Uncertainty/Probability: Office of Weather & Air Quality

Bibliography

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Background & Scope

Due to the inherent and pivotal role of uncertainty and probability in weather forecasting, the National Weather Service and Office of Weather and Air Quality (OWAQ) have invested heavily in research that examines the communication and impact of uncertainty and probabilistic forecasts. Given this investment, there are many peer-reviewed resources across different journals that focus on the many dimensions of uncertainty. While uncertainty can refer to the inherent chaos of the atmosphere that forecast probabilities describe, uncertainty also refers to the range of human interpretations of forecasts, a feeling of confusion, a lack of knowledge, decision making in reaction to probabilities, etc.

To create a comprehensive resource, OWAQ consulted with the NOAA Central Library to create an annotated bibliography to provide OWAQ and their customers with an overview of the current state of literature on uncertainty and probability communication in the weather domain. The organization of the bibliography reflects the many different ways in which researchers examine uncertainty. Through a qualitative process, sections were organized by research articles that address how people interpret, react to, and use probabilities and uncertainty. Additional articles address challenges and recommendations for communicating uncertainty and probability and what the weather community can learn about uncertainty and probability communication from non-weather hazards. Where applicable, the sections were further refined by hazard in the following order tornado, winter weather, hurricanes, flooding, short term forecast (e.g., daily forecast of high or low temperatures, daily forecast of rain chances), long term forecast (e.g., monthly, seasonal, or yearly forecasts), and fire.

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Sources Reviewed

The following databases were used to identify sources: Clarivate Analytics' Web of Science: Science Citation Index Expanded and Social Science Index; Lexis Advance; ProQuest's Science and Technology; JSTOR; EBSCO's Academic Search Complete, EconLit, and NOAA's Institutional Repository. Only English language materials were included.

Section I: Interpretation

i. Tornado

Lindell, M. K., Huang, S.-k., Wei, H.-l., & Samuelson, C. D. (2016). Perceptions and Expected Immediate Reactions to Tornado Warning Polygons. Natural Hazards, 80(1), 683-707 https://doi.org/10.1007/s11069-015-1990-5

To provide people with more specific information about tornado threats, the National Weather Service has replaced its county-wide warnings with smaller warning polygons that more specifically indicate the risk area. However, tornado warning polygons do not have a standardized definition regarding tornado strike probabilities (p ^sub s^) so it is unclear how warning recipients interpret them. To better understand this issue, 155 participants responded to 15 hypothetical warning polygons. After viewing each polygon, they rated the likelihood of a tornado striking their location and the likelihood that they would take nine different response actions ranging from continuing normal activities to getting in a car and driving somewhere safer. The results showed participants inferred that the p ^sub s^ was highest at the polygon's centroid, lower just inside the edges of the polygon, still lower (but not zero) just outside the edges of the polygon, and lowest in locations beyond that. Moreover, higher p ^sub s^ values were associated with lower expectations of continuing normal activities and higher expectations of seeking information from social sources (but not environmental cues) and higher expectations of seeking shelter (but not evacuating in their cars). These results indicate that most people make some errors in their p ^sub s^ judgments but are likely to respond appropriately to the p ^sub s^ they infer from the warning polygons. Overall, the findings from this study and other research can help meteorologists to better understand how people interpret the uncertainty associated with warning polygons and, thus, improve tornado warning systems.

Miran, S. M., Ling, C., James, J. J., Gerard, A., & Rothfusz, L. (2017). User Perception and Interpretation of Tornado Probabilistic Hazard Information: Comparison of Four Graphical Designs. Applied Ergonomics, 65, 277-285 https://doi.org/10.1016/j.apergo.2017.06.016

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

ii. Winter Weather

Novak, D. R., Brill, K. F., & Hogsett, W. A. (2014). Using Percentiles to Communicate Snowfall Uncertainty. Weather and Forecasting, 29(5), 1259-1265 https://doi.org/10.1175/waf-d-14-00019.1

An objective technique to determine forecast snowfall ranges consistent with the risk tolerance of users is demonstrated. The forecast snowfall ranges are based on percentiles from probability distribution functions that are assumed to be perfectly calibrated. A key feature of the technique is that the snowfall range varies dynamically, with the resultant ranges varying based on the spread of ensemble forecasts at a given forecast projection, for a particular case, for a particular location. Furthermore, this technique allows users to choose their risk tolerance, quantified in terms of the expected false alarm ratio for forecasts of snowfall range. The technique is applied to the 4–7 March 2013 snowstorm at two different locations (Chicago, Illinois, and Washington, D.C.) to illustrate its use in different locations with different forecast uncertainties. The snowfall range derived from the Weather Prediction Center Probabilistic Winter Precipitation Forecast suite is found to be statistically reliable for the day 1 forecast during the 2013/14 season, providing confidence in the practical applicability of the technique.

iii. Hurricane

Bostrom, A., Morss, R. E., Lazo, J. K., Demuth, J. L., Lazrus, H., & Hudson, R. (2016). A Mental Models Study of Hurricane Forecast and Warning Production, Communication, and Decision-Making. Weather, Climate, and Society, 8(2), 111-129 https://doi.org/10.1175/WCAS-D-15-0033.1

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.

Broad, K., Leiserowitz, A., Weinkle, J., & Steketee, M. (2007). Misinterpretations of the "Cone of Uncertainty" in Florida During the 2004 Hurricane Season. Bulletin of the American Meteorological Society, 88(5), 651 https://doi.org/10.1175/bams-88-5-651

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 of2004 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.

Drake, L. (2012). Scientific Prerequisites to Comprehension of the Tropical Cyclone Forecast: Intensity, Track, and Size. Weather and Forecasting, 27(2), 462-472 https://doi.org/10.1175/waf-d-11-00041.1

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.

Meyer, R., Broad, K., Orlove, B., & Petrovic, N. (2013). Dynamic Simulation as an Approach to Understanding Hurricane Risk Response: Insights from the Stormview Lab. Risk Analysis, 33(8), 1532-1552 https://doi.org/10.1111/j.1539-6924.2012.01935.x

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.

Sherman-Morris, K., & Del Valle-Martinez, I. (2017). Optimistic Bias and the Consistency of Hurricane Track Forecasts. Natural Hazards, 88(3), 1523-1543 https://doi.org/10.1007/s11069-017-2931-2

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.

Wu, H. C., Lindell, M. K., Prater, C. S., & Samuelson, C. D. (2014). Effects of Track and Threat Information on Judgments of Hurricane Strike Probability. Risk Analysis, 34(6), 1025-1039 https://doi.org/10.1111/risa.12128

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.

iv. Flooding

Bell, H. M., & Tobin, G. A. (2007). Efficient and Effective? The 100-Year Flood in the Communication and Perception of Flood Risk. Environmental Hazards, 7(4), 302-311 https://doi.org/10.1016/j.envhaz.2007.08.004

This paper presents a synopsis of several terms used to describe US policy's benchmark flood and a preliminary study of how such terms are interpreted. Questionnaire surveys were conducted in a flood prone community with residents living in and out of official flood plains. Comparable questions regarding uncertainty, perceived need for protection, and concern were asked in connection with four descriptive methods: a 100-year flood; a flood with a 1 percent chance of occurring in any year; a flood with a 26 percent chance of occurring in 30 years; and a flood risk map. Statistical analysis and qualitative observation showed a disjuncture between understanding and persuasion, potential problems with the 26 percent chance method, and a preference for concrete references in describing risk.

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

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.

Carr, R. H., Montz, B., Semmens, K., Maxfield, K., Connolly, S., Ahnert, P.,.. Elliott, J. (2018). Major Risks, Uncertain Outcomes: Making Ensemble Forecasts Work for Multiple Audiences. Weather and Forecasting, 33(5), 1359-1373 https://doi.org/10.1175/waf-d-18-0018.1

When extreme river levels are possible in a community, effective communication of weather and hydrologic forecasts is critical to protecting life and property. Residents, emergency personnel, and water resource managers need to make timely decisions about how and when to prepare. Uncertainty in forecasting is a critical component of this decision-making, but often poses a confounding factor for public and professional understanding of forecast products. A new suite of products from the National Weather Service's Hydrologic Ensemble Forecast System (HEFS) provides short- and long-range forecasts, ranging from 6 h to 1 yr, and shows uncertainty in hydrologic forecasts. To understand how various audiences use and interpret ensemble forecasts showing a range of hydrologic forecast possibilities, a research project was conducted using scenario-based focus groups and surveys with community residents, emergency managers, and water resource managers in West Virginia and Maryland. The research assessed the utility of the HEFS products, identified barriers to proper understanding of the products, and suggested modifications to product design that could improve the understandability and accessibility for a range of users. There was a difference between the residential users' reactions to the HEFS compared to the emergency managers and water resource managers, with the public reacting less favorably to all versions. The emergency managers preferred the revised HEFS products but had suggestions for additional changes, which were incorporated. Features such as interactive text boxes and forecaster's notes further enhanced the utility and understandability of the products.

Grounds, M. A., LeClerc, J. E., & Joslyn, S. (2018). Expressing Flood Likelihood: Return Period Versus Probability. Weather Climate and Society, 10(1), 5-17 https://doi.org/10.1175/wcas-d-16-0107.1

The likelihood of floods and other potentially destructive natural phenomena is often expressed as a return period or recurrence interval, such as a 100-yr flood. However, the expression might give users the impression that the event will occur exactly once within the described period, obscuring the intended probabilistic meaning. If so, users may think a flood is less likely when one has just occurred or more likely when it has not, leading to a ‘‘flood is due’’ effect. This hypothesis was tested experimentally in two studies reported here. Participants were given either a return period or a probability expression and asked to rate flood likelihood and concern. Flood recency was also manipulated. The results from both studies support a flood is due effect when the return period expression is used. In the return period condition alone, participants rated floods as more likely and expressed greater concern when no flood had occurred recently. When no likelihood information was conveyed in the control condition, the opposite effect was observed. Participants rated flood likelihood as higher and expressed greater concern when a flood had occurred recently. Participants using the percent chance expression were least affected by flood recency. This adds to the growing body of research suggesting that nonexperts can benefit from probabilistic weather forecasts.

Morss, R. E., Demuth, J. L., Bostrom, A., Lazo, J. K., & Lazrus, H. (2015). Flash Flood Risks and Warning Decisions: A Mental Models Study of Forecasters, Public Officials, and Media Broadcasters in Boulder, Colorado. Risk Analysis, 35(11), 2009-2028 https://doi.org/10.1111/risa.12403

Timely warning communication and decision making are critical for reducing harm from flash flooding. To help understand and improve extreme weather risk communication and management, this study uses a mental models research approach to investigate the flash flood warning system and its risk decision context. Data were collected in the Boulder, Colorado area from mental models interviews with forecasters, public officials, and media broadcasters, who each make important interacting decisions in the warning system, and from a group modeling session with forecasters. Analysis of the data informed development of a decision-focused model of the flash flood warning system that integrates the professionals' perspectives. Comparative analysis of individual and group data with this model characterizes how these professionals conceptualize flash flood risks and associated uncertainty; create and disseminate flash flood warning information; and perceive how warning information is (and should be) used in their own and others' decisions. The analysis indicates that warning system functioning would benefit from professionals developing a clearer, shared understanding of flash flood risks and the warning system, across their areas of expertise and job roles. Given the challenges in risk communication and decision making for complex, rapidly evolving hazards such as flash floods, another priority is development of improved warning content to help members of the public protect themselves when needed. Also important is professional communication with members of the public about allocation of responsibilities for managing flash flood risks, as well as improved system-wide management of uncertainty in decisions.

