Time Relevance	Author(s)	Title
x	Bostrom, A., R. E. Morss, J. K. Lazo, J. Demuth, H. Lazrus, and R. Hudson	A Mental Models Study of Hurricane Forecast and Warning Production, Communication, and Decision-Making
x	Bostrom, Ann, Rebecca Morss, Jeffrey K. Lazo, Julie Demuth, and Heather Lazrus	Eyeing the storm: How residents of coastal Florida see hurricane forecasts and warnings
	Broad, Kenneth, Anthony Leiserowitz, Jessica Weinkle, and Marissa Steketee	Misinterpretations of the "Cone of Uncertainty" in Florida during the 2004 Hurricane Season

x	Carr, Rachel Hogan, Burrell Montz, Keri Maxfield, Stephanie Hoekstra, Kathryn Semmens, and Elizabeth Goldman	Effectively Communicating Risk and Uncertainty to the Public: Assessing the National Weather Service's Flood Forecast and Warning Tools
x	Cox, Jonathan, Donald House, and Michael Lindell	Visualizing Uncertainty in Predicted Hurricane Tracks
	Czajkowski, J.	Is It Time to Go Yet? Understanding Household Hurricane Evacuation Decisions from a Dynamic Perspective
	Demuth, J.L., Morss, R.E., Lazo, J.K., and Trumbo, C.	The Effects of Past Hurricane Experiences on Evacuation Intentions through Risk Perception and Efficacy Beliefs: A Mediation Analysis.

Demuth, Julie L., Rebecca E. Morss, Betty Hearn Morrow, and Jeffrey K. Lazo	Creation and Communication of Hurricane Risk Information
Dobson, Michael W.	Choropleth Maps Without Class Intervals?: A Comment
Dobson, Michael W.	Perception of continuously shaded maps
Drake, Lori	Scientific Prerequisites to Comprehension of the Tropical Cyclone Forecast: Intensity, Track, and Size

Eosco, G. M.	A study of visual communication: cyclones, cones, and confusion
Gedminas, L.	Evaluating Hurricane Advisories Using Eye-Tracking and Biometric Data
Hamill, Thomas M., Michael J. Brennan, Barbara Brown, Mark DeMaria, Edward N. Rappaport, and Zoltan Toth	NOAA'S Future Ensemble-Based Hurricane Forecast Products
Harrower, Mark, & Brewer, Cynthia Anne	ColorBrewer.org: an online tool for selecting colour schemes for maps

	Joslyn, S., Savelli, S., and Nadav-Greenberg, L.	Reducing Probabilistic Weather Forecasts to the Worst-Case Scenario: Anchoring Effects.
	Lazo, J.K., Bostrom, A., Morss, R.E., Demuth, J.L., and Lazrus, H.	Factors Affecting Hurricane Evacuation Intentions.
x	Liu, L., M. Mirzargar, R.M. Kirby, R. Whitaker, and D. H. House	Visualizing Time-Specific Hurricane Predictions, with Uncertainty, from Storm Path Ensemble

x	Liu, Le, Alexander P. Boone, Ian T. Ruginski, Lace Padilla, Mary Hegarty, Sarah H. Creem-Regehr, William B. Thompson, Cem Yuksel, and Donald H. House	Uncertainty Visualization by Representative Sampling from Prediction Ensembles
x	Losee, J.E., K.Z. Naufel, L. Locker, and G.D. Webster	Weather Warning Uncertainty: High Severity Influences Judgment Bias
x	Martinez, A.	How Quickly Can We Adapt to Change? An Assessment of Hurricane Damage Mitigation Efforts Using Forecast Uncertainty
	Matyas, Corene, Sivaramakrishnan Srinivasan, Ignatius Cahyanto, Brijesh Thapa, Lori Pennington-Gray, and Jorge Villegas	Risk perception and evacuation decisions of Florida tourists under hurricane threats: a stated preference analysis

x	Meyer, Robert J., Jay Baker, Kenneth Broad, Jeff Czajkowski, and Ben Orlove	The Dynamics of Hurricane Risk Perception: Real-Time Evidence from the 2012 Atlantic Hurricane Season
x	Meyer, Robert, Kenneth Broad, Ben Orlove, and Nada Petrovic	Dynamic Simulation as an Approach to Understanding Hurricane Risk Response: Insights from the Stormview Lab
x	Milch, Kerry, Kenneth Broad, Ben Orlove, and Robert Meyer	Decision Science Perspectives on Hurricane Vulnerability: Evidence from the 2010–2012 Atlantic Hurricane Seasons
x	Morrow, Betty, and Jeffrey K. Lazo	Broadcast media on-line survey on extratropical and tropical cyclone information: NOAA Storm Surge Roadmap, and Hurricane Forecast Improvement Program

	Morrow, Betty, and Jeffrey K. Lazo	Emergency Managers On-Line Survey on Extratropical and Tropical Cyclone Forecast Information: Hurricane Forecast Improvement Program/Storm Surge Roadmap
x	Morss, R. E., J. Demuth, J. K. Lazo, K. Dickinson, H. Lazrus, and B. H. Morrow	Understanding Public Hurricane Evacuation Decisions and Responses to Forecast and Warning Messages*
	National Research Council	Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts

x National Transportation Safety Board — Safety Recommendation Report: Tropical Cyclone Information for Mariners (accident number DCA16MM001)

NOAA National Weather Service — Service assessment: Hurricane Charley, August 9-15, 2004

NOAA National Weather Service — Service assessment: Hurricane Katrina, August 23-31, 2005

	NOAA National Weather Service	Service assessment: Hurricane Irene, August 21-30, 2011
x	NOAA National Weather Service	Service assessment: Hurricane/Post-Tropical Cyclone Sandy, October 22-29, 2012

x	NOAA National Weather Service	Service assessment: October 2016 Hurricane Matthew
x	Padilla, Lace M., Ian T. Ruginski, and Sarah H. Creem-Regehr	Effects of ensemble and summary displays on interpretations of geospatial uncertainty data
	Pang, Alex.	Visualizing Uncertainty in Natural Hazards
x	Pugh, Ashley J., Christopher D. Wickens, Nathan Herdener, Benjamin A. Clegg, and C. A. P. Smith	Effect of Visualization on Spatial Trajectory Prediction under Uncertainty

x	Radford, Laura, Jason C. Senkbeil, and Meganne Rockman	Suggestions for alternative tropical cyclone warning graphics in the USA
	Regnier, Eva	Public Evacuation Decisions and Hurricane Track Uncertainty
x	Ruginski, Ian T., Alexander P. Boone, Lace M. Padilla, Le Liu, Nahal Heydari, Heidi S. Kramer, Mary Hegarty, William B. Thompson, Donald H. House & Sarah H. Creem-Regehr	Non-expert interpretations of hurricane forecast uncertainty visualizations

	Sanyal, Jibonananda; Zhang, Song; Dyer, Jamie; Mercer, Andrew; Amburn, Philip; Moorhead, Robert	Noodles: A Tool for Visualization of Numerical Weather Model Ensemble Uncertainty
x	Saunders, Michelle E., and Jason C. Senkbeil	Perceptions of hurricane hazards in the mid-Atlantic region
	Savelli, Sonia; Joslyn Susan	The Advantages of Predictive Interval Forecasts for Non-Expert Users and the Impact of Visualizations

	Senkbeil, J.C., D. M. Brommer, P.G. Dixon, M.E. Brown, K. Sherman-Morris	The perceived landfall location of evacuees from Hurricane Gustav
x	Sherman-Morris, Kathleen, and Idamis Del Valle-Martinez	Optimistic bias and the consistency of hurricane track forecasts
	Sherman-Morris, Kathleen, Jason Senkbeil, and Robert Carver	WHO'S GOOGLING WHAT? What Internet Searches Reveal about Hurricane Information Seeking
x	Spiegelhalter, David	Risk and Uncertainty Communication

Stephens, Elisabeth M., Tamsin L. Edwards, and David Demeritt	Communicating probabilistic information from climate model ensembles—lessons from numerical weather prediction
Tversky, A., and Kahneman, D.	Judgment Under Uncertainty: Heuristics and Biases
Wang, Junpeng & Hazarika, Subhashis & Li, Cheng & Shen, Han-Wei.	Visualization and Visual Analysis of Ensemble Data: A Survey

	Whitaker, Ross T.; Mirzargar, Mahsa; Kirby, Robert M.	Contour Boxplots: A Method for Characterizing Uncertainty in Feature Sets from Simulation Ensembles
	Wilks, Danielle S., Charles J. Neumann, and Miles B. Lawrence	Statistical Extension of the National Hurricane Center 5-Day Forecasts
X	Wu, Hao-Che, Michael K. Lindell, and Carla S. Prater	Process Tracing Analysis of Hurricane Information Displays
x	Wu, Hao-Che, Michael K. Lindell, and Carla S. Prater	Strike probability judgments and protective action recommendations in a dynamic hurricane tracking task

x | Wu, Hao-Che, Michael K. Lindell, Carla S. Prater, and Charles D. Samuelson | Effects of Track and Threat Information on Judgments of Hurricane Strike Probability

