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Forecasting Natural Disasters

The Economics of Natural Disasters: Moving from Risk Assessment to Risk Reduction

Abstract

A significant focus of natural disaster research is aimed at improving the science, or the hazard assessment of natural disaster risk. For example, improving the skill of short-term extreme weather or long-term climate forecasts, or enhancing the hazard and/or vulnerability component of natural disaster catastrophe models. This aim implicitly assumes a user of this information will fully understand the scientific data and incorporate this into making well-informed rational decisions based on a systematic analysis of the tradeoffs between benefits and costs. Or given the enhanced scientific aspects of a catastrophe model, losses will be able to be better predicted and ultimately managed lower. Unfortunately, while hazard assessments have improved, many forms of losses from natural disasters have increased over time with innumerable instances of inadequate investments in loss reduction measures and poor-decision making being experienced pre and post events.

An increasing body of research provides empirical evidence of individuals exhibiting systematic biases and using simplified decision rules when making choices with respect to low probability/high impact events such as natural disasters. It is found that how the scientific information is framed and presented can influence choices, so the way that natural disaster risk is communicated will have an enormous impact on the static and dynamic actions undertaken by individuals and organizations in the public and private sectors under the threat of this risk. Further, little of this behavioral-based knowledge has been incorporated into natural disaster risk assessment including catastrophe modeling. Natural disaster losses may therefore be reduced by employing appropriate economic incentives and risk management strategies that utilize this behavioral-based knowledge.

"Experience has shown that a purely technical assessment of risk, however sophisticated and cutting-edge, is by itself unlikely to trigger actions that reduce risk. Successful risk assessments produce information that is targeted, authoritative, understandable, and usable." *(UNISDR, 2015 pg.148)*

Introduction

Recent decades have seen significant progress in not only observing and understanding the weather, but also in the ability to provide more skillful and accurate forecasts (NRC, 2010; Hirschberg et al., 2011). This is congruently true for a number of extreme weather events such as hurricanes as evidenced by the National Hurricane Center's reduced annual average track forecast errors from 1970 to 2014 (Figure 1). For example, the 72 hour track forecast error has improved from nearly 450 nautical miles on average in 1970 (least squares trend line) down to less than 100 nautical miles in 2014. And these forecast improvements have been credited with a number of associated benefits including a substantial reduction in the number of direct fatalities stemming from these events such as reduced U.S. hurricane fatality risk due to improved evacuation (Rappaport, 2000 & 2014; Gladwin et al., 2007). Likewise, the significant improvements in the science and modeling of these extreme weather hazards (see Lin et al., 2012 for an example of storm surge modeling) have led to the proliferation of the use of catastrophe models for natural hazard risk assessment since the early 1990s by the insurance industry, and ultimately the broad implementation of various associated natural hazard risk transfer mechanisms including reinsurance and capital markets (Grossi and Kunreuther, 2005). These risk transfer mechanisms have allowed for the relatively uneventful absorption of natural hazard economic losses by the insurance industry in recent years.

Despite these benefits of improved extreme weather scientific risk assessment, a number of concerning elements persist in regard to overall natural hazard risk reduction. Firstly, the evidence suggests an upward trend over time in economic losses from various types of natural disasters worldwide (Figure 2), increasing steadily to an estimated annual average loss approaching $300 billion (UNISDR, 2015). This is coupled with continued population and exposure growth in high hazard areas

(UNSIDR, 2013; UNISDR 2015) leading to at the least more people being affected by natural disasters, interdependencies in economic and social systems that increase vulnerability to disruptions, and potentially exacerbated hazard risks stemming from climate change impacts (UNISDR, 2015). Moreover, many of the reduced mortality benefits have been limited to select developed countries[1] (UNISDR, 2015) and much of the non-insured and non-direct property losses including indirect losses and recovery are difficult to quantify and hence thought to be substantially underestimated (UNISDR, 2015). Finally, even in a relatively sophisticated natural disaster risk management landscape like the U.S. there have been innumerable instances of inadequate investments in loss reduction measures in natural hazard contexts such as with Hurricane Katrina 2005 and Hurricane Sandy 2012, as well as poor decision making, for example with the 2013 Oklahoma City tornado where residents should have sheltered in place but were advised to evacuate south in their cars by a local meteorologist. In other words, if the goal is to better manage natural hazards to ultimately reduce losses, there is a need to move beyond a primary focus on accurate hazard science in and of itself.