Pappenberger, F., Stephens, E., Thielen, J., Salamon, P., Demeritt, D., van Andel, S. J.,… Alfieri, L. (2013). Visualizing Probabilistic Flood Forecast Information: Expert Preferences and Perceptions of Best Practice in Uncertainty Communication. Hydrological Processes, 27(1), 132-146 https://doi.org/10.1002/hyp.9253

The aim of this article is to improve the communication of the probabilistic flood forecasts generated by hydrological ensemble prediction systems (HEPS) by understanding perceptions of different methods of visualizing probabilistic forecast information. This study focuses on interexpert communication and accounts for differences in visualization requirements based on the information content necessary for individual users. The perceptions of the expert group addressed in this study are important because they are the designers and primary users of existing HEPS. Nevertheless, they have sometimes resisted the release of uncertainty information to the general public because of doubts about whether it can be successfully communicated in ways that would be readily understood to nonexperts. In this article, we explore the strengths and weaknesses of existing HEPS visualization methods and thereby formulate some wider recommendations about the best practice for HEPS visualization and communication. We suggest that specific training on probabilistic forecasting would foster use of probabilistic forecasts with a wider range of applications. The result of a case study exercise showed that there is no overarching agreement between experts on how to display probabilistic forecasts and what they consider the essential information that should accompany plots and diagrams. In this article, we propose a list of minimum properties that, if consistently displayed with probabilistic forecasts, would make the products more easily understandable.

Todhunter, P. E. (2011). Caveant Admonitus ("Let the Forewarned Beware") the 1997 Grand Forks (USA) Flood Disaster. Disaster Prevention and Management, 20(2), 125-139 https://doi.org/10.1108/09653561111126076

Purpose - This paper aims to review the performance of the flood forecasting, warning, and response system (FFWRS) during the 1997 Red River of the North flood to identify the factors that contributed to FFWRS underperformance during this flood disaster. Design/methodology/approach - The individual components of the FFWRS are reviewed data collection, flood forecasting, forecast dissemination, decision-making, and action implementation, as well as the communication linkages between each system category. The unique challenges and breakdowns that occurred at each system category and communication linkage are identified for this catastrophic flood event. Findings - Forecast uncertainty was poorly communicated by flood forecasters, and misunderstood by decision makers. Both forecasters and decision makers were rigidly committed to probability-thinking based on what they thought was most likely to happen; neither group adequately considered the possibility of a worst-case scenario. Practical implications - Forecast uncertainty must be clearly communicated to and understood by local decision makers. Significant efforts at improved knowledge transfer to decision makers should be made to improve their ability to make rapid and informed decisions during catastrophic hazard events. Originality/value - Decision makers would benefit from adopting a possibility-thinking approach that thoroughly considered the possibility of a worst-case scenario before such an event actually occurred.

Wernstedt, K., Roberts, P. S., Arvai, J., & Redmond, K. (2019). How Emergency Managers (Mis?)Interpret Forecasts. Disasters, 43(1), 88-109 https://doi.org/10.1111/disa.12293

Emergency managers who work on floods and other weather-related hazards constitute critical frontline responders to disasters. Yet, while these professionals operate in a realm rife with uncertainty related to forecasts and other unknowns, the influence of uncertainty on their decision-making is poorly understood. Consequently, a national-level survey of county emergency managers in the United States was administered to examine how they interpret forecast information, using hypothetical climate, flood, and weather scenarios to simulate their responses to uncertain information. The study revealed that even emergency managers with substantial experience take decision shortcuts and make biased choices, just as do members of the general population. Their choices vary depending on such features as the format in which probabilistic forecasts are presented and whether outcomes are represented as gains or losses. In sum, forecast producers who consider these decision processes when developing and communicating forecasts could help to improve flood preparation and potentially reduce disaster losses.

v. Short Term Forecast

Abraham, S., Bartlett, R., Standage, M., Black, A., Charlton-Perez, A., & McCloy, R. (2015). Do Location-Specific Forecasts Pose a New Challenge for Communicating Uncertainty? Meteorological Applications, 22(3), 554-562 https://doi.org/10.1002/met.1487

In the last decade, the growth of local, site-specific weather forecasts delivered by mobile phone or website represents arguably the fastest change in forecast consumption since the beginning of television weather forecasts 60years ago. In the present study, a street-interception survey of 274 members of the public a clear first preference for narrow weather forecasts above traditional broad weather forecasts is shown for the first time, with a clear bias towards this preference for users under 40 years. The impact of this change on the understanding of forecast probability and intensity information is explored. While the correct interpretation of the statement 'There is a 30% chance of rain tomorrow' is still low in the cohort, in common with previous studies, a clear impact of age and

educational attainment on understanding is shown, with those under 40 and educated to degree level or above more likely to correctly interpret it. The interpretation of rainfall intensity descriptors ('light', 'moderate' and 'heavy') by the cohort is shown to be significantly different to official and expert assessment of the same descriptors and to have large variance amongst the cohort. However, despite these key uncertainties, members of the cohort generally seem to make appropriate decisions about rainfall forecasts. There is some evidence that the decisions made are different depending on the communication format used, and the cohort expressed a clear preference for tabular over graphical weather forecast presentation.

American Meteorological Society. (2008). Enhancing Weather Information with Probability Forecasts: An Information Statement of the American Meteorological Society. Bulletin of the American Meteorological Society, 89(7), 1049-1053 https://doi.org/10.1175/1520-0477-89.7.1041

Probability forecasts can also be produced directly from NWP models or from statistical analyses of the output from these models.3 Uncertainty can be expressed in ways other than probabilistic terms, such as odds or frequencies.4 But studies by social scientists have indicated repeatedly that expressing uncertainty in qualitative terms, such as "likely," creates unnecessary ambiguity, with one user interpreting the same term as reflecting a higher probability than would another user. [...] a number of challenges must be addressed to ensure their optimal formulation, dissemination, and use: * Developing approaches for creating ensemble forecasts that represent the full range and all of the sources of forecast uncertainty associated with the forecasting process; * Improving methods for the post-processing, calibration, and verification of probability forecasts; * Developing improved methods and new tools for communicating uncertainty information (e.g., more effective ways to display such information); * Developing awareness among forecasters of the unique needs of specific users (e.g., emergency managers); * Assisting users in understanding probability forecasts and exactly what is being forecast; * Helping users make optimal use of the uncertainty information; and * Documenting the use and economic value of probability forecasts in real-world decision-making situations.

de Elia, R., & Laprise, R. (2005). Diversity in Interpretations of Probability: Implications for Weather Forecasting. Monthly Weather Review, 133(5), 1129-1143 https://doi.org/10.1175/mwr2913.1

Over the last years, probability weather forecasts have become increasingly popular due in part to the development of ensemble forecast systems. Despite its widespread use in atmospheric sciences, probability forecasting remains a subtle and ambiguous way of representing the uncertainty related to a future meteorological situation. There are several schools of thought regarding the interpretation of probabilities, none of them without flaws, internal contradictions, or paradoxes. Usually, researchers tend to have personal views that are mostly based on intuition and follow a pragmatic approach. These conceptual differences may not matter when accuracy of a probabilistic forecast is measured over a long period (e.g., through the use of Brier score), which may be useful for particular objectives such as cost/benefit decision making. However, when scientists wonder about the exact meaning of the probabilistic forecast in a single case (e.g., rare and extreme event), the differences of interpretation become important. This work intends to describe this problem by first drawing attention to the more commonly accepted interpretations of probability, and then, the consequences of these assumptions are studied. Results suggest that without agreement on the interpretation, the usefulness of the probability forecast as a tool for single events—which include record-breaking events—remains

unknown. An open discussion of this topic within the community would be useful to clarify the communication among researchers, with the public and with decision makers.

Demuth, J. L., Lazo, J. K., & Morss, R. E. (2011). Exploring Variations in People's Sources, Uses, and Perceptions of Weather Forecasts. Weather Climate and Society, 3(3), 177-192 https://doi.org/10.1175/2011wcas1061.1

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

Fischhoff, B. (1994). What Forecasts (Seem to) Mean. International Journal of Forecasting, 10(3), 387-403 https://doi.org/10.1016/0169-2070(94)90069-8

A forecast is just the set of probabilities attached to a set of future events. In order to understand a forecast, all one needs to do is to interpret those two bits of information. Unfortunately, there are pitfalls to communicating each element, so that the user of a forecast understands what its producer means. One source of potential problems is ambiguity regarding the event being predicted and what exactly is being said about it. Another is the difficulty of determining the relevance of the problem that the forecaster has solved for the problem that the user is facing. Problems can also arise out of epistemological and sociological issues of trust and context. A simple framework is offered for considering these communication problems and is then illustrated with a mixture of systematic data and anecdotal observation. The criticality of these different problems is considered, along with procedures that might reduce them.

Gigerenzer, G., Hertwig, R., van den Broek, E., Fasolo, B., & Katsikopoulos, K. V. (2005). "A 30% Chance of Rain Tomorrow": How Does the Public Understand Probabilistic Weather Forecasts? Risk Anal, 25(3), 623-629 https://doi.org/10.1111/j.1539-6924.2005.00608.x

The weather forecast says that there is a "30% chance of rain," and we think we understand what it means. This quantitative statement is assumed to be unambiguous and to convey more information than does a qualitative statement like "It might rain tomorrow." Because the forecast is expressed as a single-event probability, however, it does not specify the class of events it refers to. Therefore, even numerical probabilities can be interpreted by members of the public in multiple, mutually contradictory ways. To find out whether the same statement about rain probability evokes various interpretations, we randomly surveyed pedestrians in five metropolises located in countries that have had different degrees of exposure to probabilistic forecasts--Amsterdam, Athens, Berlin, Milan, and New York. They were asked what a "30% chance of rain tomorrow" means both in a multiple-choice and a free-response format. Only in New York did a majority of them supply the standard meteorological interpretation, namely, that when the weather conditions are like today, in 3 out of 10 cases there will be (at least a trace of) rain the next day. In each of the European cities, this alternative was judged as the least appropriate. The preferred interpretation in Europe was that it will rain tomorrow "30% of the time," followed by "in 30% of the area." To improve risk communication with the public, experts need to specify the reference class, that is, the class of events to which a single-event probability refers.

Greis, M., Avci, E., Schmidt, A., Machulla, T., & Acm. (2017). Increasing Users' Confidence in Uncertain Data by Aggregating Data from Multiple Sources. https://doi.org/10.1145/3025453.3025998

We often base our decisions on uncertain data - for instance, when consulting the weather forecast before deciding what to wear. Due to their uncertainty, such forecasts can differ by provider. To make an informed decision, many people compare several forecasts, which is a time-consuming and cumbersome task. To facilitate comparison, we identified three aggregation mechanisms for forecasts: manual comparison and two mechanisms of computational aggregation. In a survey, we compared the mechanisms using different representations. We then developed a weather application to evaluate the most promising candidates in a real-world study. Our results show that aggregation increases users' confidence in uncertain data, independent of the type of representation. Further, we find that for daily events, users prefer to use computationally aggregated forecasts. However, for high-stakes events, they prefer manual comparison. We discuss how our findings inform the design of improved interfaces for comparison of uncertain data, including non-weather purposes.

Grounds, M. A., Joslyn, S., & Otsuka, K. (2017). Probabilistic Interval Forecasts: An Individual Differences Approach to Understanding Forecast Communication. Advances in Meteorology https://doi.org/10.1155/2017/3932565

Predictive interval forecasts, showing a range of values with specified probability, have the potential to improve decisions compared to point estimates. The research reported here demonstrates that this advantage extends from college undergraduates to a wide user group and does not depend on education. In two experiments, participants made decisions based on predictive intervals or point estimates and answered questions about them. In Experiment 1, they also completed numeracy and working memory span tests. Those using predictive intervals were better able to identify situations requiring precautionary action. Nonetheless, two errors were noted: (1) misinterpreting predictive intervals as diurnal fluctuation (deterministic construal errors) and (2) judging the probability of events within and beyond the interval, when asked about them separately, as greater than 100%. These errors were only partially explained by WMS and numeracy. Importantly, omitting visualizations eliminated deterministic construal errors and overestimation of percent chance was not consistently related to

decision quality. Thus, there may be important benefits to predictive interval forecasts that are not dependent on a full understanding of the theoretical principles underlying them or an advanced education, making them appropriate for a broad range of users with diverse backgrounds, weather concerns, and risk tolerances.