Journal / Publisher	Year	Method
Weather, Climate, and Society	2016	Interviews, group decision modeling, qualitative coding
International Journal of Disaster Risk Reduction	2018	Interviews, written questionnaire, decision modeling, qualitative coding
Bulletin of the American Meteorological Society	2007	Interviews, survey, literature review

Bulletin of the American Meteorological Society	2016	Focus groups
Int. J. Uncertainty Quantification	2013	Controlled experiment, questionnaire
Natural Hazards Review	2011	Technical Study
Weather Climate and Society	2016	Survey

Bulletin of the American Meteorological Society	2012	Interviews
1973 The Ohio State University	1973	Literature review (commentary)
Annals of the Association of American Geographers	1980	Literature review (commentary)
Weather Forecasting	2011	Technical study, literature review

PhD dissertation	2008	Interviews
Unpublished paper. Master's thesis, Faculty Dept. Geography, East Carolina University, Greenville, NC.	2011	Controlled experiment, questionnaire
Bulletin of the American Meteorological Society	2012	Technical Study
The Cartographic Journal	2003	Technical study

Journal of Experimental Psychology Applied	2011	Controlled experiment, questionnaire
Risk Analysis	2015	Survey
Computer Graphics Forum	2015	Technical study

IEEE Trans Vis Comput Graph.	2017	Controlled experiment, questionnaire
American Meteorological Society	2017	Controlled experiment
University of Oxford Department of Economics Discussion Paper Series	2017	Technical study
Natural Hazards	2011	Survey

Bulletin of the American Meteorological Society	2014	Survey
Risk Analysis	2013	Controlled experiment (simulation)
Atmosphere	2018	Phone surveys
National Center for Atmospheric Research	2013	Survey online

National Center for Atmospheric Research	2012	Survey online
Weather Forecasting	2016	Survey
The National Academies Press (Washington, DC)	2006	Study (committee meetings)

National Transportation Safety Board	2017	Safety Recommendation Report
NOAA National Weather Service	2006	Service assessment
NOAA National Weather Service	2006	Service assessment

NOAA National Weather Service	2012	Service Assessment
NOAA National Weather Service	2013	Service assessment

NOAA National Weather Service	2017	Service assessment
Cognitive Research	2017	Stimuli (scenario testing via Qualtrics)
Risk, Governance and Society	2008	Technical study
Proceedings of the Human Factors and Ergonomics Society Annual Meeting	2017	Experiment scenarios conducted by E-Prime

Disaster Prevention and Management: An International Journal	2013	Survey
Management Science	2008	Study (technical analysis)
Spatial Cognition & Computation	2016	Cognitive experiement; participants were randomly assigned one of five visualizataons as a betwee-subjects factor; initial task trials followed by additional 12 think-aloud trials and an online questionnaire

IEEE Transactions on Visualization and Computer Graphics	2010	Technical study, usability testing
Meteorological Applications	2017	Qualtrics survey showing eight hypothetical scenarios with varied storm track and storm size to assess risk perception of hurricane hazards and characteristics. Each scenario showed a four-paneled map featuring the cone, storm surge map, and a new damaging wind map created by the authors.
Applied Cognitive Psychology	2013	Controlled experiments

Natural Hazards	2010	Surve (face-to-face)
Natural Hazards	2017	Online survey at that asked risk perception questions about a series of forecast graphics.
Bulletin of American Meteorological Society	2011	Technical Study
Annual Review of Statistics and Its Application	2017	Literature review

WIREs Clim Change	2012	Technical Study
Science (American Association for the Advancement of Science)	1974	Technical Study
IEEE Transactions on Visualization and Computer Graphics	2018	Technical study

IEEE Transactions on Visualization and Computer Graphics	2013	Technical Study
Weather Forecasting	2009	Technical study
Risk Analysis	2015	Controlled experiment, literature review
Natural Hazards	2015	Controlled experiment

Risk Analysis	2014	Controlled experiment

Sample	Geographic Locatic
8 NWS forecasters, 5 broadcasters, and 6 public officials	Miami-Dade County
28 members of the public	Miami-Dade County, FL
Emergency manager, media outlets, other government agencies	Florida

Flood-prone communities in Easton, PA and Lambertville, NJ	Delaware River basin (Pennsylvania–New Jersey)
23 participatnts from the School of Computing at Clemson University.	Gulf of Mexico
N/A dataset	Gulf of Mexico
255 Miami-Date County residents in evacuation zones	Miami-Dade County, FL

NHC, WFO, emergency managers, media outlets	Gulf of Mexico
N/A	N/A
N/A	N/A
N/A Dataset used	Gulf of Mexico

Forecasters and meteorologists National Weather Service, the National Hurricane Center, The Weather Channel, and Weatherbug.	Gulf of Mexico
35 students	Mid-Atlantic coast
N/A	Gulf of Mexico
N/A	N/A

Undergraduate students	Washington state (where the experiment was conducted)
457 Miami-Dade residents; 347 Houston-Galveston residents (over 18 years old)	Miami-Dade, FL and Houston-Galveston, TX
N/A Dataset used	Gulf of Mexico (areas affected by Katrina, Rita, Ida)

133 participants from the University of California, Santa Barbara and University of Utah	Louisiana (area presented)
214 undergraduate students	Unknown
N/A Dataset used	Areas affected by land-falling hurricanes in the Atlantic basin of the U.S.
448 tourists	central Florida

Residents with telephone lines in areas affected by hurricanes Isaac (93 respondents) and Sandy (89 respondents)	Gulf coast - Florida panhandle; Mid-Atlantic - northeastern NJ
356 residents of southern and central Florida	Florida
Random sample of residents in coastal areas threatened by Hurricanes Earl, Irene, Isaac, and Sandy during 2010–2012 season	coastal residents threatened by Hurricanes Earl, Irene, Isaac, and Sandy
Broadcast meteorologists employed by major U.S. TV outlets	Covered broadcasters employed on Atlantic, Gulf, and Pacific (including Hawaii) coasts

Emergency manager	Atlantic, Gult, Pacific, and Alaska coasts
255 residents of coastal Miami-Dade County, Florida	Miami-Dade County
N/A	N/A

N/A report	Bahamas (location of accident, not data-gathering)
Emergency managers, media outlets, and the public	Florida
40 emergency managers and brocasters	Central Gulf Coast

14 WFOs and 3 River Forecast Cetners	Caribbean; East Coast
WFOs, emergency managers, federal partners of NWS, media, existing data from a public survey	Caribbean, Eastern Seaboard

WFOs and federal partners of NWS	Caribbean to Virginia
Undergraduate students	University of Utah
N/A	N/A
88 students	Unknown

315 respondents (Convenience sample)	Pensacola and Jacksonville, FL
N/A Dataset used for technical analysis	Atlantic and Gulf coasts
200 students from the Universiry of Utah and the Univrsiety of California, Santa Barbara	University of Utah/University of California Santa Barbara

Dataset utilized, two meteorologists tested and gave feedback	N/A
105 participants from Mid-Atlantic (DE, MD, VA, DC)	Mid-Atlantic
350 students	N/A

Evacuees of Hurricane Gustav	Coastal Louisiana, Alabama, Tennessee, Georgia. Face-to-face surveys conducted at interstate rest stops
133 students at University of Puerto Rico at Mayagu¨ez and 72 students by East Carolina University—served by NHC and NWS.	University of Puerto Rico at Mayagu¨ez (UPRM) and East Carolina University (ECU)
N/A dataset utitlizd	South Texas, Western Gulf, National/Katrina, FloraBama, Wilmington
N/A Dataset used for analysis	US/Europe

N/A Dataset used for analysis	N/A
N/A	N/A
N/A Dataset used for analysis	N/A

N/A	N/A
N/A Dataset used for analysis	Altantic and Gulf coasts of the U.S.
80 students from Texas A&M University	Gulf of Mexico (area shown to participants)
80 students	Texas A&M University student population (sample)

162 students	Gulf of Mexico (area shown to participants)

Abstract

The 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.

This paper examines the societal dimensions of warning decisions during extreme weather events in one of the most hurricane-prone areas in the U.S., Miami-Dade County, Florida. With the aim of informing improvements in the hurricane forecast and warning system, and better understanding warning decisions in extreme weather events, we explore how members of the public obtain and use hurricane forecasts and warnings in decision making. Results from in depth mental models interviews with members of the public (N = 28) and survey data from three counties in Florida (N = 460) show that a large majority of respondents have some hurricane experience, which influences their thinking about storm impacts, individual actions to mitigate the hazard, and vulnerability to the hazard. Comparison with results from previous research with warning system professionals (National Weather Service forecasters, media broadcasters, and public officials) indicates several gaps between professionals and laypeople including different perceptions of hurricane risks overall and related to flooding from storm surge. The findings suggest several areas for improvements in the hurricane forecast and warning system.