In this paper we outline frontiers in how the traditional natural hazard forecast risk space may better transition from risk assessment to risk reduction. Illustrative examples show how a traditional natural hazard forecast risk space may be placed into a broader overview of event risk in time, importantly including behavioral implications of intertemporal decision-making. We further describe an economic model of decision-making in this risk space highlighting the potential sources of bias as have been found in recent research.

Defining the Natural Hazard Forecast Risk Space

Natural hazard risk is defined as the probability of a natural hazard event occurrence combined with the expected impact of the event should it occur (Kunreuther and Useem, 2010). Thus, the concept of natural hazard risk has two key components, hazard probability and impact, each of which has an

[1] It is often the inability to forecast disasters in advance and provide early warnings in developing countries that is a root cause of this

element of uncertainty associated with it. Geoff Love and Michel Jarraud of the World Meteorological Organization provide a schematic of this natural hazard risk space (Figure 3) with the probability of the hazard on the y-axis and the impact on the x-axis (Kunreuther and Useem, 2010). Uncertainty is represented by the shaded region surrounding the three representative risks illustrated.

Quite often, the emphasis for physical scientists in their respective fields working in this natural hazard forecast risk space is on the likelihood of occurrence of the event (y-axis) such as the return period for a flood event. As an illustrative example of this predisposition, of the National Oceanic and Atmospheric Administration's 2008 budget of $4 billion, only 0.6 percent of this is directed toward social science activities (NRC, 2010), or what would be more likely focused on the impact side of the risk. Likewise, in a catastrophe modeling framework of combined hazard, exposure and vulnerability components leading to loss (Grossi and Kunreuther, 2005), a heavy emphasis is typically placed on the hazard component of the framework despite differences in the other components potentially making large differences in losses and hence the overall risk. For example, a Risk Management Solutions study found that loss estimates could change by a factor of 4 when property exposure data gaps were filled or inaccurate information was corrected (RMS, 2008). Furthermore, catastrophe models focus primarily on the built environment, but hazards also create losses in the natural environment (Alliance Development Works, 2012).

Given the state of existing natural hazard losses already described, there is a clear need for a more developed understanding of the impact side of the natural hazard risk equation (Kunreuther and Useem, 2010) if overall risk reduction is the goal. For example, Botzen et al. (2015) find that in New York City overall flood risk perception is underestimated due to underestimation of the hazard impact component. Truly integrated loss modeling between physical scientists and other disciplines such as the engineering and the social sciences is critical in this regard to better understand the multitude of concurrent factors ultimately driving natural hazard risk (Kunreuther and Useem, 2010; Morss et al., 2011; Tye et al., 2014). Czajkowski and Done (2014) and Czajkowski et al., (2013) provide two examples of this integrated discipline (physical scientists and economists) natural hazard impact-assessment research for hurricane risks in coastal locations and inland flooding from tropical cyclones respectively.[2] The NRC (2010) provides an overview of the literature discussing progress on integrating socioeconomic considerations into weather research including six specific examples of successful programs (NRC, 2010 pgs. 34 and 35). Significantly, following the tornadic event tragedies in 2011 impact-based warnings for tornados (Figure 4) have been implemented by the NWS (NWS, 2015).[3] A better understanding of the notions of uncertainty surrounding these impacts (Hirschberg et al., 2011) is also critical for natural hazard loss reduction in this forecast risk space (Kunreuther and Useem, 2010).