Handmer, J., & Proudley, B. (2007). Communicating Uncertainty Via Probabilities: The Case of Weather Forecasts. Environmental Hazards, 7(2), 79-87 https://doi.org/https://doi.org/10.1016/j.envhaz.2007.05.002

Capturing uncertainty through numerical probabilistic statements is orthodoxy in risk science—and most of science and technology. There are a wide range of views on the utility of such statements for risk communication, and they are often seen as being central to the failure to generate common understanding about risks between science and non-scientists. The extent to which probability statements are understood is unclear. If such statements are misunderstood by many, what alternatives might communicate uncertainty better? These questions are examined in the context of daily weather forecasts. The probabilities used in such statements concern daily events experienced by everyone, unlike the extremely small probabilities about unfamiliar events often used in risk communication. If people do not understand weather forecasts, there is little hope that statements about unfamiliar events using unfamiliar language will be understood. Some jurisdictions use numerical probabilistic statements on the likelihood of precipitation, and a variety of qualitative or categorical forecasts are also used. Drawing on a range of sources including public surveys conducted by the Australian Bureau of Meteorology, the paper examines public understanding of probabilities and public and specialist understanding of verbal categorical forecast terms. The majority of those surveyed have basic understanding about probabilities as used in weather forecasts, but significant groups do not. However, there was limited agreement among forecasters on what the probabilistic statements meant. Similarly, there was limited shared meaning between forecasters and the public on the verbal forecast expression examined.

Joslyn, S., & Savelli, S. (2010). Communicating Forecast Uncertainty: Public Perception of Weather Forecast Uncertainty. Meteorological Applications, 17(2), 180-195 https://doi.org/10.1002/met.190

The general public understands that there is uncertainty inherent in deterministic forecasts as well as understanding some of the factors that increase uncertainty. This was determined in an online survey of 1340 residents of Washington and Oregon, USA. Understanding was probed using questions that asked participants what they expected to observe when given a deterministic forecast with a specified lead time, for a particular weather parameter, during a particular time of year. It was also probed by asking participants to estimate the number of observations, out of 100, that they expected to fall within specified ranges around the deterministic forecast. Almost all respondents (99.99%) anticipated some uncertainty in the deterministic forecast. Furthermore, their answers suggested that they expected greater uncertainty for longer lead times when the forecasted value deviated from climatic norms. Perhaps most noteworthy was that they expected specific forecast biases (e.g. over-forecasting of extremes), most of which were not borne out by an analysis of local National Weather Service verification data. In summary, users had well-formed uncertainty expectations suggesting that they are prepared to understand explicit uncertainty forecasts for a wide range of parameters. Indeed, explicit uncertainty estimates may be necessary to overcome some of the anticipated forecast biases that may be affecting the usefulness of existing weather forecasts. Despite the fact that these bias expectations

are largely unjustified, they could lead to adjustment of forecasts that could in turn have serious negative consequences for users, especially with respect to extreme weather warnings. Copyright © 2010 Royal Meteorological Society

Juanchich, M., & Sirota, M. (2016). How to Improve People's Interpretation of Probabilities of Precipitation. Journal of Risk Research, 19(3), 388-404 https://doi.org/10.1080/13669877.2014.983945

Most research into uncertainty focuses on how people estimate probability magnitude. By contrast, this paper focuses on how people interpret the concept of probability and why they often misinterpret it. In a weather forecast context, we hypothesised that the absence of an explicit reference class and the polysemy of the percentage format are causing incorrect probability interpretations, and test two interventions to help people make better probability interpretation. In two studies (N=1337), we demonstrate that most people from the UK and the US do not interpret probabilities of precipitation correctly. The explicit mention of the reference class helped people to interpret probabilities of precipitation better when the target area was explicit; but this was not the case when it was not specified. Furthermore, the polysemy of the percentage format is not likely to cause these misinterpretations, since a non-polysemous format (e.g. verbal probability) did not facilitate a correct probability interpretation in our studies. A Bayes factor analysis supported both of these conclusions. We discuss theoretical and applied implications of our findings.

Lazo, J. K., Morss, R. E., & Demuth, J. L. (2009). 300 Billion Served Sources, Perceptions, Uses, and Values of Weather Forecasts. Bulletin of the American Meteorological Society, 90(6), 785-798 https://doi.org/10.1175/2008bams2604.1

Understanding the public's sources, perceptions, uses, and values of weather forecasts is integral to providing those forecasts in the most societally beneficial manner. To begin developing this knowledge, we conducted a nationwide survey with more than 1,500 respondents to assess 1) where, when, and how often they obtain weather forecasts; 2) how they perceive forecasts; 3) how they use forecasts; and 4) the value they place on current forecast information. Our results indicate that the average U.S. adult obtains forecasts 115 times per month, which totals to more than 300 billion forecasts per year by the U.S. public. Overall, we find that respondents are highly satisfied with forecasts and have decreasing confidence in forecasts as lead time increases. Respondents indicated that they use forecasts across a range of decision-making contexts. Moreover, nearly three-quarters stated that they usually or always use forecasts simply to know what the weather will be like. Using a simplified valuation approach, we estimate the value of current weather forecast information to be approximately $286 per U.S. household per year, or $31.5 billion total per year value to U.S. households. This compares favorably with total U.S. public and private sector meteorology costs of $5.1 billion a year. To better support the provision of societally beneficial weather information, we advocate for well-designed periodic evaluations of the public's sources, perceptions, uses, and values of weather forecasts. These should include investigations of other important topics such as interpretations of hazardous weather warnings and presentation of uncertainty information.

Marimo, P., Kaplan, T. R., Mylne, K., & Sharpe, M. (2015). Communication of Uncertainty in Temperature Forecasts. Weather and Forecasting, 30(1), 5-22 https://doi.org/10.1175/WAF-D-14-00016.1

Experimental economics is used to test whether undergraduate students presented with a temperature forecast with uncertainty information in a table and bar graph format were able to use the extra information to interpret a given forecast. Participants were asked to choose the most probable temperature-based outcome between a set of "lotteries." Both formats with uncertainty information were found on average to significantly increase the probability of choosing the correct outcome. However, in some cases providing uncertainty information was damaging. Factors that influence understanding are statistically determined. Furthermore, participants who were shown the graph with uncertainty information took on average less response time compared to those who were shown a table with uncertainty information. Over time, participants improve in speed and initially improve in accuracy of choosing the correct outcome.

Morss, R. E., Demuth, J. L., & Lazo, J. K. (2008). Communicating Uncertainty in Weather Forecasts: A Survey of the U.S. Public. Weather and Forecasting, 23(5), 974-991 https://doi.org/10.1175/2008waf2007088.1

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

Pardowitz, T., Kox, T., Gober, M., & Butow, A. (2015). Human Estimates of Warning Uncertainty: Numerical and Verbal Descriptions. Mausam, 66(3), 625-634 Retrieved from http://metnet.imd.gov.in/mausamdocs/166324_F.pdf

The uncertainty of weather warnings is mostly expressed only in textual form (e.g., "thunderstorms are possible tomorrow afternoon"). Thus linguistic uncertainty might be added to the numerical uncertainty of the warnings. Two questions arise: can human forecasters estimate the uncertainty and how well is this done in verbal terms. Subjective and statistical forecasts of the probability of the occurrence of

severe weather events for the city of Berlin were verified. Human estimates of the probability for the occurrence of thunderstorms and wind gusts > 14 m/s in Berlin were found to be reliable and possess significant skill in comparison to the statistical reference forecast. Additionally, the verbal description of warning uncertainty in an operational textual warning report was classified and objectively verified. Results indicate that forecasters actually are aware of the inherent uncertainty, yet express this by means of a multitude of verbal terms. In order to improve the communication and reduce confusions arising from linguistic uncertainty inherent to severe weather information, forecasts should thus contain few and well defined verbal phrases expressing forecast uncertainty. Relating numerical to verbal descriptions of uncertainty revealed a fundamentally different usage of wording when comparing warnings of thunderstorms and wind gusts >14 m/s, with "stronger" wording used in case of thunderstorms. This might indicate that risk information rather than probability information is communicated to the users of the considered warning information.

Peachey, J. A., Schultz, D. M., Morss, R., Roebber, P. J., & Wood, R. (2013). How Forecasts Expressing Uncertainty Are Perceived by UK Students. Weather, 68(7), 176-181 https://doi.org/10.1002/wea.2094

Uncertainty is inherent in all weather forecasts (National Research Council, 2006). It may be expressed as an indication of the likelihood of an event (e.g. '60% chance of rain') or in the provision of a range of possible outcomes (e.g. 'a maximum temperature of 18–22°C'), in contrast to deterministic forecasts that provide a definitive statement (e.g. 'top temperature 20°C'). In the USA, the public have had access to probabilistic forecasts of precipitation from the National Weather Service (formerly the Weather Bureau) since 1965 (Murphy et al., 1980; Murphy and Winkler, 1984; Monahan and Steadman, 1996), and a survey of the American public found that the chance of precipitation is the second most important component of a weather forecast (Lazo et al., 2009). By comparison, probabilistic forecasts for the UK public are rarely provided by most forecasters, although the Met Office (2011) has begun to experiment with the best approaches for offering such forecasts. Indeed, parliament recommended that the Met Office should develop a communications strategy … to enhance the ways in which it presents probabilistic weather forecast information and recommended that broadcasters make greater use of probabilistic information in their weather forecasts, as is done in the United States (http://www.publications.parliament.uk/pa/cm201213/cmselect/cmsctech/162/16204.htm: item 13).

Savelli, S., & Joslyn, S. (2012). Boater Safety: Communicating Weather Forecast Information to High-Stakes End Users. Weather, Climate, and Society, 4(1), 7-19 https://doi.org/10.1175/WCAS-D-11-00025.1

Recreational boaters in the Pacific Northwest understand that there is uncertainty inherent in deterministic forecasts as well as some of the factors that increase uncertainty. This was determined in an online survey of 166 boaters in the Puget Sound area. Understanding was probed using questions that asked respondents what they expected to observe when given a deterministic forecast with a specified lead time, for a particular weather parameter, during a particular time of year. It was also probed by asking respondents to estimate the number of observations, out of 100 or out of 10, that they expected to fall within specified ranges around the deterministic forecast. Almost all respondents anticipated some uncertainty in the deterministic forecast as well as specific biases, most of which were born out by an analysis of local National Weather Service verification data. Interestingly, uncertainty and biases were anticipated for categorical forecasts indicating a range of values as well, suggesting that

specifying numeric uncertainty would improve understanding. Furthermore, respondents' answers suggested that they expected a high rate of false alarms among warning and advisory forecasts. Nonetheless, boaters indicated that they would take precautionary action in response to such warnings, in proportions related to the size of boat they were operating. This suggests that uncertainty forecasts would be useful to these experienced forecast consumers, allowing them to adapt the forecast to their specific boating situation with greater confidence.

Sivle, A. D., Kolsto, S. D., Hansen, P. J. K., & Kristiansen, J. (2014). How Do Laypeople Evaluate the Degree of Certainty in a Weather Report? A Case Study of the Use of the Web Service Yr.No. Weather Climate and Society, 6(3), 399-412 https://doi.org/10.1175/wcas-d-12-00054.1

Many people depend on and use weather forecasts to plan their schedules. In so doing, ordinary people with no expertise in meteorology are frequently called upon to interpret uncertainty with respect to weather forecasts. With this in mind, this study addresses two main questions: 1) How do laypeople interpret online weather reports with respect to their degree of certainty and how is previous knowledge drawn upon in this interpretation? and 2) How do laypeople integrate information in weather reports to determine their degree of certainty? This qualitative study is based on semistructured interviews with 21 Norwegians. The results show the following: (a) only a portion of uncertainty information was used, (b) symbols were sometimes ascribed different meanings than intended, and (c) interpretations were affected by local experiences with wind direction and forecast quality. The informants' prior knowledge was found to prevail in the event of a conflict with forecast information, and an expected range of uncertainty was often inferred into single-valued forecasts. Additionally, (d) interpretations were affected by the integration of information used to predict the time and location of precipitation. Informants typically interpreted the degree of certainty differently (more or less uncertain) than was intended. Clearer presentation of uncertainty information, a clear intent of all nuances in information, a thorough use of multimodal information, and consideration of users' needs can help improve communication of forecast uncertainty. The diversity of user approaches makes forecast uncertainty more difficult to communicate and provides possible explanations for why communicating uncertainty is challenging.