This article reviews the evolution, communication, and differing interpretations of the National Hurricane Center's “cone of uncertainty” hurricane forecast graphic. It concludes with a discussion of this graphic from the perspective of risk communication theory. The 2004 hurricane season, in which five named storms struck Florida, demonstrated that hurricane forecast graphics, despite admirable attempts by the forecast community to make user-friendly products, are still subject to misinterpretation by many members of the public. This exploratory analysis draws upon interviews with key government officials and media figures, archival research of Florida newspapers, analysis of 962 public comments on the National Hurricane Center's cone of uncertainty graphic, a separate multiagency study of 2004 hurricane behavior, and relevant risk communication literature, to identify several characteristics of this graphic that likely contribute to public misinterpretation. Forecast providers should consider more formal, rigorous pretesting of forecast graphics, using standard social science techniques, in order to minimize the probability of misinterpretation.

Given 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.

The error cone is a display produced by the National Hurricane Center in order to present its predictions of the path of a hurricane. While the error cone is one of the primary tools used by officials, and the general public, to make emergency response decisions, the uncertainty underlying this display can be easily misunderstood. This paper explores the design of an alternate display that provides a continually updated set of possible hurricane tracks, whose ensemble distribution closely matches the underlying statistics of a hurricane prediction. We explain the underlying algorithm and data structures, and demonstrate how our displays compare with the error cone. Finally, we review the design and results of a user study that we conducted as a preliminary test of the efficacy of our approach in communicating prediction uncertainty

To better understand household hurricane evacuation decisions, this paper addresses a limitation to existing hurricane evacuation modeling aspects by developing a dynamic model of hurricane evacuation behavior. A household's evacuation decision is framed as an optimal stopping problem in which every potential evacuation time period prior to the actual hurricane landfall, the household's optimal choice is to either evacuate or to wait one more time period for a revised hurricane forecast. We build a realistic multiperiod model of evacuation that incorporates actual forecast and evacuation cost data for our designated Gulf of Mexico region. Results from our multiperiod model are calibrated with existing evacuation timing data from a number of hurricanes. Given the calibrated dynamic framework, a number of policy questions that plausibly affect the timing of household evacuations are analyzed, and a deeper understanding of existing empirical outcomes in regard to the timing of the evacuation decision is achieved.

Individuals' past experiences with a hazard can encompass many different aspects, which can influence how they judge and respond to a future hurricane risk. This study, which utilizes survey data from coastal residents who are at risk from hurricanes, adds to understanding of past hazard experience in two ways. First, it examines six different aspects of people's past hurricane experiences and the relationships among them. Then, it draws on risk theories of behavioral responses to explore how these different experiences influence people's evacuation intentions for a hypothetical hurricane as mediated through multiple dimensions of risk perception (cognitive, negative affective) and efficacy beliefs (self efficacy, response efficacy). The results suggest that people can experience emotional or otherwise severe impacts from a hurricane even if they do not have experiences with evacuation, property damage, or financial loss. The results also reveal that different past hurricane experiences operated through different combinations of mediating variables to influence evacuation intentions. Some of these processes enhanced intentions; for instance, experience with evacuation, financial loss, or emotional impacts heightened negative affective risk perceptions, which increased evacuation intentions. Other processes dampened evacuation intentions; for instance, people with past hurricane-related emotional impacts had lower self efficacy, which decreased evacuation intentions. In some cases, these enhancing and dampening processes competed. Exploring people's different past weather experiences and the mechanisms by which they can influence future behaviors is important for more deeply understanding populations at risk and how they respond to weather threats.

Reducing loss of life and harm when a hurricane threatens depends on people receiving hurricane risk information that they can interpret and use in protective decisions. To understand and improve hurricane risk communication, this article examines how National Weather Service (NWS) forecasters at the National Hurricane Center and local weather forecast offices, local emergency managers, and local television and radio media create and convey hurricane risk information. Data from in-depth interviews and observational sessions with members of these groups from Greater Miami were analyzed to examine their roles, goals, and interactions, and to identify strengths and challenges in how they communicate with each other and with the public. Together, these groups succeed in partnering with each other to make information about approaching hurricane threats widely available. Yet NWS forecasters sometimes find that the information they provide is not used as they intended; media personnel want streamlined information from NWS and emergency managers that emphasizes the timing of hazards and the recommended response and protective actions; and emergency managers need forecast uncertainty information that can help them plan for different scenarios. Thus, we recommend that warning system partners 1) build understanding of each other's needs and constraints; 2) ensure formalized, yet flexible mechanisms exist for exchanging critical information; 3) improve hurricane risk communication by integrating social science knowledge to design and test messages with intended audiences; and 4) evaluate, test, and improve the NWS hurricane-related product suite in collaboration with social scientists.

N/A commentary on literature

N/A commentary on literature

The communication by forecasters of tropical cyclone (TC) descriptions and forecasts to user communities necessarily involves the transmission of information based in science to different classes of users composed primarily of nonscientists. Inherent in the problem is the necessity of translating or converting the scientific content of the forecast, including its associated uncertainty, which is mathematical and statistical in its native structure, into restructured content comprehensible to populations not generally schooled in those disciplines. The forecast interpretation problem encompasses not only the forms in which the information is presented or communicated (e.g., text versus graphics), but even more so the complexity and transparency of the scientific content contained between those forms. This article investigates the substantive areas of dissonance and disconnect between the scientific content of TC descriptions and forecasts, including the uncertainty, and the ability of end users to accurately comprehend and interpret the information. It centers on the three storm attributes for which there is a forecast, namely intensity, track, and size, within the context of existing research studies, public surveys, and original official documents that specifically provide insights into this subject matter. The results suggest that the TC descriptions and forecasts, once their scientific substance has been processed for the benefit of nonscientists, still require some preexisting scientific knowledge that may or may not be present among the different groups of nonspecialist users.

Visuals are at the forefront of providing information in today's society. They are on the front page of newspapers, the evening news, the Internet, and textbooks. They are particularly important in explaining risk and scientific processes such as the intricacies of climate change or the risks of cancer treatments. These visuals do not simply appear in the newspaper or on television without thought but often have distinct objectives or purposes given to them by their designer. The original objective of the graphic may not be achieved, however, if viewers misunderstand or misinterpret the graphic. Misinterpretations of risk visuals, such as hurricane track graphics, may have especially harmful consequences. Therefore, it is critically important to understand how scientific intent translates through visuals to evoke public understanding of science and risk assessment, a process that I call visual validity. To do attain scientific validity, the scientist's objective for the graphic must be known as well as the public's interpretation of the graphic. This thesis looks at the concept of visual validity from the scientist's point of view using a graphic called the "cone of uncertainty," a highly visible hurricane track graphic. Using a grounded theory approach, I conducted 19 indepth interviews with forecasters and meteorologists from a variety of government and private sector institutions including the National Weather Service, the National Hurricane Center, The Weather Channel, and Weatherbug. I found that the cone of uncertainty has four main message objectives: (1) to communicate uncertainty, (2) to emphasize risks and impacts, (3) to show confidence in the forecast, and lastly, (4) to encourage individuals to listen to their emergency managers. The results suggest that a complicated relationship exists between the design of a visual and its many message objectives. Additionally, two potential characteristics of achieving visual validity emerged out of the data. First, the role of transactional communication between the designer of a visual and its intended audience appears to play a role in accurate understanding and risk assessment. Second, supplementing a visual with an explanation also appears to play a role in attaining visual validity. These findings have implications for the visual literacy process, as well as the extent to which an individual understands complex science and risk visuals. Future research to seek out additional potential characteristics of the visual validity process will include the public's interpretation of the cone of uncertainty.

The cartography of hurricane advisories is challenged with communicating complex information regarding hazards and spatio-temporal uncertainty. This research presents an exploratory geovisualization study assessing how hurricane advisory maps are perceived. In an experimental laboratory setting, study compared student responses to official National Hurricane Center advisory maps and alternative test map products. Research measured human behavioral response and environmental perception using eye-tracking, electroencephalograms (EEG), electrocardiography (ECG), electromyography (EMG), and a survey questionnaire to support analysis of participants' objective and expressed responses to competing geovisualization products. This approach allows the investigation of biometric responses with digital precision in order to infer cartographic design effects on individual map readers.

Uncertainty information from ensemble prediction systems can enhance and extend the suite of tropical cyclone (TC) forecast products. This article will review progress in ensemble prediction of TCs and the scientific issues in ensemble system development for TCs. Additionally, it will discuss the needs of forecasters and other users for TC uncertainty information and describe some ensemble-based products that may be able to be disseminated in the near future. We hope these proposals will jump-start a community-wide discussion of how to leverage ensemble-based uncertainty information for TC prediction.

Choosing effective colour schemes for thematic maps is surprisingly difficult. ColorBrewer is an online tool designed to take some of the guesswork out of this process by helping users select appropriate colour schemes for their specific mapping needs by considering: the number of data classes; the nature of their data (matched with sequential, diverging and qualitative schemes); and the end-use environment for the map (e.g., CRT, LCD, printed, projected, photocopied). ColorBrewer contains 'learn more' tutorials to help guide users, prompts them to test-drive colour schemes as both map and legend, and provides output in five colour specification systems.