Natural Hazard Forecast Risk Space in Time

While forecasts of natural hazard risks are directly tied to an event, the extent of overall impacts is not isolated in time associated only to the event, but rather tied to a broader view of risk over time in the impacted areas. Herman Leonard and Arnold Howitt of Kennedy School of Government at Harvard provide a time oriented view of events (Figure 5) including the oft-underappreciated stages of pre-event preparation and post-event recovery (Kunreuther and Useem, 2010). While the majority of activity surrounding a natural hazard event is focused on the crisis management based stages of response preparation and the actual response (during and immediately afterward), much of the resulting socio-economic impacts are rooted in the pre-event prevention and mitigation activities as well as the post-event long-term recovery process and pre-event recovery planning. Predominantly focusing risk reduction efforts in a narrow component of the overall timescale such as the event stage will likely not allow for optimal total risk reduction efforts. The ability to expand the timescale of the natural hazard

[2] A number of other recent impact focused assessments for extreme events exist as well such as Chavas et al. (2012); Malmstadt et al. (2009); Mendelsohn et al. (2012); Murnane and Elsner (2012); Murphy and Strobl (2010); Nordhaus (2006, 2010); Schmidt et al. (2009, 2010); Strobl (2011); and Zhai and Jiang (2014) amongst others for hurricanes.

[3] See Harrison et al., (2014) for a report assessment of the impact based tool.

risk-event space to earlier and later stages of the event is thus critical. For example, how would warning messages of potential natural hazard event risk in the relatively distant future affect pre-event preparation activities today (NOAA, 2015)?

Although expanding the timescale of the risk space is essential, interjecting the notion of time is potentially problematic given temporal behavioral biases often exhibited such as underweighting the future through hyperbolic discounting[4] (Kunreuther et al., 2013). For example, while the costs of pre-event preparation and mitigation are immediate and certain, the benefits associated with the action are somewhere in the distant future and uncertain in both time and return. Even if properly discounted benefits accrued over time (i.e., at a constant and appropriate discount rate) would outweigh the upfront costs, individuals would tend to disproportionately discount the future given the aversion for delayed gratification (Kunreuther et al., 2013). A number of other intertemporal behavioral biases (Kunreuther et al., 2013) could likely exist in an expanded risk space timescale preventing optimal level of pre-event mitigation including myopic planning (limited time horizon focused only over the next few years), underestimation of the risk (hazard probability or impact), and affective forecasting errors (poor predictors of future emotional states including anchoring beliefs of future feelings based upon feelings today).[5] Clearly here we begin to highlight the importance of behavioral tendencies of decision making in the natural hazard risk space.

Decision Making in Natural Hazard Risk Space from an Economic Perspective

[4] Hyperbolic discounting rapidly discounts valuations for small time periods and slowly discounts valuations for longer time delays. Exponential discounting on the other hand, discounts by a constant factor per unit delay, regardless of the total length of the delay.

[5] It is also possible that intertemporal bias of duration neglect (Kunreuther et al., 2013) could exist in the post-event recovery phase where there is a tendency to overestimate the time to recover and hence future protection would be overvalued

From a rational economic perspective in the natural hazard risk space, individual decisions at any one point in time are made based upon expected utility theory.[6] For example, when one is deciding to evacuate from a forecasted hurricane (Figure 6) utility (or disutility) would be assigned to each possible future state (landfall hit or miss) given the possible action (stay or evacuate), and where each possible future state is assigned a known probability with all probabilities summing to one. The choice of staying or evacuating would be determined by selecting the action with the highest expected outcome across all possible states, or from Figure 6 choosing to evacuate. Unfortunately, in this natural hazard risk space context this decision-making process can be quite complex (especially over multiple forecast periods)[7] and rarely do those under the warning act rationally in reality. Rather, the combination of systematic biases coupled with simplified decision rules play a primary role leading to choices that differ from what would be predicted by expected utility theory (Kunreuther and Useem, 2010; Kunreuther et al., 2013).