Zabini, F., Grasso, V., Magno, R., Meneguzzo, F., & Gozzini, B. (2015). Communication and Interpretation of Regional Weather Forecasts: A Survey of the Italian Public. Meteorological Applications, 22(3), 495-504 https://doi.org/10.1002/met.1480

The aim of the present study is to contribute to the correctness and effectiveness of weather forecast communication, the importance of which has been steadily growing along with the improvement in numerical weather prediction models and methods as well as the general awareness about the increase of extreme events within a context of global climate change. An extensive survey was conducted among the general users of the weather forecasts issued by the regional meteorological service of Tuscany, Italy (LaMMA Consortium), which resulted in 2388 volunteers responding to the questions aimed at better understanding of how people access, interpret and use weather forecasts. The survey also includes some items investigated in previous research, allowing comparison with similar findings in other countries. The most critical issue concerns the uncertainty information, investigated with the main aim of verifying the existence and relevance of inferential mechanisms in the interpretation of weather icons and maps used in LaMMA forecasts to assess uncertainty. The present study also discusses users' interpretations of the probability of precipitation forecasts and their preferences on how forecast

uncertainty is conveyed. Results show that, even if the Italian public is accustomed to strictly deterministic weather forecasts, people attribute uncertainty to them on their own even if lacking any explicit indication, thus suggesting the need to supplement the existing forecasts with both graphical and textual information about uncertainty, particularly in the case of precipitation forecasts.

vi. Long Term Forecast

Budescu, D. V., Por, H.-h., & Broomell, S. B. (2012). Effective Communication of Uncertainty in the IPCC Reports. Climatic Change, 113(2), 181-200 https://doi.org/10.1007/s10584-011-0330-3

The Intergovernmental Panel on Climate Change (IPCC) publishes periodical assessment reports informing policymakers and the public on issues relevant to the understanding of human induced climate change. The IPCC uses a set of 7 verbal descriptions of uncertainty, such as unlikely and very likely to convey the underlying imprecision of its forecasts and conclusions. We report results of an experiment comparing the effectiveness of communication using these words and their numerical counterparts. We show that the public consistently misinterprets the probabilistic statements in the IPCC report in a regressive fashion, and that there are large individual differences in the interpretation of these statements, which are associated with the respondents' ideology and their views and beliefs about climate change issues. Most importantly our results suggest that using a dual (verbal--numerical) scale would be superior to the current mode of communication as it (a) increases the level of differentiation between the various terms, (b) increases the consistency of interpretation of these terms, and (c) increases the level of consistency with the IPCC guidelines. Most importantly, these positive effects are independent of the respondents' ideological and environmental views.

Patt, A., & Dessai, S. (2005). Communicating Uncertainty: Lessons Learned and Suggestions for Climate Change Assessment. Comptes Rendus Geoscience, 337(4), 425-441 https://doi.org/10.1016/j.crte.2004.10.004

Assessments of climate change face the task of making information about uncertainty accessible and useful to decision-makers. The literature in behavior economics provides many examples of how people make decisions under conditions of uncertainty relying on inappropriate heuristics, leading to inconsistent and counterproductive choices. Modern risk communication practices recommend a number of methods to overcome these hurdles, which have been recommended for the Intergovernmental Panel on Climate Change (IPCC) assessment reports. This paper evaluates the success of the most recent IPCC approach to uncertainty communication, based on a controlled survey of climate change experts. Evaluating the results from the survey, and from a similar survey recently conducted among university students, the paper suggests that the most recent IPCC approach leaves open the possibility for biased and inconsistent responses to the information. The paper concludes by suggesting ways to improve the approach for future IPCC assessment reports.

vii. Fire

Wall, T. U., Brown, T. J., & Nauslar, N. J. (2017). Spot Weather Forecasts: Improving Utilization, Communication, and Perceptions of Accuracy in Sophisticated User Groups. Weather Climate and Society, 9(2), 215-226 https://doi.org/10.1175/wcas-d-15-0055.1

Spot weather forecasts (SWFs) are issued by Weather Service offices throughout the United States and are primarily for use by wildfire and prescribed fire practitioners for monitoring local-scale weather conditions. This paper focuses on use of SWFs by prescribed fire practitioners. Based on qualitative, in-depth interviews with fire practitioners and National Weather Service forecasters, this paper examines factors that influence perceptions of accuracy and utilization of SWFs. Results indicate that, while several well-understood climatological, topographical, and data-driven factors influence forecast accuracy, social factors likely have the greater impact on perceptions of accuracy, quantitative accuracy, and utilization. These include challenges with building and maintaining relationships between forecasters and fire managers, communication issues around updating SWFs, and communicating forecast confidence and uncertainty. Operationally, improved quantitative skill in a forecast is always desirable, but key opportunities for improving accuracy and utilization of these forecasts lie in 1) enhancing the processes and mechanisms for communication between a Weather Forecast Office and fire practitioners—before, during, and after an SWFs is issued—and 2) working with the wildland fire community to experiment with forecast uncertainty and confidence information in SWFs and evaluate impacts of these approaches.

Section II: Behavior/Decision Making

i. Tornado

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

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

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

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

ii. Winter Weather

Grounds, M. A., & Joslyn, S. L. (2018). Communicating Weather Forecast Uncertainty: Do Individual Differences Matter? Journal of Experimental Psychology-Applied, 24(1), 18-33 https://doi.org/10.1037/xap0000165

Research suggests that people make better weather-related decisions when they are given numeric probabilities for critical outcomes (Joslyn & Leclerc, 2012, 2013). However, it is unclear whether all users can take advantage of probabilistic forecasts to the same extent. The research reported here assessed key cognitive and demographic factors to determine their relationship to the use of probabilistic forecasts to improve decision quality. In two studies, participants decided between spending resources to prevent icy conditions on roadways or risk a larger penalty when freezing temperatures occurred. Several forecast formats were tested, including a control condition with the night-time low temperature alone and experimental conditions that also included the probability of freezing and advice based on expected value. All but those with extremely low numeracy scores made better decisions with probabilistic forecasts. Importantly, no groups made worse decisions when probabilities were included. Moreover, numeracy was the best predictor of decision quality, regardless of forecast format, suggesting that the advantage may extend beyond understanding the forecast to general decision strategy issues. This research adds to a growing body of evidence that numerical uncertainty estimates may be an effective way to communicate weather danger to general public end users.

Joslyn, S. L., & Grounds, M. A. (2015). The Use of Uncertainty Forecasts in Complex Decision Tasks and Various Weather Conditions. Journal of Experimental Psychology-Applied, 21(4), 407-417 https://doi.org/10.1037/xap0000064

Recent research on weather-related decision-making suggests that the inclusion of numeric uncertainty estimates in weather forecasts improves decision quality over single value forecasts or specific advice. However, it is unclear if the benefit of uncertainty estimates extends to more complex decision tasks, presumably requiring greater cognitive effort, or to tasks in which the decision is clear-cut, perhaps making the additional uncertainty information unnecessary. In the present research, participants completed a task in which they used single value weather forecasts, either alone, with freeze probabilities, advice, or both, to decide whether to apply salt to roads in winter to prevent icing or to withhold salt and risk a penalty. Participants completed either a simple binary choice version of the task or a complex version with 3 response options and accompanying rules for application. Some participants were shown forecasts near the freezing point, such that the need for salt was ambiguous, whereas other participants were shown forecasts well below the freezing point. Results suggest that participants with uncertainty estimates did better overall, and neither the task complexity nor the coldness of the forecasts reduced that advantage. However, unexpectedly colder forecasts lead to poorer decisions and an advantage for specific advice.

Joslyn, S. L., & LeClerc, J. E. (2012). Uncertainty Forecasts Improve Weather-Related Decisions and Attenuate the Effects of Forecast Error. Journal of Experimental Psychology-Applied, 18(1), 126-140 https://doi.org/10.1037/a0025185

Although uncertainty is inherent in weather forecasts, explicit numeric uncertainty estimates are rarely included in public forecasts for fear that they will be misunderstood. Of particular concern are situations in which precautionary action is required at low probabilities, often the case with severe events. At present, a categorical weather warning system is used. The work reported here tested the relative benefits of several forecast formats, comparing decisions made with and without uncertainty forecasts. In three experiments, participants assumed the role of a manager of a road maintenance company in charge of deciding whether to pay to salt the roads and avoid a potential penalty associated with icy conditions. Participants used overnight low temperature forecasts accompanied in some conditions by uncertainty estimates and in others by decision advice comparable to categorical warnings. Results suggested that uncertainty information improved decision quality overall and increased trust in the forecast. Participants with uncertainty forecasts took appropriate precautionary action and withheld unnecessary action more often than did participants using deterministic forecasts. When error in the forecast increased, participants with conventional forecasts were reluctant to act. However, this effect was attenuated by uncertainty forecasts. Providing categorical decision advice alone did not improve decisions. However, combining decision advice with uncertainty estimates resulted in the best performance overall. The results reported here have important implications for the development of forecast formats to increase compliance with severe weather warnings as well as other domains in which one must act in the face of uncertainty.

LeClerc, J., & Joslyn, S. (2012). Odds Ratio Forecasts Increase Precautionary Action for Extreme Weather Events. Weather Climate and Society, 4(4), 263-270 https://doi.org/10.1175/wcas-d-12-00013.1

What is the best way to communicate the risk of rare but extreme weather to the public? One suggestion is to communicate the relative risk of extreme weather in the form of odds ratios; but, to the authors' knowledge, this suggestion has never been tested systematically. The experiment reported here provides an empirical test of this hypothesis. Participants performed a realistic computer simulation task in which they assumed the role of the manager of a road maintenance company and used forecast information to decide whether to take precautionary action to prevent icy conditions on a town's roads. Participants with forecasts expressed as odds ratios were more likely to take appropriate precautionary action on a single target trial with an extreme low temperature forecast than participants using deterministic or probabilistic forecasts. However, participants using probabilistic forecasts performed better on trials involving weather within the normal range than participants with only deterministic forecast information. These results may provide insight into how best to communicate extreme weather risk. This paper offers clear evidence that people given relative risk information are more inclined to take precautionary action when threatened with an extreme weather event with a low probability than people given only single-value or probabilistic forecasts.

LeClerc, J., & Joslyn, S. (2015). The Cry Wolf Effect and Weather-Related Decision Making. Risk Analysis, 35(3), 385-395 https://doi.org/10.1111/risa.12336

Despite improvements in forecasting extreme weather events, noncompliance with weather warnings among the public remains a problem. Although there are likely many reasons for noncompliance with weather warnings, one important factor might be people's past experiences with false alarms. The research presented here explores the role of false alarms in weather-related decision making. Over a series of trials, participants used an overnight low temperature forecast and advice from a decision aid to decide whether to apply salt treatment to a town's roads to prevent icy conditions or take the risk of withholding treatment, which resulted in a large penalty when freezing temperatures occurred. The decision aid gave treatment recommendations, some of which were false alarms, i.e., treatment was recommended but observed temperatures were above freezing. The rate at which the advice resulted in false alarms was manipulated between groups. Results suggest that very high and very low false alarm rates led to inferior decision making, but that lowering the false alarm rate slightly did not significantly affect compliance or decision quality. However, adding a probabilistic uncertainty estimate in the forecasts improved both compliance and decision quality. These findings carry implications about how weather warnings should be communicated to the public.