Many weather forecast providers believe that forecast uncertainty in the form of the worst-case scenario would be useful for general public end users. We tested this suggestion in 4 studies using realistic weather-related decision tasks involving high winds and low temperatures. College undergraduates, given the statistical equivalent of the worst-case scenario (1 boundary of the 80% predictive interval), demonstrated biased understanding of future weather conditions compared with those given both bounds or no uncertainty information. We argue that this was due to an anchoring effect on numeric estimates, which were closer to the worst-case scenario than was warranted and increased linearly as the anchor became more extreme. In many situations tested here, anchoring in numeric estimates also extended to subsequent binary decisions, leading participants with the worst-case scenario to take action more often than did other participants. These results suggest that worst-case scenario forecasts can mislead the user. They appear to convince people that wind speeds will be higher and temperatures will be lower than what are indicated by the forecast. In addition, participants systematically “corrected” the forecast they were given. This effect was most prominent in the condition in which no uncertainty was provided, suggesting that people feel compelled to take uncertainty into account, even when it is not acknowledged by the forecast. Both the anchoring and correction biases were least evident when both bounds were provided, suggesting that balanced uncertainty leads to the best understanding of future weather conditions.

Protective actions for hurricane threats are a function of the environmental and information context; individual and household characteristics, including cultural worldviews, past hurricane experiences, and risk perceptions; and motivations and barriers to actions. Using survey data from the Miami-Dade and Houston-Galveston areas, we regress individuals’ stated evacuation intentions on these factors in two information conditions: (1) seeing a forecast that a hurricane will hit one's area, and (2) receiving an evacuation order. In both information conditions having an evacuation plan, wanting to keep one's family safe, and viewing one's home as vulnerable to wind damage predict increased evacuation intentions. Some predictors of evacuation intentions differ between locations; for example, Florida respondents with more egalitarian worldviews are more likely to evacuate under both information conditions, and Florida respondents with more individualist worldviews are less likely to evacuate under an evacuation order, but worldview was not significantly associated with evacuation intention for Texas respondents. Differences by information condition also emerge, including: (1) evacuation intentions decrease with age in the evacuation order condition but increase with age in the saw forecast condition, and (2) evacuation intention in the evacuation order condition increases among those who rely on public sources of information on hurricane threats, whereas in the saw forecast condition evacuation intention increases among those who rely on personal sources. Results reinforce the value of focusing hurricane information efforts on evacuation plans and residential vulnerability and suggest avenues for future research on how hurricane contexts shape decision making.

The U.S. National Hurricane Center (NHC) issues advisories every six hours during the life of a hurricane. These advisories describe the current state of the storm, and its predicted path, size, and wind speed over the next five days. However, from these data alone, the question “What is the likelihood that the storm will hit Houston with hurricane strength winds between 12:00 and 14:00 on Saturday?” cannot be directly answered. To address this issue, the NHC has recently begun making an ensemble of potential storm paths available as part of each storm advisory. Since each path is parameterized by time, predicted values such as wind speed associated with the path can be inferred for a specific time period by analyzing the statistics of the ensemble. This paper proposes an approach for generating smooth scalar fields from such a predicted storm path ensemble, allowing the user to examine the predicted state of the storm at any chosen time. As a demonstration task, we show how our approach can be used to support a visualization tool, allowing the user to display predicted storm position – including its uncertainty – at any time in the forecast. In our approach, we estimate the likelihood of hurricane risk for a fixed time at any geospatial location by interpolating simplicial depth values in the path ensemble. Adaptivelysized radial basis functions are used to carry out the interpolation. Finally, geometric fitting is used to produce a simple graphical visualization of this likelihood. We also employ a non-linear filter, in time, to assure frame-to-frame coherency in the visualization as the prediction time is advanced. We explain the underlying algorithm and definitions, and give a number of examples of how our algorithm performs for several different storm predictions, and for two different sources of predicted path ensembles.

Data ensembles are often used to infer statistics to be used for a summary display of an uncertain prediction. In a spatial context, these summary displays have the drawback that when uncertainty is encoded via a spatial spread, display glyph area increases in size with prediction uncertainty. This increase can be easily confounded with an increase in the size, strength or other attribute of the phenomenon being presented. We argue that by directly displaying a carefully chosen subset of a prediction ensemble, so that uncertainty is conveyed implicitly, such misinterpretations can be avoided. Since such a display does not require uncertainty annotation, an information channel remains available for encoding additional information about the prediction. We demonstrate these points in the context of hurricane prediction visualizations, showing how we avoid occlusion of selected ensemble elements while preserving the spatial statistics of the original ensemble, and how an explicit encoding of uncertainty can also be constructed from such a selection. We conclude with the results of a cognitive experiment demonstrating that the approach can be used to construct storm prediction displays that significantly reduce the confounding of uncertainty with storm size, and thus improve viewers' ability to estimate potential for storm damage.

Information about hurricanes changes as the storm approaches land. Additionally, people tend to think that severe events are more likely to occur even if the probability of that event occurring is the same as a less severe event. Thus, holding probability constant, this research tested the influence of severity on storm judgments in the context of updates about the approaching storm’s severity. In two studies, participants watched one of four (experiment 1) or one of five (experiment 2) sequences of updating hurricane warnings. The position of category 1 and category 5 hurricane warnings in the sequences varied (e.g., category 1 first and category 5 last, or category 5 first and category 1 last). After the videos, participants made judgments about the approaching storm. In experiment 1, participants generally overestimated the threat of the storm if they saw a category 5 hurricane warning in any position. Experiment 2, designed to test whether experiment 1 results were due to a contrast effect, revealed a similar pattern to experiment 1. Overall, when participants saw a category 5 hurricane warning, they anchored to severity regardless of updates that the storm had decreased in severity. Importantly, however, the extent of anchoring to severity depended on the type of judgment participants made. In terms of policy, the study proposes that weather warning agencies focus on message content at least as much as they focus on message accuracy.

Our ability to adapt to extreme weather is increasingly relevant as the frequency and intensity of these events alters due to climate change. It is important to understand the effectiveness of adaptation given the uncertainty associated with future climate events. However, there has been little analysis of short-term adaptation efforts. We propose a novel approach of using errors from hurricane forecasts to evaluate short-term hurricane damage mitigation efforts. We construct a statistical model of damages for all hurricanes to strike the continental United States since 1955. While we allow for many possible drivers of damages, using model selection methods we find that a small subset explains most of the variation. We also find evidence supporting short-term adaptation effects prior to a hurricane landfall. Our results show that the 67 percent improvement in hurricane forecasts over the past 60 years is associated with damages being 16-63 percent lower than they otherwise would have been. Accounting for outlying observations narrows this range to 16-24 percent.

Though most hurricane evacuation studies have focused on residents, tourists are also a vulnerable population. To assess their perceptions of risk and evacuation likelihood under different hurricane conditions, we surveyed 448 tourists visiting central Florida. Respondents viewed four maps emulating track forecast cones produced by the National Hurricane Center and text information featuring variations of storm intensity, coast of landfall, centerline position relative to the survey site, time until landfall, and event duration. We performed chi-square tests to determine which hurricane conditions, and aspects of tourists such as their demographics and previous hurricane experience, most likely influenced their ratings of risk and evacuation likelihood for respondents located on Pinellas County beaches or inland near Orlando, FL. Highly rated scenarios featured a Category 4 hurricane making landfall along the Gulf Coast with the centerline passing over the sampling site. Overall, tourists that indicated the highest risk and evacuation ratings were not previously affected by a hurricane, had a trip duration of less than 6 days, and had checked for the possibility of a hurricane strike before departure. However, results for other tourist attributes differed between tourists in coastal and inland locations. We found that although somewhat knowledgeable about hurricanes, tourists misinterpreted the track forecast cone and hurricane conditions, which led to a lower perception of risk and subsequent likelihood to evacuate. Tourists, particularly those from outside of Florida, need to be better educated about the risks they face from hurricanes that make landfall.

Findings are reported from two field studies that measured the evolution of coastal residents' risk perceptions and preparation plans as two hurricanes—Isaac and Sandy—were approaching the U.S. coast during the 2012 hurricane season. The data suggest that residents threatened by such storms had a poor understanding of the threat posed by the storms; they overestimated the likelihood that their homes would be subject to hurricane-force wind conditions but underestimated the potential damage that such winds could cause, and they misconstrued the greatest threat as coming from wind rather than water. These misperceptions translated into preparation actions that were not well commensurate with the nature and scale of the threat that they faced, with residents being well prepared for a modest wind event of short duration but not for a significant wind-and-water catastrophe. Possible causes of the biases and policy implications for improving hurricane warning communication are discussed.