Kahneman (2011) highlights the difference between intuitive and deliberative thinking where he documents the extensive research on intuitive biases that operate in lieu of ideal deliberative decision making and could cause suboptimal choices for low probability-high consequence events such as natural disasters. For example, the availability bias where the likelihood of disaster occurrence is estimated based upon saliency of the event as opposed to objective hazard probabilities. Or, protective action is not undertaken given that the subjective probability of expected impact is below some threshold level

[6] Other social science theories of decision making in a natural hazard context include the psychometric paradigm of psychology (Perception of hazards taking into account qualitative information (i.e. dread) rather than just statistical (i.e. probability)); cultural theory of risk in anthropology (social and cultural influences on risk perception); mental models approach of psychology and risk (individuals have a 'mental model' - model of reality influenced by social interactions and experiences - that they use as a lens to view risky situations); Protection Motivation Theory of psychology (People protect themselves based on their perception of severity, probability, effectiveness of protective action, and self efficacy); and Social Amplification of Risk Framework of geography (risks are amplified or attenuated due to individual, social, and cultural factors). (NOAA, 2015)

[7] Czajkowski (2011) illustrates this decision over time from a dynamic perspective where each forecast period the evacuee has the ability to evacuate or wait for an additional forecast.

of concern. Kunreuther and Useem (2010) discuss a whole host of other behavioral biases found in the research including those associated with group behavior, risk culture, fear and emotions, and trust.[8]

A considerable amount of research has been aimed at what factors drive positive behavior in this context controlling for these behavioral biases. Meyer et al. (2013) uses an experimental environment to better understand risk perception and decision making in a realistic simulated stormview environment, whereas Meyer et al. (2014) interviews over 2000 respondents in real-time under the threat of hurricane strikes during the 2010 to 2012 hurricane seasons. Beatty et al. (2015) use a big data approach in analyzing water bottle sales before and after a hurricane. In their review and assessment on risk communication and behavior, NOAA (2015) points to Mileti et al. (2006), which identifies a number of factors across several categories consistently found to matter in the warning response context including: socio-demographic (female, white, more education, and children present); personal (experience, knowledge of hazard and actions, self-efficacy, fear, risk and vulnerability perception, more resources available, large and strong social network); source/channel (environmental or social cues present, official source, in person, familiar source, multiple sources); information (specific, credible, certain, frequent, consistent, and provides guidance on actions); and threat (less lead time available, greater severity, close, confirmed). Lastly, from a catastrophe model perspective little of this behavioral-based knowledge has been incorporated into natural disaster risk assessment.

Conclusions

Despite significant advances made in recent decades in observing, understanding, and forecasting extreme weather, the impacts and threat from natural disasters remain extensive. We have defined and provided a context for decision-making in the natural disaster risk space where behavioral biases play a significant role. Frontiers in reducing natural disaster risk will necessarily incorporate appropriate

[8] Chapter 4 Cognitive Constraints and Behavioral Biases discusses these in more detail as does Chapter 5 The Five Neglects: Risks Gone Amiss from an expected utility perspective.

economic incentives and risk management strategies that utilize this behavioral-based knowledge. We recommend a few here as an outcome of this overview:

- Develop warning and forecast products that assess and communicate risk from both probability and impact perspective, including the notion of uncertainty.
- Extend the timescale of the risk forecast space into pre-event preparation/mitigation and post-event recovery planning
- Account for the various behavioral biases to have been extensively shown in the socio-economic research literature when designing risk communication tools or incentivizing more proactive preparation/mitigation and/or recovery activities
- Extend catastrophe models to include risk perception and behavior components via agent-based modeling techniques

