respond to unfolding natural disasters. Results hold significance with regard to providing timely assistance for both official institutions and netizens.