This article investigates the use of dynamic laboratory simulations as a tool for studying decisions to prepare for hurricane threats. A prototype web-based simulation named Stormview is described that allows individuals to experience the approach of a hurricane in a computer-based environment. In Stormview participants can gather storm information through various media, hear the opinions of neighbors, and indicate intentions to take protective action. We illustrate how the ability to exert experimental control over the information viewed by participants can be used to provide insights into decision making that would be difficult to gain from field studies, such as how preparedness decisions are affected by the nature of news coverage of prior storms, how a storm's movement is depicted in graphics, and the content of word-of-mouth communications. Data from an initial application involving a sample of Florida residents reveal a number of unexpected findings about hurricane risk response. Participants who viewed forecast graphics, which contained track lines depicting the most likely path of the storm, for example, had higher levels of preparation than those who saw graphics that showed only uncertainty cones—even among those living far from the predicted center path. Similarly, the participants who were most likely to express worry about an approaching storm and fastest to undertake preparatory action were those who, ironically, had never experienced one. Finally, external validity is evidenced by a close rank-order correspondence between patterns of information use revealed in the lab and that found in previous cross-sectional field studies.

Although the field has seen great advances in hurricane prediction and response, the economic toll from hurricanes on U.S. communities continues to rise. We present data from Hurricanes Earl (2010), Irene (2011), Isaac (2012), and Sandy (2012) to show that individual and household decisions contribute to this vulnerability. From phone surveys of residents in communities threatened by impending hurricanes, we identify five decision biases or obstacles that interfere with residents' ability to protect themselves and minimize property damage: (1) temporal and spatial myopia, (2) poor mental models of storm risk, (3) gaps between objective and subjective probability estimates, (4) prior storm experience, and (5) social factors. We then discuss ways to encourage better decision making and reduce the economic and emotional impacts of hurricanes, using tools such as decision defaults (requiring residents to opt out of precautions rather than opt in) and tailoring internet-based forecast information so that it is local, specific, and emphasizes impacts rather than probability.

This report on a survey of broadcast meteorologists (also referred to as the media) is part of a larger body of work to better understand how National Oceanic and Atmospheric Administration weather forecast products might improve public understanding and response to tropical and extratropical storms. The June - July 2012 web-based survey obtained responses from 51 broadcast meteorologists at local television stations serving the Atlantic, Gulf and Pacific coasts as well as Alaska, Puerto Rico, and Hawaii. The major focus of the survey is on storm surge, but we also solicited media opinions on topics such as their perceptions of public understanding of forecasts and their assessments of several tropical cyclone forecast track and wind graphics as well as several graphic prototypes developed for communicating storm forecast information. Broadcast meteorologists indicated strong support for the NWS issuing storm surge watches and warnings - 90% agreed that watches should be issued and 95% supported a storm surge warning. Most believed these products would result in greater attention to these threats in their weathercasts and to the public paying more attention to storm surge

The National Weather Service (NWS), an agency of the National Oceanic and Atmospheric Administration (NOAA), issues suites of text and graphical products to communicate forecasts of severe storms. During tropical cyclone (TC) conditions, the National Hurricane Center (NHC) issues text and graphical products to communicate the forecasts. During both tropical and extratropical (ET) cyclones and other unique events resulting in storm surge, such as high astronomical tides, local Weather Forecast Offices (WFOs) issue Coastal Flood Advisories, Watches, and Warnings, which include detailed, localized information on expected storm surge and other hazards. This survey of emergency managers (EMs) is part of a larger body of work with the goal of better understanding how certain NOAA weather forecast products might improve public understanding and response to TC and ET events. The major focus is on storm surge products, but EMs from areas subject to TCs were also asked to comment about several forecast track and wind graphics. Major funding for this project came from the NOAA National Ocean Service project, “Assessing Current Storm Surge Information from the Public Perspective.” As an extension of that project, we also leveraged resources from the NOAAfunded “Hurricane Forecast Improvement Project (HFIP) Socio-Economic Impacts Assessment” (through Eastern Research Group, Inc. (ERG). To meet the objectives of this expanded project, we solicited opinions from EMs, broadcast meteorologists, NWS Warning Coordination Meteorologists, and the general public. Here we report the findings from the survey of coastal EMs.

This study uses data from a survey of coastal Miami-Dade County, Florida, residents to explore how different types of forecast and warning messages influence evacuation decisions, in conjunction with other factors. The survey presented different members of the public with different test messages about the same hypothetical hurricane approaching Miami. Participants’ responses to the information were evaluated using questions about their likelihood of evacuating and their perceptions of the information and the information source. Recipients of the test message about storm surge height and the message about extreme impacts from storm surge had higher evacuation intentions, compared to nonrecipients. However, recipients of the extreme-impacts message also rated the information as more overblown and the information source as less reliable. The probabilistic message about landfall location interacted with the other textual messages in unexpected ways, reducing the other messages’ effects on evacuation intentions. These results illustrate the importance of considering trade-offs, unintended effects, and information interactions when deciding how to convey weather information. Recipients of the test message that described the effectiveness of evacuation had lower perceptions that the information was overblown, suggesting the potential value of efficacy messaging. In addition, respondents with stronger individualist worldviews rated the information as significantly more overblown and had significantly lower evacuation intentions. This illustrates the importance of understanding how and why responses to weather messages vary across subpopulations. Overall, the analysis demonstrates the potential value of systematically investigating how different people respond to different types of weather risk messages.

Uncertainty is a fundamental characteristic of weather, seasonal climate, and hydrological prediction, and no forecast is complete without a description of its uncertainty. Effective communication of uncertainty helps people better understand the likelihood of a particular event and improves their ability to make decisions based on the forecast. Nonetheless, for decades, users of these forecasts have been conditioned to receive incomplete information about uncertainty. They have become used to single-valued (deterministic) forecasts (e.g., "the high temperature will be 70 degrees Farenheit 9 days from now") and applied their own experience in determining how much confidence to place in the forecast. Most forecast products from the public and private sectors, including those from the National Oceanographic and Atmospheric Administration’s National Weather Service, continue this deterministic legacy. Fortunately, the National Weather Service and others in the prediction community have recognized the need to view uncertainty as a fundamental part of forecasts. By partnering with other segments of the community to understand user needs, generate relevant and rich informational products, and utilize effective communication vehicles, the National Weather Service can take a leading role in the transition to widespread, effective incorporation of uncertainty information into predictions. "Completing the Forecast" makes recommendations to the National Weather Service and the broader prediction community on how to make this transition.

The National Transportation Safety Board (NTSB) is providing the following information to urge the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service (NWS; a component of NOAA), and the US Coast Guard to take action on the safety recommendations in this report. The recommendations address, in the interest of mariner safety, the development of tropical cyclone information and its availability to mariners. The recommendations derive primarily from factual information gathered during the NTSB's ongoing investigation into the sinking of cargo vessel El Faro on October 1, 2015. The factual data revealed that critical tropical cyclone information issued by the NWS is not always available to mariners via well-established broadcast methods. The data also suggest that modifying the way the NWS develops certain tropical cyclone forecasts and advisories could help mariners at sea better understand and respond to tropical cyclones. Further, factual data on the official forecasts for Hurricane Joaquin and other recent tropical cyclones suggest that a new emphasis on improving hurricane forecasts is warranted. The NTSB has yet to determine the probable cause of, or contributing factors in, El Faro's sinking. Nevertheless, based on the meteorological facts gathered thus far, plus discussions with the NWS and the Coast Guard, the NTSB makes ten recommendations in this report. Two recommendations are addressed to NOAA, seven to the NWS, and one to the Coast Guard.

Hurricane Charley made landfall on the southwest coast of Florida near Cayo Costa, just west of Ft. Myers around 3:45 p.m. EDT on August 13, with maximum sustained surface winds near 150 mph. This made Charley a category 4 storm on the Saffir-Simpson Scale. The maximum storm surge associated with Charley was six to seven feet on Sanibel and Estero Islands. This was less than expected due to a number of factors including an increase in the storm's speed, the eyewall shrinking, and the tide receding. Charley then moved north-northeastward causing significant damage across the Florida peninsula from Punta Gorda, Port Charlotte, Orlando, to Palm Coast (north of Daytona Beach). Charley caused ten direct fatalities in the U.S. and an estimated $14 billion in economic losses. It was a harbinger of things to come, being the first of four hurricanes to affect Florida in August and September of 2004. This assessment evaluates the service of the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) before and during the landfall of Hurricane Charley and provides recommendations to improve services in the future. It takes into consideration the affected audiences in the media and emergency management communities as well as the public. Service assessments significantly enhance ongoing efforts to improve the quality, timeliness, and value of NWS products and services. Findings of this assessment will further NOAA's goal to serve society's needs for water and weather information.