Figures and Tables

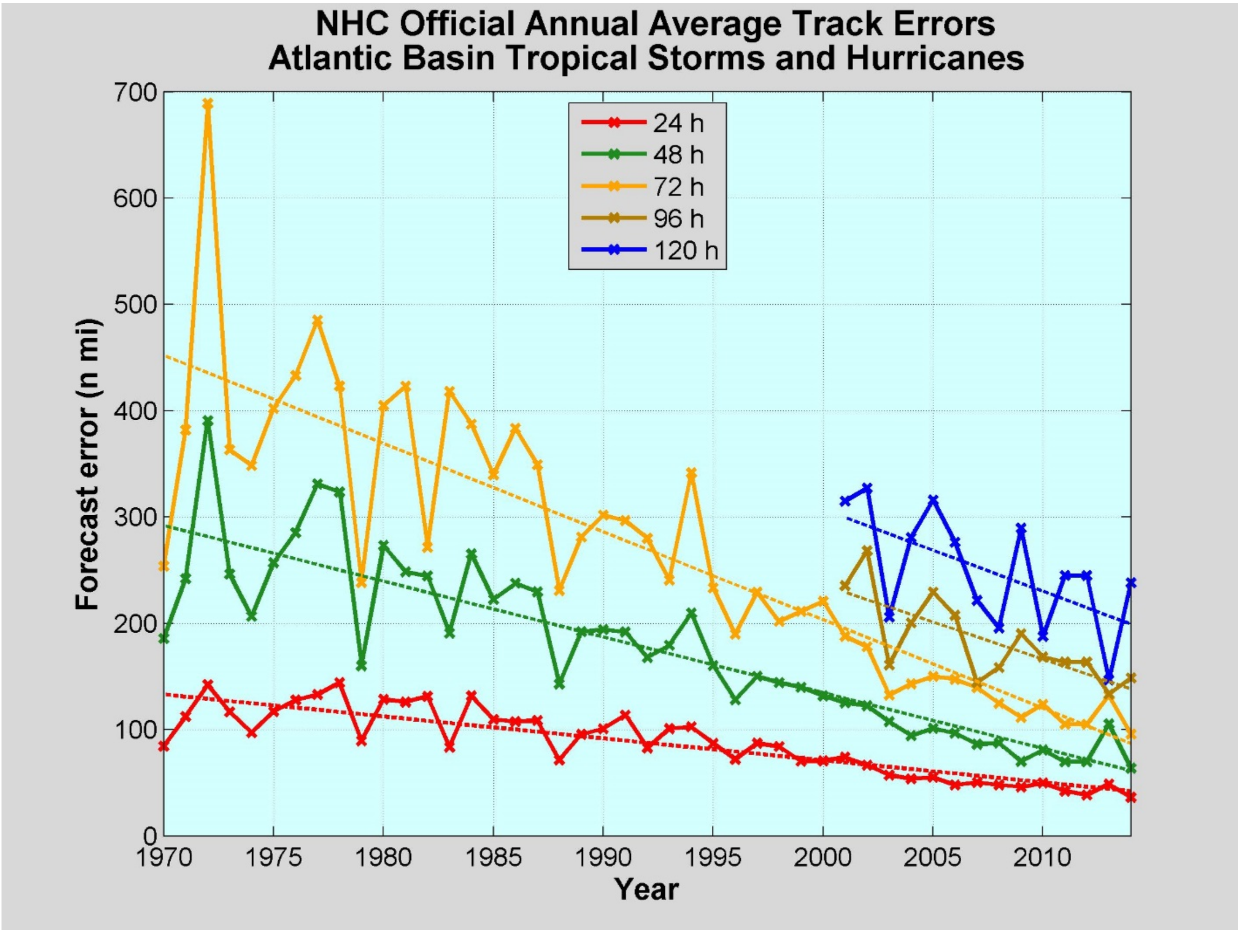

Figure 1. National Hurricane Center aAnnual average official track errors for Atlantic basin tropical storms and hurricanes for the period 1970-2014, with least-squares trend lines superimposed (Source: http://www.nhc.noaa.gov/verification/verify5.shtml)