Roulston, M. S., Bolton, G. E., Kleit, A. N., & Sears-Collins, A. L. (2006). A Laboratory Study of the Benefits of Including Uncertainty Information in Weather Forecasts. Weather and Forecasting, 21(1), 116-122 https://doi.org/10.1175/WAF887.1

Modern operational methods of numeric**al weather prediction, such as "ensemble forecasting,"** allow assessments of state-dependent predictability to be made. This means that forecast-specific estimates of the forecast standard errors are possible. Quantitative estimates of forecast uncertainty are often not communicated to the public as it is unclear what the value of this information will be to people who must make weather-dependent decisions. Using laboratory-based methods developed by experimental economists to study individual choice it is found that nonspecialists are able to make better decisions

that increase their expected reward while reducing their exposure to risk, when provided with information about the day-to-day uncertainty associated with temperature forecasts. The experimental framework used herein may provide a useful tool for evaluating the effectiveness with which weather forecasts can be communicated to end users.

iii. Hurricane

Bostrom, A., Morss, R., Lazo, J. K., Demuth, J., & Lazrus, H. (2018). Eyeing the Storm: How Residents of Coastal Florida See Hurricane Forecasts and Warnings. International Journal of Disaster Risk Reduction, 30, 105-119 https://doi.org/10.1016/j.ijdrr.2018.02.027

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.

Morss, R. E., Demuth, J. L., Lazo, J. K., Dickinson, K., Lazrus, H., & Morrow, B. H. (2016). Understanding Public Hurricane Evacuation Decisions and Responses to Forecast and Warning Messages. Weather and Forecasting, 31(2), 395-417 https://doi.org/10.1175/waf-d-15-0066.1

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.

Wu, H.-C., Lindell, M. K., & Prater, C. S. (2015). Strike Probability Judgments and Protective Action Recommendations in a Dynamic Hurricane Tracking Task. Natural Hazards, 79(1), 355-380 https://doi.org/10.1007/s11069-015-1846-z

This experiment assessed the strike probability (p ^sub 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 ^sub 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 ^sub 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 ^sub s^ judgments, but failed to make the appropriate inferences about the significance of those p ^sub 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.

iv. Flooding

Morss, R. E., Lazo, J. K., & Demuth, J. L. (2010). Examining the Use of Weather Forecasts in Decision Scenarios: Results from a Us Survey with Implications for Uncertainty Communication. Meteorological Applications, 17(2), 149-162 https://doi.org/10.1002/met.196

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

Ramos, M. H., van Andel, S. J., & Pappenberger, F. (2013). Do Probabilistic Forecasts Lead to Better Decisions? Hydrology and Earth System Sciences, 17(6), 2219-2232 https://doi.org/10.5194/hess-17-2219-2013

The last decade has seen growing research in producing probabilistic hydro-meteorological forecasts and increasing their reliability. This followed the promise that, supplied with information about uncertainty, people would take better risk-based decisions. In recent years, therefore, research and operational developments have also started focusing attention on ways of communicating the probabilistic forecasts to decision-makers. Communicating probabilistic forecasts includes preparing tools and products for visualisation, but also requires understanding how decision-makers perceive and use uncertainty information in real time. At the EGU General Assembly 2012, we conducted a laboratory style experiment in which several cases of flood forecasts and a choice of actions to take were presented as part of a game to participants, who acted as decision-makers. Answers were collected and analysed. In this paper, we present the results of this exercise and discuss if we indeed make better decisions on the basis of probabilistic forecasts.

v. Short Term Forecast

Hoss, F., & Fischbeck, P. (2018). Use of Observational Weather Data and Forecasts in Emergency Management: An Application of the Theory of Planned Behavior. Weather Climate and Society, 10(2), 275-290 https://doi.org/10.1175/wcas-d-16-0088.1

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

Joslyn, S., & LeClerc, J. (2013). Decisions with Uncertainty: The Glass Half Full. Current Directions in Psychological Science, 22(4), 308-315 https://doi.org/10.1177/0963721413481473

Each of us makes important decisions involving uncertainty in domains in which we are not experts, such as retirement planning, medical treatment, and precautions against severe weather. Often, reliable information about uncertainty is available to us, although how effectively we incorporate it into the decision process remains in question. Previous research suggests that people are error-prone when reasoning with probability. However, recent research in weather-related decision making is more encouraging. Unlike earlier work that compares people's decisions with a rational standard, this research compares decisions made by people with and without uncertainty information. The results suggest that including specific numeric uncertainty estimates in weather forecasts increases trust and

gives people a better idea of what to expect in terms of both the range of possible outcomes and the amount of uncertainty in the particular situation, all of which benefit precautionary decisions. However, the advantage for uncertainty estimates depends critically on how they are expressed. It is crucial that the expression is compatible with both the decision task and cognitive processes of the user.

Kim, I. G., Kim, J. Y., Kim, B. J., & Lee, K. K. (2014). The Collective Value of Weather Probabilistic Forecasts According to Public Threshold Distribution Patterns. Meteorological Applications, 21(3), 795-802 https://doi.org/10.1002/met.1424

The Korea Meteorological Administration has limited understanding of how users interpret probabilistic forecast information and use it in their decision-making processes. Thus, a survey was conducted among users to find out at which probability threshold for adverse weather they would react and take protective action to minimize the losses. According to previous studies, probability threshold depends on the type of users but they are in general higher than a 50% forecasts chance of adverse weather, even though research has shown that the forecast value is maximized when actions are taken for probability of adverse weather lower than 50%. A collective value score model, defined as a weighted sum of user's satisfaction and threshold distribution in a group of users, is introduced as a measure of total satisfaction of a user group. The collective value score model is applied to a set of precipitation probabilistic forecasts of Seoul, South Korea during 2002-2011. The results show that the collective value score can be improved if the range of users' probability thresholds is widened rather than improving the forecast accuracy.

Kox, T., Gerhold, L., & Ulbrich, U. (2015). Perception and Use of Uncertainty in Severe Weather Warnings by Emergency Services in Germany. Atmospheric Research, 158, 292-301 https://doi.org/10.1016/j.atmosres.2014.02.024

In the course of the WEXICOM project at the Hans-Ertel-Centre for Weather Research of the Deutscher Wetterdienst (DWD), a survey was conducted in autumn 2012 to question how weather warnings are communicated to professional end-users in the emergency community and how the warnings are converted into mitigation measures. 161 members of emergency services (e.g. fire fighters, police officers and civil servants) across Germany answered an online questionnaire. Questions included user's confidence in forecasts, their understanding of probabilistic information and their perception and use of uncertainty in forecasts and warnings. A large number of open questions were selected to identify new topics of interest, unknown problems, and research gaps in the field of communicating weather information in Germany. Results show that the emergency service personnel who participated in this survey generally have a good appreciation of the uncertainty of weather forecasts. Although no single probability threshold could be identified for organisations to start with preparatory mitigation measures, it became clear that emergency services tend to avoid forecast based on low probabilities as basis for their decisions. This paper suggests that when trying to enhance weather communication by reducing the uncertainty in forecasts, the focus should not only be on improving computer models and observation tools, but also on the communication aspect, as uncertainty also arises from linguistic origins. Here, improvements are also possible and thus uncertainty might be reducible.

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

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

Mu, D., Kaplan, T. R., & Dankers, R. (2018). Decision Making with Risk-Based Weather Warnings. International Journal of Disaster Risk Reduction, 30, 59-73 https://doi.org/10.1016/j.ijdrr.2018.03.030

We study decisions under different weather warning systems that vary in format and/or information conveyed using a laboratory experiment. Participants have to decide between a safe but costly option (spending to protect from a storm) and a risky option (of not spending for protection). We ran three treatments based upon the severe weather warning system for the UK that the Met Office has been using since 2011 - a risk matrix to communicate the impact and likelihood of an event. In Treatment 1, participants received a colored table with a check in the box of the matrix that showed the likelihood and impact level of the warning. In Treatment 2, participants had the colored table and the color of the warning communicated but without a check in the exact box. In Treatment 3, participants only had the color of the warning communicated without seeing the associated table. Overall our work shows that while increasing the information with content of warnings is usually beneficial and increases the trust in the warning system, it must be done with caution since better decisions (judged by higher profits) are not always made with an increase of information.

Sivle, A. D., & Kolsto, S. D. (2016). Use of Online Weather Information in Everyday Decision-Making by Laypeople and Implications for Communication of Weather Information. Meteorological Applications, 23(4), 650-662 https://doi.org/10.1002/met.1588

Many people use weather reports to plan their activities. Previous studies on this type of decision-making have been concerned primarily with the use of selected pieces of information detached from the context of a full weather report. Therefore, this study contains two areas of focus: (1) factors influencing the amount of information from a full weather report that is used by laypeople for everyday decision-making and (2) how the complexity in information in a full weather report is handled in the decision-

making processes. In this qualitative study, semi-structured interviews were conducted with 21 people from Norway. Farmers, exterior painters, tour guides, teachers and students were included in the sample to obtain a fair variance in the number of user situations. Interviews were centred on a multimodal weather report from the online web service www.yr.no. In the present study, a varying amount of information was used by the participants in their decision-making; furthermore, the amount of information used appeared to depend on (1) the importance of the envisaged activity and (2) the suitability of the weather conditions. The amount of information (i.e. complexity) had to be reduced to make a quick decision, which typically was accomplished by (1) choosing a suitable starting point and leaving out evaluations of (2) weather dynamics and (3) forecast uncertainty. Communicating a multiplicity of representations in weather reports appears favourable for enabling the use of different types and amounts of information, such that it allows both quick and more elaborate decision-making processes.

vi. Wind

Potter, S. H., Kreft, P. V., Milojev, P., Noble, C., Montz, B., Dhellemmes, A., . . . Gauden-Ing, S. (2018). The Influence of Impact-Based Severe Weather Warnings on Risk Perceptions and Intended Protective Actions. International Journal of Disaster Risk Reduction, 30, 34-43 https://doi.org/10.1016/j.ijdrr.2018.03.031

This paper presents the results of an online survey of the New Zealand public (n=1364), conducted in 2015, that tested the influence of impact-based severe weather warnings on risk perceptions and intended protective actions. We used a hypothetical severe weather event involving strong winds, with 50% of participants receiving an impact-based warning, and 50% receiving a more traditional phenomenon-based warning (which in this case is when the wind speed is expected to be higher than a given number). Our results indicate that impact-based warnings may be more effective than phenomenon-based warnings in influencing the recipient's perception of the hazardous event (their sense of threat, concern, and understanding of the potential impacts), but this does not translate to a higher level of action. Characteristics of gender, age, and location of residence were also influences on risk perceptions and intended actions. However, experience with having been affected by strong winds in the past was not a strong influence on intending to respond. Our findings support the inclusion of information about hazards, impacts, and 'what to do' information in a warning message.

Section III: Use

Hoss, F., & Fischbeck, P. (2016). Increasing the Value of Uncertain Weather and River Forecasts for Emergency Managers. Bulletin of the American Meteorological Society, 97(1) https://doi.org/10.1175/bams-d-13-00275.1

Emergency managers (EMs) use National Weather Service (NWS) forecasts to prepare for and respond to severe weather events. To effectively facilitate such decision making, the NWS needs to understand this large and important group of clients. EMs translate the forecasts to local topography, suggest actions to take in preparation of high water levels, and use their local network and reputation to make people act. For this study, 17 EMs in towns along rivers were interviewed and asked to describe their

use of river and weather forecasts.Forecast uncertainty is one of the many uncertainties an EM has to manage when coordinating an emergency response. Each of the interviewed EMs who uses river forecasts was acutely aware that river forecasts often have substantial uncertainty. To cope with this uncertainty, EMs engage in extensive information gathering before forming their own judgments. However, EMs often do not communicate their judgment of the situation to the public, fearing potential liability claims and backlash from the media. For emergency management decisions, while EMs do consider forecast data, they rely heavily on recorded data and monitoring crews, limiting the benefits of forecasts that can be made with significant lead time. This paper arrives at recommendations for the NWS on how to increase the value of river and weather forecasts for decision making in emergency management.