The devastation along the Gulf Coast from Hurricane Katrina was staggering. The physical destruction and personal suffering surmounted that of any U.S. weather disaster in recent history. The loss of life and extraordinary damage made Katrina the costliest hurricane in U.S. history and one of the five deadliest hurricanes to ever strike the U.S. However, without NOAA's National Weather Service forecasts, warnings, communication, outreach, and education, the impacts and loss of life would have been far greater.
I chartered a team to assess NWS performance during the event. The Team found the NWS performed exceptionally well in forecasting, warning, communication, preparedness, and post-storm recovery efforts. This is confirmed by the overwhelming positive response received from users and partners of the NWS.
Our National Hurricane Center predicted the central Gulf Coast, including the New Orleans metropolitan area, would be directly affected by Katrina as a major hurricane about 56 hours before landfall. Forecasts of Katrina's path from NHC were better than long-term average errors and better than the Government Performance and Results Act (GPRA) 2006 goals established for hurricane track forecasts.
The evacuation rate during Hurricane Katrina was near 80 percent. This is an impressive public response to an approaching threat. This remarkable response resulted from a long-working relationship and open communication between NWS, the emergency management community at all levels, and the media.
While NOAA's National Weather Service performed well in forecasts and services, there is room for improvement. The Assessment Team made 16 recommendations, most of which concern the infrastructure of the NWS such as electrical power, communications, computing systems, and data gathering systems. During extremely difficult working conditions, the ingenuity, dedication, and sheer will of NWS employees enabled the provision of products and services as infrastructure and back-up systems failed. Relying on NWS employees to overcome infrastructure failure is not an ideal solution. The recommendations in this report will be addressed and the 13 best practices will be considered nationwide.

On August 21-29, 2011, Hurricane Irene left a devastating imprint on the Caribbean and U.S. East Coast. The storm took the lives of more than 40 people, caused an estimated $6.5 billion in damages, unleashed major flooding, downed trees and power lines, and forced road closures, evacuations, and major rescue efforts. The effects of Hurricane Irene were felt from the U.S. Virgin Islands and Puerto Rico to the Canadian Maritime Provinces, and as far west as the Catskill Mountains of New York. The storm produced widespread, devastating flooding in Vermont, New York, New Jersey, and parts of New Hampshire and damaging storm surge along the coasts of North Carolina and Connecticut. Hurricane Irene left 8 million people without power—some for as long as a week—and resulted in the closure of several major airports, the suspension of Amtrak train service, and the historic closure of the New York City mass transit system.

In response to the significant effects of the event, the National Oceanic and Atmospheric Administration formed a service assessment team to document and evaluate the performance and overall effectiveness of National Weather Service products and services, decision support, collaboration and communication, operational procedures, and preparedness activities. The NWS should thoroughly consider implementing the team's recommendations as they are written; however, the organization may implement alternate solutions to resolve the findings and meet the intent of the service assessment team's recommendations. Alternate solutions may be implemented because they are, for example, more effective, more rapidly deployed, or less costly. The National Weather Service will use the findings and recommendations from this assessment to improve the quality of products and services, enhance awareness, and help guard the Nation against loss of life and property.

On October 22-29, 2012, Hurricane/Post-Tropical Cyclone Sandy moved from the Caribbean to the U.S. Eastern Seaboard, ultimately making landfall near Brigantine, NJ, around 7:30 p.m. on October 29. The storm resulted in an enormous impact to life and property in both the Caribbean and continental United States. The National Hurricane Center's Tropical Cyclone Report estimated the death count from Hurricane Sandy at 147 direct deaths. Sandy damaged or destroyed at least 650,000 houses and left approximately 8.5 million customers without power during the storm and its aftermath. The effects of Sandy extended as far west as Wisconsin. This late season storm also generated blizzard conditions in western North Carolina and West Virginia, resulting in snowfall totals as high as 3 feet.

Storm surge created some of the most devastating impacts, including flooding in New York City's subway tunnels, water overtopping runways at La Guardia (Figure 1) and Kennedy airports, and damage to the New Jersey Transit System estimated at approximately $400 million.

In light of the Sandy's significance, the National Oceanic and Atmospheric Administration (NOAA) formed a Service Assessment Team to document and evaluate the agency's performance and effectiveness. The Team focused on three key points: first, the National Weather Service's forecast, watch, and warning products, including its underlying philosophies and policies and its dissemination/communication tools. Second, the Team reviewed the NWS Figure 1: LaGuardia Airport during Sandy. Source: The Port Authority of New York and New Jersey v web presence as a tool for communicating with the public. Finally, the Team looked at NWS's production and issuance of storm-surge related products.

NOAA will use the findings and recommendations in this assessment to increase awareness of critical needs during future extreme weather events and improve products and services to further protect life and property. Given the relationship of this assessment to the agency's broader portfolio, NOAA will also improve integration and collaboration across mission lines to ensure ongoing responsiveness to partner needs in light of Sandy's impacts.

Hurricane Matthew left a trail of destruction from the Caribbean to Virginia from September 29 – October 9, 2016. High winds, pounding surf, storm surge, and historic flooding led to widespread, devastating impacts along the southeast U.S. coastline. Hurricane Matthew traveled northward nearly parallel to the coast before making landfall in South Carolina. The storm produced winds in excess of 100 mph, storm surge in excess of 7 feet, and up to 20 inches of rainfall. Weather-related fatalities occurred up and down the southeast U.S. coast. The majority of fatalities were the result of flooding, making inland flooding a primary focus for this assessment. Because of the significant impacts of the event, the National Weather Service (NWS) formed a service assessment team to evaluate its performance before and during Hurricane Matthew's impacts. The NWS Mission Delivery Council will review and consider the findings and recommendations from this assessment. As appropriate, the recommendations will then be integrated into the Annual Operating Plan to improve the quality of operational products and services and enhance the NWS's public education and awareness materials related to flooding and other tropical cyclone hazards. The ultimate goal of this report is to help the NWS meet its mission to protect life and property and enhance the national economy.

Ensemble and summary displays are two widely used methods to represent visual-spatial uncertainty; however, there is disagreement about which is the most effective technique to communicate uncertainty to the general public. Visualization scientists create ensemble displays by plotting multiple data points on the same Cartesian coordinate plane. Despite their use in scientific practice, it is more common in public presentations to use visualizations of summary displays, which scientists create by plotting statistical parameters of the ensemble members. While prior work has demonstrated that viewers make different decisions when viewing summary and ensemble displays, it is unclear what components of the displays lead to diverging judgments. This study aims to compare the salience of visual features – or visual elements that attract bottom-up attention – as one possible source of diverging judgments made with ensemble and summary displays in the context of hurricane track forecasts. We report that salient visual features of both ensemble and summary displays influence participant judgment. Specifically, we find that salient features of summary displays of geospatial uncertainty can be misunderstood as displaying size information. Further, salient features of ensemble displays evoke judgments that are indicative of accurate interpretations of the underlying probability distribution of the ensemble data. However, when participants use ensemble displays to make point-based judgments, they may overweight individual ensemble members in their decision-making process. We propose that ensemble displays are a promising alternative to summary displays in a geospatial context but that decisions about visualization methods should be informed by the viewer's task.

Good visualizations are designed to answer a particular question or the needs of a particular task. They are created as comprehensively as possible taking into account numerous factors such as the application domain, established conventions in the community, nature of the question or task, technical constraints such as interactivity or large data sets, presentation concerns such as visual clutter and complexity, and the quality of the data. Care must also be taken to ensure that any artifacts are not inadvertently introduced into the visualization. This paper provides an overview of current visualization practices and techniques that incorporate data uncertainty in the presentations. Emphasis is placed on geospatial data sets. The paper also describes some of the challenges and research directions in uncertainty visualization research.

Spatial predictions of uncertain trajectories are challenging, but are often associated with overconfidence. This study explored how a visualization influenced prediction of uncertain spatial trajectories (e.g., unknown path of a downed aircraft or future path of a hurricane). Mean and variance estimates were compared for participants provided with a gradient-shaded "cone of uncertainty" visualization and those who were not provided with a visualization. Participants exhibited less error in mean estimations when a visualization was present, but performed worse than controls once the visualization was removed. For variance estimations, participants provided with a visualization did not retain any advantage in their estimations once the visualization was removed. Combined these findings suggest that visualizations may support some aspects of spatial predictions under uncertainty, but they can be associated with costs for the underlying knowledge being developed.

Purpose
– The cone of uncertainty (COU) warning graphic has created confusion for people trying to make evacuation and safety decisions. The purpose of this research was to create several alternative tropical cyclone graphics and present them to the public and college students via face-to-face surveys and polling.
Design/methodology/approach
– Surveys depicting hypothetical landfall scenarios were administered in Pensacola and Jacksonville, FL. Respondents ranked five graphics in order of preference, and were encouraged to discuss their rankings. Following this initial field research, the most popular graphic of these five was compared to a graphic resembling the one used by The Australian Bureau of Meteorology. Comments were recorded for respondents favoring or disliking the Australian graphic in two separate analyses. A final graphic emphasizing post-landfall hazards was also created as a suggestion for future research and evaluated directly against the most popular graphics from field research.
Findings
– A graphic called the color-probability-cone was the most popular graphic in field research. There were subtle differences in graphic preference resulting from age and gender influences, with only one significant result. Comments from subsequent analyses reveal that the Australian graphic causes mixed reactions. A final analysis with a larger sample of college students revealed that the color-probability-cone was the most popular choice; however, comments reveal that many respondents who had used hurricane graphics before liked the pecificity presented by the Australian graphic and the hazards graphic.
Originality/value
– This research represents a possible initial step in the process of establishing a tropical cyclone warning graphic that is informative, visually appealing, and effective.