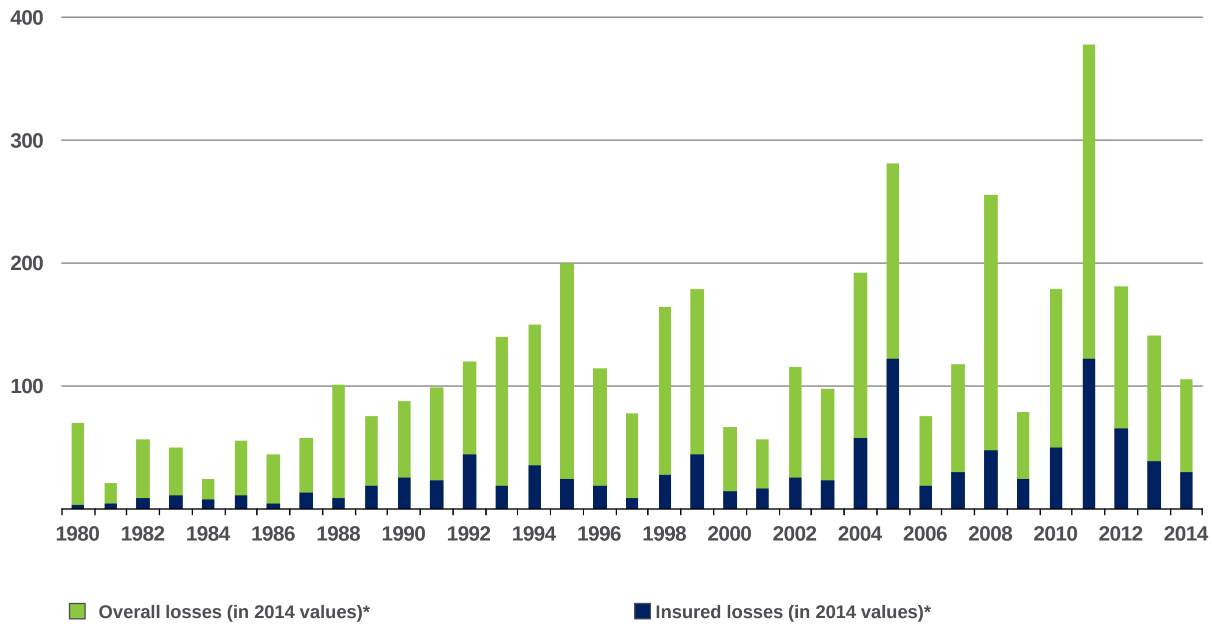

Figure 2. NatCatSERVICE Loss events worldwide 1980 – 2014, Overall and insured losses © 2015 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE – As at January 2015

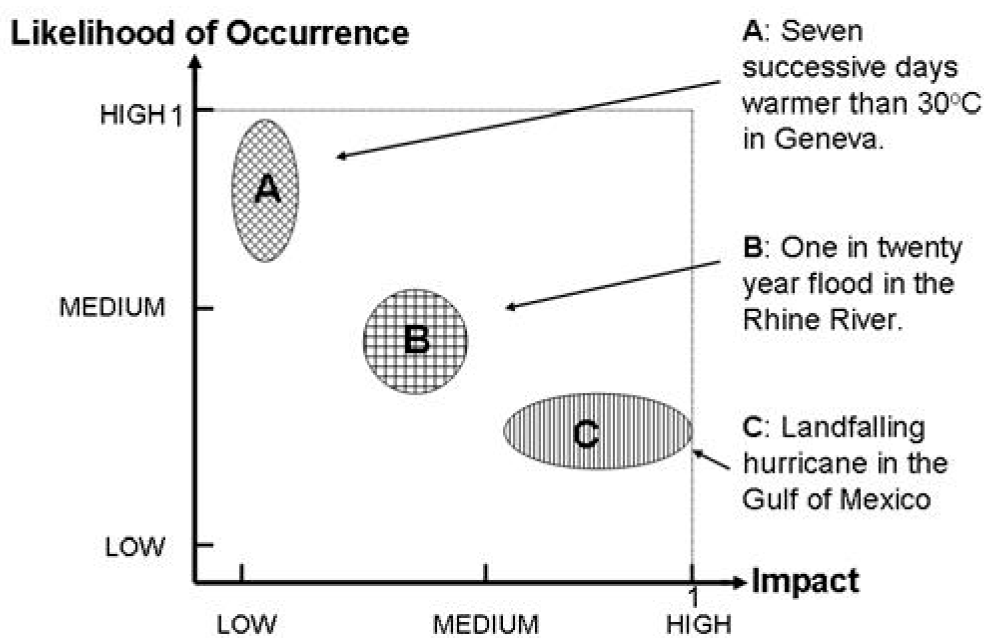

Figure 3. Natural Hazard Forecast Risk Space. Figure 3.1 Sourced from Kunreuther and Useem (2010)

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BULLETIN - EAS ACTIVATION REQUESTED
TORNADO WARNING
NATIONAL WEATHER SERVICE SIOUX FALLS SD
722 PM CDT FRI OCT 4 2013

...TORNADO EMERGENCY FOR WASHTA...