Lazo, J. K., Morss, R. E., & Demuth, J. L. (2009). 300 Billion Served Sources, Perceptions, Uses, and Values of Weather Forecasts. Bulletin of the American Meteorological Society, 90(6), 785-798 https://doi.org/10.1175/2008bams2604.1

Understanding the public's sources, perceptions, uses, and values of weather forecasts is integral to providing those forecasts in the most societally beneficial manner. To begin developing this knowledge, we conducted a nationwide survey with more than 1,500 respondents to assess 1) where, when, and how often they obtain weather forecasts; 2) how they perceive forecasts; 3) how they use forecasts; and 4) the value they place on current forecast information. Our results indicate that the average U.S. adult obtains forecasts 115 times per month, which totals to more than 300 billion forecasts per year by the U.S. public. Overall, we find that respondents are highly satisfied with forecasts and have decreasing confidence in forecasts as lead time increases. Respondents indicated that they use forecasts across a range of decision-making contexts. Moreover, nearly three-quarters stated that they usually or always use forecasts simply to know what the weather will be like. Using a simplified valuation approach, we estimate the value of current weather forecast information to be approximately $286 per U.S. household per year, or $31.5 billion total per year value to U.S. households. This compares favorably with total U.S. public and private sector meteorology costs of $5.1 billion a year. To better support the provision of societally beneficial weather information, we advocate for well-designed periodic evaluations of the public's sources, perceptions, uses, and values of weather forecasts. These should include investigations of other important topics such as interpretations of hazardous weather warnings and presentation of uncertainty information.

Zabini, F. (2016). Mobile Weather Apps or the Illusion of Certainty. Meteorological Applications, 23(4), 663-670 https://doi.org/10.1002/met.1589

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

around weather forecasts appear to be inconsistent with current forecasting capabilities, particularly with their inherent uncertainties in space and time, as well as in the nature of the predicted weather events.

Section IV: Challenges & Recommendations

i. Tornado

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

Cold-season tornadoes, defined here as those occurring during November–February (NDJF), pose many societal risks. Not only do they occur when tornadoes are least common in the United States, but NDJF tornadoes also tend to be nocturnal and are most prevalent in the Southeast, where complex terrain, limited resources, and a high mobile home density add social vulnerabilities. In the period 1953–2015, within the domain of 258–42.58N, 758–1008W, over 900 people were killed as a result of NDJF tornadoes. Moreover, NDJF tornado frequency is increasing much faster than that of annual tornadoes. Given the enhanced societal risk, particularly in the Southeast, effective communication between professionals and the public is imperative during a cold-season tornado event. This study investigates communication strategies and barriers from the perspective of National Weather Service and broadcast meteorologists, as well as emergency managers, through a post event survey of four major tornado events from November 2016 to February 2017. Barriers to tornado risk communication identified by the professionals included public ‘‘me-centeredness,’’ inconsistent messages, and timing and meteorological uncertainties, as well as case-specific factors. Meteorologists perceived their communities as vulnerable to tornadoes in general, yet also prepared and receptive to warnings. Factors influencing perceived barriers and vulnerability are incorporated into a conceptual model of tornado risk communication, which is applicable to tornadoes in general. Ideas for overcoming these barriers include consolidation of warning graphics, collaboration between the meteorological and social science communities, and improved education of tornado risks for the most vulnerable sectors of society.

ii. Winter Weather

Winkler, R. L. (2015). The Importance of Communicating Uncertainties in Forecasts: Overestimating the Risks from Winter Storm Juno. Risk Anal, 35(3), 349-353 https://doi.org/10.1111/risa.12398

In decision analysis and risk analysis, making rational decisions in the face of uncertainty necessitates the consideration of uncertainty. Since probability is the mathematical language of uncertainty, ideally the uncertainty should be communicated in probabilistic form. Summaries such as interval forecasts convey some information, as do qualitative expressions of uncertainty (e.g., “snow is likely”), but the quantitative nature of probabilities makes them much more informative. Probabilities are needed to understand the risk associated with potential decisions as well as to determine measures such as expected payoffs and expected utilities. They are an essential input to decision modeling and decision making.

iii. Hurricane

Demuth, J. L., Morss, R. E., Morrow, B. H., & Lazo, J. K. (2012). Creation and Communication of Hurricane Risk Information. Bulletin of the American Meteorological Society, 93(8), 1133-1145 https://doi.org/10.1175/bams-d-11-00150.1

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.

Melton, G., Gall, M., Mitchell, J. T., & Cutter, S. L. (2009). Hurricane Katrina Storm Surge Delineation: Implications for Future Storm Surge Forecasts and Warnings. Natural Hazards, 54(2), 519-536 https://doi.org/10.1007/s11069-009-9483-z

The storm surge in coastal Mississippi caused by Hurricane Katrina was unprecedented in the region. The height and geographic extent of the storm surge came as a surprise to many and exceeded pre-impact surge scenarios based on SLOSH models that were the basis for emergency preparedness and local land use decision-making. This paper explores the spatial accuracy of three interpolated storm surge surfaces derived from post event reconnaissance data by comparing the interpolation results to a specific SLOSH run. The findings are used to suggest improvements in the calibration of existing pre-event storm surge models such as SLOSH. Finally, the paper provides some suggestions on an optimal surge forecast map that could enhance the communication of storm surge risks to the public.

Munroe, R., Montz, B., & Curtis, S. (2018). Getting More out of Storm Surge Forecasts: Emergency Support Personnel Needs in North Carolina. Weather Climate and Society, 10(4), 813-820 https://doi.org/10.1175/wcas-d-17-0074.1

Storm surge has been identified as a dangerous and damaging coastal hazard that is expected to be exacerbated by rising sea levels. However, storm surge research and applications are relatively new and poorly understood compared to other storm-related hazards. This survey-based research of emergency

support personnel across eastern North Carolina aims to connect ongoing research with the needs of storm surge users. Results indicate that emergency managers and other emergency support functions depend on storm surge information to assess and communicate risk, to educate the public, to evacuate the public, or for long-term resilience and recovery planning. They were generally satisfied with the type and timing of currently available surge information, but desired additional types of surge information (i.e., timing) and longer lead times.

iv. Flooding

Dale, M., Wicks, J., Mylne, K., Pappenberger, F., Laeger, S., & Taylor, S. (2014). Probabilistic Flood Forecasting and Decision-Making: An Innovative Risk-Based Approach. Natural Hazards, 70(1), 159-172 https://doi.org/10.1007/s11069-012-0483-z

Flood forecasting is becoming increasingly important across the world. The exposure of people and property to flooding is increasing and society is demanding improved management of flood risk. At the same time, technological and data advances are enabling improvements in forecasting capabilities. One area where flood forecasting is seeing technical developments is in the use of probabilistic forecasts—these provide a range of possible forecast outcomes that indicate the probability or chance of a flood occurring. While probabilistic forecasts have some distinct benefits, they pose an additional decision-making challenge to those that use them: with a range of forecasts to pick from, which one is right? (or rather, which one(s) can enable me to make the correct decision?). This paper describes an innovative and transferable approach for aiding decision-making with probabilistic forecasts. The proposed risk-based decision-support framework has been tested in a range of flood risk environments: from coastal surge to fluvial catchments to urban storm water scales. The outputs have been designed to be practical and proportionate to the level of flood risk at any location and to be easy to apply in an operational flood forecasting and warning context. The benefits of employing a benefit-cost inspired decision-support framework are that flood forecasting decision-making can be undertaken objectively, with confidence and an understanding of uncertainty, and can save unnecessary effort on flood incident actions. The method described is flexible such that it can be used for a wide range of flood environments with multiple flood incident management actions. It uses a risk-based approach taking into account both the probability and the level of impact of a flood event. A key feature of the framework is that it is based on a full assessment of the flood-related risk, taking into account both the probability and the level of impact of a flood event. A recommendation for action may be triggered by either a higher probability of a lower impact flood or a low probability of a very severe flood. Hence, it is highly innovative as it is the first application of such a risk-based method for flood forecasting and warning purposes. A final benefit is that it is considered to be transferrable to other countries.

Demeritt, D., Nobert, S., Cloke, H., & Pappenberger, F. (2010). Challenges in Communicating and Using Ensembles in Operational Flood Forecasting. Meteorological Applications, 17(2), 209-222 https://doi.org/10.1002/met.194

Following trends in operational weather forecasting, where ensemble prediction systems (EPS) are now increasingly the norm, flood forecasters are beginning to experiment with using similar ensemble methods. Most of the effort to date has focused on the substantial technical challenges of developing coupled rainfall-runoff systems to represent the full cascade of uncertainties involved in predicting future flooding. As a consequence much less attention has been given to the communication and

eventual use of EPS flood forecasts. Drawing on interviews and other research with operational flood forecasters from across Europe, this paper highlights a number of challenges to communicating and using ensemble flood forecasts operationally. It is shown that operational flood forecasters understand the skill, operational limitations, and informational value of EPS products in a variety of different and sometimes contradictory ways. Despite the efforts of forecasting agencies to design effective ways to communicate EPS forecasts to non-experts, operational flood forecasters were often skeptical about the ability of forecast recipients to understand or use them appropriately. It is argued that better training and closer contacts between operational flood forecasters and EPS system designers can help ensure the uncertainty represented by EPS forecasts is represented in ways that are most appropriate and meaningful for their intended consumers, but some fundamental political and institutional challenges to using ensembles, such as differing attitudes to false alarms and to responsibility for management of blame in the event of poor or mistaken forecasts are also highlighted. Copyright © 2010 Royal Meteorological Society

Michaels, S. (2014). Probabilistic Forecasting and the Reshaping of Flood Risk Management. Journal of Natural Resources Policy Research, 7(1), 41-51 https://doi.org/10.1080/19390459.2014.970800

Advances in probabilistic forecasting, notably based on ensemble prediction systems, are transforming flood risk management. Four trends shaping the assimilation of probabilistic flood forecasting into flood risk management are longer forecasting lead times, advances in decision-making aids, inclusion of probabilistic forecasting in hazard mitigation and collaboration between researchers and managers. Confronting how to use probabilistic flood forecasts to make binary management decisions for reducing flood losses requires developing institutional capacity while acknowledging flood risk estimation is one component of decision making under uncertainty in an evolving policy landscape.

Pagano, T. C., Wood, A. W., Ramos, M. H., Cloke, H. L., Pappenberger, F., Clark, M. P., . . . Verkade, J. S. (2014). Challenges of Operational River Forecasting. Journal of Hydrometeorology, 15(4), 1692-1707 https://doi.org/10.1175/jhm-d-13-0188.1

Skillful and timely streamflow forecasts are critically important to water managers and emergency protection services. To provide these forecasts, hydrologists must predict the behavior of complex coupled human–natural systems using incomplete and uncertain information and imperfect models. Moreover, operational predictions often integrate anecdotal information and unmodeled factors. Forecasting agencies face four key challenges: 1) making the most of available data, 2) making accurate predictions using models, 3) turning hydrometeorological forecasts into effective warnings, and 4) administering an operational service. Each challenge presents a variety of research opportunities, including the development of automated quality-control algorithms for the myriad of data used in operational streamflow forecasts, data assimilation, and ensemble forecasting techniques that allow for forecaster input, methods for using human generated weather forecasts quantitatively, and quantification of human interference in the hydrologic cycle. Furthermore, much can be done to improve the communication of probabilistic forecasts and to design a forecasting paradigm that effectively combines increasingly sophisticated forecasting technology with subjective forecaster expertise. These areas are described in detail to share a real-world perspective and focus for ongoing research endeavors.