Public officials with the authority to order hurricane evacuations face a difficult trade-off between risks to life and costly false alarms. Evacuation decisions must be made on the basis of imperfect information, in the form of forecasts. The quality of these decisions can be improved if they are also informed by measures of uncertainty about the forecast, including estimates of the value of waiting for updated, more accurate, forecasts. Using a stochastic model of storm motion derived from historic tracks, this paper explores the relationship between lead time and track uncertainty for Atlantic hurricanes and the implications of this relationship for evacuation decisions. Typical evacuation clearance times and track uncertainty imply that public officials who require no more than a 10% probability of failing to evacuate before a striking hurricane (a false negative) must accept that at least 76%—and for some locations over 90%—of evacuations will be false alarms. Reducing decision lead times from 72 to 48 hours for major population centers could save an average of hundreds of millions of dollars in evacuation costs annually, with substantial geographic variation in savings.

Uncertainty represented in visualizations is often ignored or misunderstood by the non-expert user. The National Hurricane Center displays hurricane forecasts using a track forecast cone, depicting the expected track of the storm and the uncertainty in the forecast. Our goal was to test whether different graphical displays of a hurricane forecast containing uncertainty would influence a decision about storm characteristics. Participants viewed one of five different visualization types. Three varied the currently used forecast cone, one presented a track with no uncertainty, and one presented an ensemble of multiple possible hurricane tracks. Results show that individuals make different decisions using uncertainty visualizations with different visual properties, demonstrating that basic visual properties must be considered in visualization design and communication.

Numerical weather prediction ensembles are routinely used for operational weather forecasting. The members of these ensembles are individual simulations with either slightly perturbed initial conditions or different model parameterizations, or occasionally both. Multi-member ensemble output is usually large, multivariate, and challenging to interpret interactively. Forecast meteorologists are interested in understanding the uncertainties associated with numerical weather prediction; specifically variability between the ensemble members. Currently, visualization of ensemble members is mostly accomplished through spaghetti plots of a single midtroposphere pressure surface height contour. In order to explore new uncertainty visualization methods, the Weather Research and Forecasting (WRF) model was used to create a 48-hour, 18 member parameterization ensemble of the 13 March 1993 "Superstorm". A tool was designed to interactively explore the ensemble uncertainty of three important weather variables: water-vapor mixing ratio, perturbation potential temperature, and perturbation pressure. Uncertainty was quantified using individual ensemble member standard deviation, inter-quartile range, and the width of the 95% confidence interval. Bootstrapping was employed to overcome the dependence on normality in the uncertainty metrics. A coordinated view of ribbon and glyph-based uncertainty visualization, spaghetti plots, iso-pressure colormaps, and data transect plots was provided to two meteorologists for expert evaluation. They found it useful in assessing uncertainty in the data, especially in finding outliers in the ensemble run and therefore avoiding the WRF parameterizations that lead to these outliers. Additionally, the meteorologists could identify spatial regions where the uncertainty was significantly high, allowing for identification of poorly simulated storm environments and physical interpretation of these model issues.

The mid-Atlantic region of the United States is susceptible to tropical cyclone hazards. Within the past 15 years this region has experienced Hurricane Isabel in 2003, Hurricane Irene in 2011 and several tropical storms. The region was also impacted by post-tropical Sandy in 2012. The perception of hurricane hazards among residents of the mid-Atlantic region has not been directly researched. Furthermore, there is a lack of research on the comprehension of information from hurricane warning graphics that influences hazard perception. This research used a total of eight hypothetical scenarios (four pairs) that varied storm track and storm size to assess risk perception of hurricane hazards and characteristics. Each scenario was represented using a four-panelled map featuring the National Hurricane Center's cone of uncertainty, a new storm surge map and a new damaging wind map created by the authors. A Qualtrics survey was used to collect responses to questions about concern for personal harm and evacuation intent. Residents of the region perceived falling trees, potential for damaging winds and the size of the storm to be the greatest threats. Scenarios depicting larger storms with track lines that moved inland were seen as more hazardous, resulting in greater concern and evacuation intent. Coastal residents showed greater concern about distance from the track for all scenarios and greater evacuation intent for larger storms compared to inland residents.

Three experiments demonstrated advantages over conventional deterministic forecasts for participants making temperature estimates and precautionary decisions with predictive interval weather forecasts showing the upper and lower boundaries within which the observed value is expected with a specified probability. Participants using predictive intervals were better able to identify unreliable forecasts, expected a narrower range of outcomes, and were more decisive than were participants using deterministic forecasts. Predictive interval format was also manipulated to determine whether adding visualizations enhanced understanding. Some participants using visualizations misinterpreted predictive intervals as expressions of diurnal fluctuations (deterministic forecasts). Almost no misinterpretations occurred when the predictive interval was expressed in text alone. Moreover, no advantages were found for visualizations over text-only formats, demonstrating that visualizations, especially those investigated in these studies, may not be suitable for expressing this concept. Thus, predictive intervals are both understandable and advantageous to non-expert decision makers, as long as they are carefully expressed.

Hurricane evacuations in the United States are costly, chaotic, and sometimes unnecessary. Many coastal residents consider evacuation after viewing a forecasted graphic of where the storm is anticipated to make landfall. During the evacuation process, hurricane tracks commonly deviate from the forecasted landfall track and many evacuees may not pay attention to these track deviations after evacuating. Frequently, a disconnect may occur between the actual landfall track, the official forecasted track, and the perceived track of each individual as they made their evacuation decision. Specifically for evacuees, a shift in track may decrease the hazards associated with a landfalling hurricane since evacuees perceive their threat level to be high at the time of evacuation. Using survey data gathered during the evacuation from Hurricane Gustav (2008) in coastal Louisiana (USA), we calculated a type of Z-score to measure the distance error between each evacuee's perceived landfall location and the actual landfall location from each evacuee's home zip code. Results indicate a personal landfall bias in the direction of home zip code for evacuees of three metropolitan regions. Evacuees from the greater New Orleans area displayed the highest error, followed by evacuees from greater Lafayette. Furthermore, we validate the authenticity of the previous results by employing two additional methods of error assessment. A large regional error score might possibly be a predictor of evacuation complacency for a future hurricane of similar magnitude, although there are many other variables that must be considered.

Forecast graphics depicting a hurricane track and uncertainty cone have become pervasive in the communication of hurricane risk. This study examined whether the effect of hurricane tracks on risk perception is influenced by the consistency and optimistic bias. Specifically, it focused on the differences between forecasts that remain consistent compared to those that veer away for a forecast period. To answer the research question, this study conducted online surveys in which respondents from two coastal universities were asked risk perception questions based on a series of forecast graphics. Other variables measured included dispositional optimism, general hurricane risk perception, and hurricane information use. Optimistic bias was calculated from two of the risk perception questions. Results did not indicate strong support for an influence of optimistic bias or changing forecast track on risk perception. There was limited evidence that a veering track scenario may lead to differences in risk judgments about another location, but most measures of personal risk estimation were not influenced by the track. Dispositional optimism was not related to optimistic bias or many of the risk perception variables tested, including general hurricane risk perception. There did appear to be an interaction between track scenario and optimistic bias with more relationships being significant among those who received the consistent track scenario.

Two freely available, searchable databases that track the normalized interest in specific search queries, Google Trends and Google Insights, were used to illustrate spatial and temporal patterns in hurricane information seeking. Searches for the word "hurricane" showed a seasonal pattern with spikes in hurricane searches that corresponded to the severity of the storms making landfall. Regional variation in "hurricane" searches was largely driven by the location and magnitude of hurricane landfalls. Catastrophic hurricanes such as Hurricane Katrina captured national attention. A great deal of regional variation in search volume existed prior to Hurricane Ike's landfall. Not as much variation was seen before Hurricane Gustav and Tropical Storm Fay. This variation appeared to be related to changes in the 5-day track forecast as well as other factors such as issuance of watches and warnings. Searches from Louisiana experienced a sharp decrease after the 5-day track forecast shifted away from the state, but before Ike made landfall. Normalized daily visits to Weather Underground during August/September 2008 followed the same pattern as the Google searches. The most popular hurricane-related search terms at the national level prior to landfall dealt with forecast track and evacuation information while searches after landfall included terms related to hurricane damage. There are limitations to using this free data source, but the study has implications for the literature as well as practical applications. This study provides new information about online search behavior before a hurricane that can be utilized by those who provide weather information to the public.

This review briefly examines the vast range of techniques used to communicate risk assessments arising from statistical analysis. After discussing essential psychological and sociological issues, I focus on individual health risks and relevant research on communicating numbers, verbal expressions, graphics, and conveying deeper uncertainty. I then consider practice in a selection of diverse case studies, including gambling, the benefits and risks of pharmaceuticals, weather forecasting, natural hazards, climate change, environmental exposures, security and intelligence, industrial reliability, and catastrophic national and global risks. There are some tentative final conclusions, but the primary message is to acknowledge expert guidance, be clear about objectives, and work closely with intended audiences.