THE NATIONAL WEATHER SERVICE IN SIOUX FALLS HAS ISSUED A

* TORNADO WARNING FOR...
  CHEROKEE COUNTY IN NORTHWEST IOWA...

* UNTIL 800 PM CDT

* AT 720 PM CDT...A LARGE AND EXTREMELY DANGEROUS TORNADO WAS
  LOCATED NEAR WASHTA...AND MOVING NORTHEAST AT 30 MPH.

  THIS IS A TORNADO EMERGENCY FOR WASHTA. TAKE COVER NOW. THIS
  IS A PARTICULARLY DANGEROUS SITUATION.

  THIS IS A PARTICULARLY DANGEROUS SITUATION.

  HAZARD...DAMAGING TORNADO.

  SOURCE...EMERGENCY MANAGEMENT CONFIRMED TORNADO.

  IMPACT...YOU ARE IN A LIFE THREATENING SITUATION. FLYING
           DEBRIS MAY BE DEADLY TO THOSE CAUGHT WITHOUT SHELTER.
           MOBILE HOMES WILL BE DESTROYED. CONSIDERABLE DAMAGE
           TO HOMES...BUSINESSES AND VEHICLES IS LIKELY AND
           COMPLETE DESTRUCTION IS POSSIBLE.

* THE TORNADO WILL BE NEAR...
  QUIMBY AROUND 730 PM CDT.
  CHEROKEE AROUND 745 PM CDT.
  AURELIA AROUND 750 PM CDT.

PRECAUTIONARY/PREPAREDNESS ACTIONS...

HEAVY RAINFALL MAY HIDE THIS TORNADO. DO NOT WAIT TO SEE OR HEAR
THE TORNADO. TAKE COVER NOW.

&&
LAT...LON 4259 9585 4291 9565 4291 9550 4283 9538
      4269 9539 4256 9569 4256 9577
TIME...MOT...LOC 0023Z 225DEG 27KT 4260 9567

TORNADO...OBSERVED
TORNADO DAMAGE THREAT...CATASTROPHIC
HAIL...1.50IN

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Figure 4. NWS Tornado Impact Based Warning Example – Tag: Catastrophic

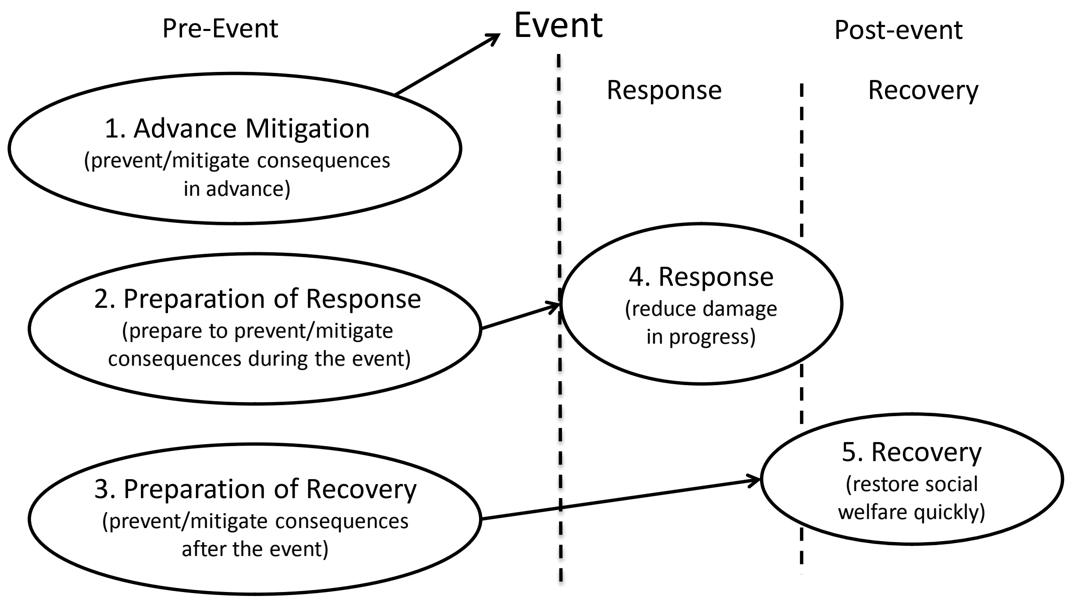

Figure 5. Overall Timeline of Natural Disaster Risk. Figure 2.2 Sourced from Kunreuther and Useem (2010)