Ramos, M. H., Mathevet, T., Thielen, J., & Pappenberger, F. (2010). Communicating Uncertainty in Hydro-Meteorological Forecasts: Mission Impossible? Meteorological Applications, 17(2), 223-235 https://doi.org/10.1002/met.202

There is a common agreement in the scientific community that communicating uncertain hydrometeorological forecasts to water managers, civil protection authorities and other stakeholders is far from being a resolved issue. This paper focuses on the communication of uncertain hydrological forecasts to decision-makers such as operational hydrologists and water managers in charge of flood warning and scenario-based reservoir operation. Results from case studies conducted together with flood forecasting experts in Europe and operational forecasters from the hydroelectric sector in France are presented. They illustrate some key issues on dealing with probabilistic hydro-meteorological forecasts and communicating uncertainty in operational flood forecasting.

v. Short Term Forecast

Demuth, J. L., Morrow, B. H., & Lazo, J. K. (2009). Weather Forecast Uncertainty Information an Exploratory Study with Broadcast Meteorologists. Bulletin of the American Meteorological Society, 90(11), 1614-1618 https://doi.org/10.1175/2009bams2787.1

There is significant interest in the meteorological community about the effective provision and use of weather forecast uncertainty information. Recent evidence of this includes the 2006 National Research Council "Completing the Forecast" report, the AMS Ad-Hoc Committee on Uncertainty in Forecasts, and the 2008 updated AMS statement on probability forecasts. However, limited empirical information exists about the provision and use of weather forecast information in general, and even less is known specifically about forecast uncertainty information. Some work has begun to tackle the important knowledge gaps that exist, but much is yet to be learned.

Du, J., & Chen, J. (2010). Necessity of Communicating Uncertainty in Weather Forecasts in View of Public Criticism. Meteorological Monthly, 36(1), 1-7 Retrieved from https://search.proquest.com/docview/745722070?accountid=28258

An example of public criticism about the accuracy of TV weather forecasting was represented and analyzed. What can meteorologists learn from it to better serve public and end-users on a solid scientific basis? Given the chaotic nature of atmospheric system and imperfect observations and numerical models, it is scientifically impossible to predict the weather in 100% accuracy. How to evaluate weather forecasts is also problematic and confusing in many ways. Reform is needed in both the ways of producing and providing weather forecast information. A forecast without explicitly describing quantitative uncertainty information is incomplete. Inclusion of forecast uncertainty can, instead, maximize the economical value of a forecast and satisfy the needs for a wider range of users. It is time to quantitatively communicate forecast uncertainty to weather, climate, water and any kind of environmental prediction. Training and education to forecasters, end-users and public is the key to the success of this revolutionary transition from a deterministic to a stochastic point of view about weather forecasting.

Gneiting, T. (2008). Editorial: Probabilistic Forecasting. Journal of the Royal Statistical Society: Series A (Statistics in Society), 171(2), 319-321 https://doi.org/10.1111/j.1467-985x.2007.00522.x

A major human desire is to make forecasts for an uncertain future. Consequently, forecasts ought to be probabilistic in nature, taking the form of probability distributions over future quantities or events (Dawid, 1984). Traditionally, probabilistic forecasts have been issued almost exclusively for binary events, stating, for example, that there is a 70% chance of rain tomorrow. It is only now that probabilistic forecasts for more general types of events, involving multicategory or continuous variables, time trajectories and spatial or spatiotemporal fields, are in high demand, with applications including weather and climate prediction (Palmer, 2002; Collins and Knight, 2007), hydrologic forecasting (Krzysztofowicz, 2001), economic and financial risk management (Timmermann, 2000) and demographic and epidemiological projections (Lutz et al., 2002; Alkema et al., 2007).

Murphy, A. H. (1991). Probabilities, Odds, and Forecasts of Rare Events. Weather and Forecasting, 6(2), 302-307 https://doi.org/10.1175/1520-0434(1991)006<0302:Poafor>2.0.Co;2

Several issues related to the mode of expression of forecasts of rare and severe events (RSEs) are addressed in this paper. These issues include the correspondence between forecasters' judgments and their forecasts, the problem of overforecasting, and the use of forecasts as a basis for rational decision making. Neither forecasters nor users are well served by current practices, according to which operational forecasts of RSEs are generally expressed in a categorical format.

It is argued here that sound scientific and economic reasons exist for expressing forecasts of RSEs in terms of probabilities. Although quantification of uncertainty in forecasts of RSEs-and the communication of such information to users-presents some special problems, evidence accumulated from a multitude of operational and experimental probabilistic weather forecasting programs suggests that these problems involve no insurmountable difficulties. Moreover, when a probabilistic format is employed, forecasts of RSEs can correspond to forecasters' true judgments, the forecasting and decision-making tasks can be disentangled, the rationale for overforecasting RSEs is eliminated, and the needs of all users can be met in an optimal manner.

Since the probabilities of RSEs seldom achieve high values, it might be desirable to provide users with information concerning the likelihood of such events relative to their climatological likelihood. Alternatively, the relative odds-that is, the ratio of an event's forecast odds to its climatological odds-could be reported. This supplemental information should help to focus users' attention on those occasions on which the probability of RSEs is relatively high.

Novak, D. R., Bright, D. R., & Brennan, M. J. (2008). Operational Forecaster Uncertainty Needs and Future Roles. Weather and Forecasting, 23(6), 1069-1084 https://doi.org/10.1175/2008waf2222142.1

Key results of a comprehensive survey of U.S. National Weather Service operational forecast managers concerning the assessment and communication of forecast uncertainty are presented and discussed. The survey results revealed that forecasters are using uncertainty guidance to assess uncertainty, but that limited data access and ensemble underdispersion and biases are barriers to more effective use.

Some respondents expressed skepticism as to the added value of formal ensemble guidance relative to simpler approaches of estimating uncertainty, and related the desire for feature-specific ensemble verification to address this skepticism. Respondents reported receiving requests for uncertainty information primarily from sophisticated users such as emergency managers, and most often during high-impact events. The largest request for additional training material called for simulator-based case studies that demonstrate how uncertainty information should be interpreted and communicated. Respondents were in consensus that forecasters should be significantly involved in the communication of uncertainty forecasts; however, there was disagreement regarding if and how forecasters should adjust objective ensemble guidance. It is contended that whether forecasters directly modify objective ensemble guidance will ultimately depend on how the weather enterprise views ensemble output (as the final forecast or as a guidance supporting conceptual understanding), the enterprise's commitment to provide the necessary supporting forecast infrastructure, and how rapidly ensemble weaknesses such as underdispersion, biases, and resolution are addressed. The survey results illustrate that forecasters' operational uncertainty needs are intimately tied to the end products and services they produce. Thus, it is critical that the process to develop uncertainty information in existing or new products or services be a sustained collaborative effort between ensemble developers, forecasters, academic partners, and users. As the weather enterprise strives to provide uncertainty information to users, it is asserted that addressing the forecaster needs identified in this survey will be a prerequisite to achieve this goal.

Raftery, A. E. (2016). Use and Communication of Probabilistic Forecasts. Stat Anal Data Min, 9(6), 397-410 https://doi.org/10.1002/sam.11302

Probabilistic forecasts are becoming more and more available. How should they be used and communicated? What are the obstacles to their use in practice? I review experience with five problems where probabilistic forecasting played an important role. This leads me to identify five types of potential users: Low Stakes Users, who don't need probabilistic forecasts; General Assessors, who need an overall idea of the uncertainty in the forecast; Change Assessors, who need to know if a change is out of line with expectations; Risk Avoiders, who wish to limit the risk of an adverse outcome; and Decision Theorists, who quantify their loss function and perform the decision-theoretic calculations. This suggests that it is important to interact with users and to consider their goals. The cognitive research tells us that calibration is important for trust in probability forecasts, and that it is important to match the verbal expression with the task. The cognitive load should be minimized, reducing the probabilistic forecast to a single percentile if appropriate. Probabilities of adverse events and percentiles of the predictive distribution of quantities of interest seem often to be the best way to summarize probabilistic forecasts. Formal decision theory has an important role, but in a limited range of applications.

vi. Long Term Forecast

Kumar, A., & Murtugudde, R. (2013). Predictability, Uncertainty and Decision Making: A Unified Perspective to Build a Bridge from Weather to Climate. Current Opinion in Environmental Sustainability, 5(3-4), 327-333 https://doi.org/10.1016/j.cosust.2013.05.009

In this essay, the common thread of limits of predictability and uncertainty that permeate across weather and climate prediction and projections is discussed in the context of developing a strategy for 'seamless' communication and utilization of uncertain information in decision making. In understanding why uncertainty is an unavoidable trait of predictions in the first place, a useful concept is the

separation of the Earth System (ES) into internal and external components. This separation allows one to first, recognize that for prediction at all time-scales, the inherent source for limits on predictability is due to the divergence of forecasts from a cloud of initial conditions, and second, thereby recognize that the fundamental source of uncertainty (or unpredictability) is limited by our ability to specify initial conditions for the internal component with perfect accuracy. The unavoidability of uncertainty in predictions, and accepting this fact could be advantageous in the ongoing discussions on how to communicate climate projections and the associated uncertainties by learning from the knowledge base that exists for communicating similar information on weather and seasonal predictions that are generated on a much more frequent basis. Similarly, decision-support systems for developing adaptation and mitigation strategies can use predictions on shorter range as a test-bed to hone their strategies to incorporate predictive uncertainty when dealing with longer-range projections. By practicing the use of decision making tools and the incorporation of uncertain predictions on weather and seasonal time scale, decision makers can improve their level of comfort in accepting uncertainty inherent in longer range predictions and projections on a much less infrequent basis. In this paradigm, evolving strategy for seamless predictions can be blended with a strategy for seamless communication of uncertain information and also with seamless application of decision support systems.

Parker, W. S. (2010). Predicting Weather and Climate: Uncertainty, Ensembles and Probability. Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics, 41(3), 263-272 https://doi.org/https://doi.org/10.1016/j.shpsb.2010.07.006

Simulation-based weather and climate prediction now involves the use of methods that reflect a deep concern with uncertainty. These methods, known as ensemble prediction methods, produce multiple simulations for predictive periods of interest, using different initial conditions, parameter values and/or model structures. This paper provides a non-technical overview of current ensemble methods and considers how the results of studies employing these methods should be interpreted, paying special attention to probabilistic interpretations. A key conclusion is that, while complicated inductive arguments might be given for the trustworthiness of probabilistic weather forecasts obtained from ensemble studies, analogous arguments are out of reach in the case of long-term climate prediction. In light of this, the paper considers how predictive uncertainty should be conveyed to decision makers.

Section V: Lessons from Non-Weather

Bean, H., Liu, B. F., Madden, S., Sutton, J., Wood, M. M., & Mileti, D. S. (2016). Disaster Warnings in Your Pocket: How Audiences Interpret Mobile Alerts for an Unfamiliar Hazard. Journal of Contingencies and Crisis Management, 24(3), 136-147 https://doi.org/10.1111/1468-5973.12108

This study investigates how people interpret Wireless Emergency Alerts (WEAs) and Twitter-length messages (tweets') delivered over mobile devices for an unfamiliar hazard. Specifically, through four (N=31) focus groups and 31 think-out-loud interviews, participants' understanding of, belief in and personalisation of WEAs and tweets were assessed for a mock improvised nuclear device detonation in a major U.S. metropolitan area. While participants offered a wide variety of interpretations, WEAs and tweets were often deemed confusing, difficult to believe and impersonal. Participants also consistently found WEAs and tweets to be fear inducing and uninformative. The findings compel improvements in

the way that WEAs and tweets are currently written, as well as indicate future directions for applied risk and crisis communication theory development.