Climate model ensembles are widely heralded for their potential to quantify uncertainties and generate probabilistic climate projections. However, such technical improvements to modeling science will do little to deliver on their ultimate promise of improving climate policymaking and adaptation unless the insights they generate can be effectively communicated to decision makers. While some of these communicative challenges are unique to climate ensembles, others are common to hydrometeorological modeling more generally, and to the tensions arising between the imperatives for saliency, robustness, and richness in risk communication. The paper reviews emerging approaches to visualizing and communicating climate ensembles and compares them to the more established and thoroughly evaluated communication methods used in the numerical weather prediction domains of day-to-day weather forecasting (in particular probabilities of precipitation), hurricane and flood warning, and seasonal forecasting. This comparative analysis informs recommendations on best practice for climate modelers, as well as prompting some further thoughts on key research challenges to improve the future communication of climate change uncertainties.

The subjective assessment of probability resembles the subjective assessment of physical quantities such as distance or size. These judgements are all based on data of limited validity, which processed according to heuristic rules. For example, the apparent distance of an object is determined in part by its clarity. The more sharply the object is seen, the closer it appears to be. This rule has some validity, because in any given scene the more distant objects are seen less sharply than nearer objects. However, the reliance on this rule leads to systematic errors in the estimation of distance. Specifically, distances are often overestimated when visibility is poor because the contours of objects are blurred. On the other hand, distances are often underestimated when visibility is good because the objects are seen sharply. Thus, the reliance on clarity as an indication of distance leads to common biases. Such biases are also found in the intuitive judgement of probability. This article describes three heuristics that are employed to assess probabilities and to predict values. Biases to which these heuristics lead are enumerated, and the applied and theoretical implications these observations are discussed.

Over the last decade, ensemble visualization has witnessed a significant development due to the wide availability of ensemble data, and the increasing visualization needs from a variety of disciplines. From the data analysis point of view, it can be observed that many ensemble visualization works focus on the same facet of ensemble data, use similar data aggregation or uncertainty modeling methods. However, the lack of reflections on those essential commonalities and a systematic overview of those works prevents visualization researchers from effectively identifying new or unsolved problems and planning for further developments. In this paper, we take a holistic perspective and provide a survey of ensemble visualization. Specifically, we study ensemble visualization works in the recent decade, and categorize them from two perspectives: (1) their proposed visualization techniques; and (2) their involved analytic tasks. For the first perspective, we focus on elaborating how conventional visualization techniques (e.g., surface, volume visualization techniques) have been adopted to ensemble data; for the second perspective, we emphasize how analytic tasks (e.g., comparison, clustering) have been performed differently for ensemble data. From the study of ensemble visualization literature, we have also identified several research trends, as well as some future research opportunities.

Ensembles of numerical simulations are used in a variety of applications, such as meteorology or computational solid mechanics, in order to quantify the uncertainty or possible error in a model or simulation. Deriving robust statistics and visualizing the variability of an ensemble is a challenging task and is usually accomplished through direct visualization of ensemble members or by providing aggregate representations such as an average or pointwise probabilities. In many cases, the interesting quantities in a simulation are not dense fields, but are sets of features that are often represented as thresholds on physical or derived quantities. In this paper, we introduce a generalization of boxplots, called contour boxplots, for visualization and exploration of ensembles of contours or level sets of functions. Conventional boxplots have been widely used as an exploratory or communicative tool for data analysis, and they typically show the median, mean, confidence intervals, and outliers of a population. The proposed contour boxplots are a generalization of functional boxplots, which build on the notion of data depth. Data depth approximates the extent to which a particular sample is centrally located within its density function. This produces a center-outward ordering that gives rise to the statistical quantities that are essential to boxplots. Here we present a generalization of functional data depth to contours and demonstrate methods for displaying the resulting boxplots for two-dimensional simulation data in weather forecasting and computational fluid dynamics.

U.S. National Hurricane Center (NHC) forecasts for tropical cyclone tracks and wind speeds are extended in time to produce spatially disaggregated probability forecasts for landfall location and intensity, using a weighted bootstrap procedure. Historical analogs, with respect to the forecast characteristics (location, heading, and wind speed) of a current storm, are selected. These are resampled by translating their locations to random positions consistent with the current forecast, and recent NHC forecast accuracy statistics. The result is a large number of plausible Monte Carlo realizations that jointly approximate a probability distribution for the future track and intensity of the storm. Performance of the resulting forecasts is assessed for U.S. tropical cyclone landfall probabilities during 1998–2006, and the forecasts are shown to be skillful and exhibit excellent reliability, even beyond the 120-h forecast horizon of the NHC advisory forecasts upon which they are based.

To study people's processing of hurricane forecast advisories, we conducted a computer-based experiment that examined 11 research questions about the information seeking patterns of students assuming the role of a county emergency manager in a sequence of six hurricane forecast advisories for each of four different hurricanes. The results show that participants considered a variety of different sources of information—textual, graphic, and numeric—when tracking hurricanes. Click counts and click durations generally gave the same results but there were some significant differences. Moreover, participants' information search strategies became more efficient over forecast advisories and with increased experience tracking the four hurricanes. These changes in the search patterns from the first to the fourth hurricane suggest that the presentation of abstract principles in a training manual was not sufficient for them to learn how to track hurricanes efficiently but they were able to significantly improve their search efficiency with a modest amount (roughly an hour) of practice. Overall, these data indicate that information search patterns are complex and deserve greater attention in studies of dynamic decision tasks.

This experiment assessed the strike probability (p s) judgments and protective action recommendations (PARs) of students playing the roles of county emergency managers during four different hurricane scenarios. The results show that participants' p s judgments (1) increased for target cities (projected landfall locations) and generally decreased for adjacent cities and remote cities as hurricanes approached landfall, and (2) were significantly correlated with PARs, but (3) were not consistent with the requirement that $\Sigma p\ s < 1.0$ for a set of non-exhaustive events. Participants also (4) chose more PARs as hurricanes approached landfall, especially for the counties to which they participants were assigned, but (5) failed to choose as many PARS as appropriate, especially evacuating areas at risk of hurricane impacts. Overall, the results suggest that participants were able to utilize the available hurricane information to make reasonable p s judgments, but failed to make the appropriate inferences about the significance of those p s judgments. This suggests a need for further research on people's interpretation of threat information, development of better training manuals on hurricane evacuation decision making, and better hurricane information displays to guide people's responses to hurricane threats.

Although evacuation is one of the best strategies for protecting citizens from hurricane threat, the ways that local elected officials use hurricane data in deciding whether to issue hurricane evacuation orders is not well understood. To begin to address this problem, we examined the effects of hurricane track and intensity information in a laboratory setting where participants judged the probability that hypothetical hurricanes with a constant bearing (i.e., straight line forecast track) would make landfall in each of eight 45 degree sectors around the Gulf of Mexico. The results from 162 participants in a student sample showed that the judged strike probability distributions over the eight sectors within each scenario were, unsurprisingly, unimodal and centered on the sector toward which the forecast track pointed. More significantly, although strike probability judgments for the sector in the direction of the forecast track were generally higher than the corresponding judgments for the other sectors, the latter were not zero. Most significantly, there were no appreciable differences in the patterns of strike probability judgments for hurricane tracks represented by a forecast track only, an uncertainty cone only, or forecast track with an uncertainty cone—a result consistent with a recent survey of coastal residents threatened by Hurricane Charley. The study results suggest that people are able to correctly process basic information about hurricane tracks but they do make some errors. More research is needed to understand the sources of these errors and to identify better methods of displaying uncertainty about hurricane parameters.

Research Areas

decision-making;
emergency managers;
broadcast meteorologists

decision-making; public interpretation

media and public interpretation

public interpretation;
decision-making; evacuation
implications

alternative design; public
interpretation

decision-making; evacuation
implications; public
interpretation

Decision-making

decision-making; public interpretation; emergency managers; broadcast meteorologists

Visualization, interpretation

Visualization, interpretation

public interpretation; anchor point

broadcast meteorologists; visualization; emergency managers

Interpretation

decision-making; public interpretation; emergency managers; broadcast meteorologists; alternative design; visualization

Visualization, interpretation

interpretation

Decision-making

alternative design; public interpretation

visualization; alternative design

decision-making

forecast accuracy; decision-making

decision-making; public interpretation; evacuation implications; tourists

decision-making; public interpretation; evacuation implications

public interpretation; anchor point; decision-making

decision-making; public interpretation; evacuation implications

broadcast meteorologists; visualization; alternative design

emergency managers; visualization; alternative design

decision-making; public interpretation; evacuation implications

public interpretation; decision-making; evacuation implications; emergency managers

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forecast accuracy; social
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visualization; public
interpretation; anchor point

Visualization, interpretation

public interpretation;
visualization

decision-making; public interpretation; visualization; alternative design; evacuation implications

evacuation implications; decision-making

public interpretation; visualization; alternative design; anchor point; decision-making

Visualization, interpretation

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