Doyle, E. E. H., McClure, J., Paton, D., & Johnston, D. M. (2014). Uncertainty and Decision Making: Volcanic Crisis Scenarios. International Journal of Disaster Risk Reduction, 10, 75-101 https://doi.org/10.1016/j.ijdrr.2014.07.006

The impact of uncertainty on Disaster Risk Reduction decision-making has become a pressing issue for debate over recent years. How do key officials interpret and accommodate uncertainty in science advice, forecasts and warnings into their decision making? Volcanic eruptions present a particularly uncertain hazard environment, and to accommodate this scientists utilize probabilistic techniques to inform decision-making. However, the interpretation of probabilities is influenced by their framing. We investigate how verbal or numerical probabilities affect decisions to evacuate a hypothetical town, and reasons given for that decision, based upon a volcanic eruption forecast. We find fewer evacuations for verbal terms than for equivalent numerical terms, and that the former is viewed as more ambiguous. This difference is greater for scientists, which we suggest is due to their greater familiarity with numerical probabilities and a belief that they are more certain. We also find that many participants have a poor understanding of the relationship between probability and time window stated, resulting in an incorrect assessment of overall likelihood and more evacuations for the lower likelihood version of two scenarios. Further, we find that career sector (scientist or non-scientist) influences evacuation decisions, with scientists tending to reduce the uncertainty by focusing on the quality and volume of information provided, while non-scientists tended to either acknowledge or suppress the uncertainty, focusing on actions to take. These findings demonstrate the importance of identifying communication strategies that mitigate different perceptions of forecasts, to both enhance end-user decision making and to prevent premature, delayed, or unnecessary actions.

Mileti, D. S., & Darlington, J. D. (1997). The Role of Searching in Shaping Reactions to Earthquake Risk Information. Social Problems, 44(1), 89-103 https://doi.org/10.1525/sp.1997.44.1.03x0214f

We assessed public response to an earthquake prediction for the San Francisco, Bay Area on a sample of households from eight Bay Area counties. Descriptive findings suggested that an earthquake culture exists in the study population. We tested criticisms of interactionist theory - its failure to take motives for behavior and social position into account - using multiple regression analysis. We conclude that motives and social position matter little in determining social action, and that more work is needed to determine how variations in new information create ambiguity, which differentially fosters searching, the formation of alternative definitions, and subsequent action.

Mulder, K. J., Lickiss, M., Harvey, N., Black, A., Charlton-Perez, A., Dacre, H., & McCloy, R. (2017). Visualizing Volcanic Ash Forecasts: Scientist and Stakeholder Decisions Using Different Graphical Representations and Conflicting Forecasts. Weather, Climate, and Society, 9(3), 333-348 https://doi.org/10.1175/WCAS-D-16-0062.1

During volcanic eruptions, Volcanic Ash Advisory Centres issue ash advisories for aviation showing the forecasted outermost extent of the ash cloud. During the 2010 Icelandic volcano Eyjafjallajökull eruption, the Met Office produced supplementary forecasts of quantitative ash concentration, due to

demand from airlines. Additionally, satellite retrievals of estimated volcanic ash concentration are now available. To test how these additional graphical representations of volcanic ash affect flight decisions, whether users infer uncertainty in graphical forecasts of volcanic ash, and how decisions are made when given conflicting forecasts, a survey was conducted of 25 delegates representing U.K. research and airline operations dealing with volcanic ash. Respondents were more risk seeking with safer flight paths and risk averse with riskier flight paths when given location and concentration forecasts compared to when given only the outermost extent of the ash. Respondents representing operations were more risk seeking than respondents representing research. Additionally, most respondents' hand-drawn no-fly zones were larger than the areas of unsafe ash concentrations in the forecasts. This conservatism implies that respondents inferred uncertainty from the volcanic ash concentration forecasts. When given conflicting forecasts, respondents became more conservative than when given a single forecast. The respondents were also more risk seeking with high-risk flight paths and more risk averse with low-risk flight paths when given conflicting forecasts than when given a single forecast. The results show that concentration forecasts seem to reduce flight cancellations while maintaining safety. Open discussions with the respondents suggested that definitions of uncertainty may differ between research and operations.

Section VI: Further Reading

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

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

Doyle, E. E. H., Johnston, D. M., Smith, R., & Paton, D. (2019). Communicating Model Uncertainty for Natural Hazards: A Qualitative Systematic Thematic Review. International Journal of Disaster Risk Reduction, 33, 449-476 https://doi.org/10.1016/j.ijdrr.2018.10.023

Natural hazard models are vital for all phases of risk assessment and disaster management. However, the high number of uncertainties inherent to these models is highly challenging for crisis communication. The noncommunication of these is problematic as interdependencies between them, especially for multi-model approaches and cascading hazards, can result in much larger deep

uncertainties. The recent upsurge in research into uncertainty communication makes it important to identify key lessons, areas for future development, and areas for future research. We present a systematic thematic literature review to identify methods for effective communication of model uncertainty. Themes identified include a) the need for clear uncertainty typologies, b) the need for effective engagement with users to identify which uncertainties to focus on, c) managing ensembles, confidence, bias, consensus and dissensus, d) methods for communicating specific uncertainties (e.g., maps, graphs, and time), and e) the lack of evaluation of many approaches currently in use. Finally, we identify lessons and areas for future investigation, and propose a framework to manage the communication of model related uncertainty with decision-makers, by integrating typology components that help identify and prioritise uncertainties. We conclude that scientists must first understand decision-maker needs, and then concentrate efforts on evaluating and communicating the decision-relevant uncertainties. Developing a shared uncertainty management scheme with users facilitates the management of different epistemological perspectives, accommodates the different values that underpin model assumptions and the judgements they prompt, and increases uncertainty tolerance. This is vital, as uncertainties will only increase as our model (and event) complexities increase.

Morss, R. E., Lazo, J. K., Brown, B. G., Brooks, H. E., Ganderton, P. T., & Mills, B. N. (2008). Societal and Economic Research and Applications for Weather Forecasts - Priorities for the North American Thorpex Program. Bulletin of the American Meteorological Society, 89(3), 335-346 https://doi.org/10.1175/bams-89-3-335

Despite the meteorological community's long-term interest in weather-society interactions, efforts to understand socioeconomic aspects of weather prediction and to incorporate this knowledge into the weather prediction system have yet to reach critical mass. This article aims to reinvigorate interest in societal and economic research and applications (SERA) activities within the meteorological and social science communities by exploring key SERA issues and proposing SERA priorities for the next decade. The priorities were developed by the authors, building on previous work, with input from a diverse group of social scientists and meteorologists who participated in a SERA workshop in August 2006. The workshop was organized to provide input to the North American regional component of THORPEX: A Global Atmospheric Research Programme, but the priorities identified are broadly applicable to all weather forecast research and applications.
To motivate and frame SERA activities, we first discuss the concept of high-impact weather forecasts and the chain from forecast creation to value realization. Next, we present five interconnected SERA priority themes—use of forecast information in decision making, communication of forecast uncertainty, user-relevant verification, economic value of forecasts, and decision support— and propose research integrated across the themes.
SERA activities can significantly improve understanding of weather-society interactions to the benefit of the meteorological community and society. However, reaching this potential will require dedicated effort to bring together and maintain a sustainable interdisciplinary community.

National Research Council. (2003). Communicating Uncertainties in Weather and Climate Information: A Workshop Summary. Washington, DC: National Academy Press. https://doi.org/10.17226/10597

When a major East Coast snowstorm was forecast during the winter of 2001, people began preparing--both the public and the decision makers responsible for public services. There was an air of urgency, heightened because just the previous year the region had been hit hard by a storm of unpredicted

strength. But this time the storm never materialized for the major metropolitan areas of the mid-Atlantic. The missing storm of 2001 left many people wondering what went wrong with the weather forecast. But did anything go wrong or did forecasters just fail to communicate their information in an effective way--a way that conveyed some real sense of the likelihood of the event and kept people up to date as information changed? There is uncertainty in all forecasts, and weather and climate forecasts are no exception. Traditional weather forecasting uses numerical models and statistical techniques to project likely future scenarios, and these techniques have some level of definable errors. Newer forecasting techniques use more sophisticated ensemble methods that provide a more quantitative measure of uncertainty under certain conditions.

National Research Council. (2006). Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts. Washington, DC: The National Academies Press. https://doi.org/10.17226/11699

All prediction is inherently uncertain and effective communication of uncertainty information in weather, seasonal climate, and hydrological forecasts benefits users' decisions (e.g., AMS, 2002; NRC, 2003b). The chaotic character of the atmosphere, coupled with inevitable inadequacies in observations and computer models, results in forecasts that always contain uncertainties. These uncertainties generally increase with forecast lead time and vary with weather situation and location. Uncertainty is thus a fundamental characteristic of weather, seasonal climate, and hydrological prediction, and no forecast is complete without a description of its uncertainty.

Robbins, J., Cunningham, C., Dankers, R., DeGennaro, M., Dolif, G., Duell, R., . . . Watkins, A. (2019). Chapter 19 - Communication and Dissemination of Forecasts and Engaging User Communities. In Sub-Seasonal to Seasonal Prediction. A. W. Robertson & F. Vitart (Eds.), (pp. 399-419): Elsevier https://doi.org/https://doi.org/10.1016/B978-0-12-811714-9.00019-X

The value of weather and climate information, at any timescale, is a function of the availability, comprehensibility, and usability of the information so that decisions and actions can be taken in response to uncertain future events. The uncertainties and available skill of sub-seasonal to seasonal (S2S) forecasts have the potential to make communication and dissemination of these forecasts more challenging, particularly in scenarios where decisions are critical to life and well-being or have significant economic impact on the users. Engagement with user communities, therefore, is essential to ensure that these forecasts provide their anticipated value and to prevent misconceptions or disparities between user expectations and the available science. This chapter describes the current state of the literature on S2S application in a range of sectors (agriculture, energy and water, disaster risk reduction (DRR), and health) and the readily available public products and services. Gaps and trends in current S2S application research are identified, and descriptions of best practice examples are synthesized to provide a set of guiding principles for S2S forecast communication, dissemination, and user engagement.

Rothfusz, L. P., Schneider, R., Novak, D., Klockow-McClain, K., Gerard, A. E., Karstens, C., . . . Smith, T. M. (2018). Facets a Proposed Next-Generation Paradigm for High-Impact Weather Forecasting. Bulletin of the American Meteorological Society, 99(10), 2025-2043 https://doi.org/10.1175/bams-d-16-0100.1

Recommendations by the National Research Council (NRC), the National Institute of Standards and Technology (NIST), and Weather-Ready Nation workshop participants have encouraged the National Oceanic and Atmospheric Administration (NOAA) and the broader weather enterprise to explore and expand the use of probabilistic information to convey weather forecast uncertainty. Forecasting a Continuum of Environmental Threats (FACETs) is a concept being explored by NOAA to address those recommendations and also potentially shift the National Weather Service (NWS) from (primarily) teletype-era, deterministic watch–warning products to high-resolution, probabilistic hazard information (PHI) spanning periods from days (and longer) to within minutes of high-impact weather and water events. FACETs simultaneously i) considers a reinvention of the NWS hazard forecasting and communication paradigm so as to deliver multiscale, user-specific probabilistic guidance from numerical weather prediction ensembles and ii) provides a comprehensive framework to organize the physical, social, and behavioral sciences, the technology, and the practices needed to achieve that reinvention. The first applications of FACETs have focused on thunderstorm phenomena, but the FACETs concept is envisioned to extend to the attributes of any environmental hazards that can be described probabilistically (e.g., winter, tropical, and aviation weather). This paper introduces the FACETs vision, the motivation for its creation, the research and development under way to explore that vision, its relevance to operational forecasting and society, and possible strategies for implementation.

Spiegelhalter, D., Pearson, M., & Short, I. (2011). Visualizing Uncertainty About the Future. Science, 333(6048), 1393-1400 https://doi.org/10.1126/science.1191181

We are all faced with uncertainty about the future, but we can get the measure of some uncertainties in terms of probabilities. Probabilities are notoriously difficult to communicate effectively to lay audiences, and in this review we examine current practice for communicating uncertainties visually, using examples drawn from sport, weather, climate, health, economics, and politics. Despite the burgeoning interest in infographics, there is limited experimental evidence on how different types of visualizations are processed and understood, although the effectiveness of some graphics clearly depends on the relative numeracy of an audience. Fortunately, it is increasingly easy to present data in the form of interactive visualizations and in multiple types of representation that can be adjusted to user needs and capabilities. Nonetheless, communicating deeper uncertainties resulting from incomplete or disputed knowledge-or from essential indeterminacy about the future-remains a challenge.