Outcome Action	Landfall Strike (P = 0.3)	Landfall Miss (P = 0.7)	Expected Utility
Stay	-2000	0	(0.3 x -2000) + (0.7 x 0) = -600
Evacuate	1500	-500	(0.3 x 1500) + (0.7 x -500) = 100

Figure 6. Evacuation Payoff Matrix. Disutility of staying during a strike would be the expected injuries or mortality; Utility of evacuating for a strike would be the avoided injuries net of cost of evacuation; and the disutility of evacuating when no strike would be the costs of evacuation.

References

Alliance Development Works, 2012, *WorldRiskReport 2012*, Alliance Development Works, 378 United Nations University, and The Nature Conservancy, Berlin, Germany, 69 pp. Available at http://www.nature.org/ourinitiatives/habitats/oceanscoasts/howwework/world-risk-report-2012-pdf.pdf

Beatty, T. K., Shimshack, J. P., & Volpe, R. J. (2015). *Disaster preparedness and disaster response: Evidence from bottled water sales before and after tropical cyclones*. University of Virginia working paper.

Botzen, W., Kunreuther, H., & Michel-Kerjan, E. (2015). *Divergence between Individual Perceptions and Objective Indicators of Tail Risks: Evidence from Floodplain Residents in New York City*. Wharton Risk Center Working Paper.

Chavas, D. R., Yonekura, E., Karamperidou, C., Cavanaugh, N., and K. Serafin (2012). US Hurricanes and economic damage: an extreme value perspective. Nat. Hazards Rev., 10.1061/(ASCE)NH.1527-6996.0000102

Czajkowski, J. (2011). Is it time to go yet? Understanding household hurricane evacuation decisions from a dynamic perspective. *Natural Hazards Review*,*12*(2), 72-84.

Czajkowski, J., Villarini, G., Michel-Kerjan, E., & Smith, J. A. (2013). Determining tropical cyclone inland flooding loss on a large scale through a new flood peak ratio-based methodology. *Environmental Research Letters*, *8*(4), 044056.

Czajkowski, J., & Done, J. (2014). As the wind blows? Understanding hurricane damages at the local level through a case study analysis. *Weather, Climate, and Society*, *6*(2), 202-217.

Gladwin, H., Lazo, J. K., Morrow, B. H., Peacock, W. G., & Willoughby, H. E. (2007). Social science research needs for the hurricane forecast and warning system. *Natural Hazards Review*, *8*(3), 87-95.

Grossi, P., & Kunreuther, H. (2005). *Catastrophe modeling: a new approach to managing risk* (Vol. 25). Springer Science & Business Media.

Harrison, J., McCoy, C., Bunting-Howarth, K., Sorensen, H., Williams, K., Ellis, C., 2014. Evaluation of the National Weather Service Impact-based Warning Tool. WISCU-T-14-001 Report. Available at http://www.seagrant.sunysb.edu/Images/Uploads/PDFs/Hurricanes-NWS-IBW_finalreport.pdf

Hirschberg, P. A., and E. Abrams, Eds., 2011: Weather and climate enterprise strategic implementation plan for generating and communicating forecast uncertainty. Amer. Meteor. Soc. Rep., 99 pp. [Available online at www.ametsoc.org/boardpges/cwce/docs /BEC/ACUF/2011-02-20-ACUF-Final-Report.pdf}

Kahneman, D. (2011). *Thinking, fast and slow*. Macmillan.

Kunreuther, H., Useem, M., (2010) Learning from Catastrophes: Strategies for Reaction and Response (with Michael Useem). Upper SaddleRiver, NJ: Wharton School Publishing

Kunreuther, H., Meyer, R., & Michel-Kerjan, E. (2013). Overcoming decision biases to reduce losses from natural catastrophes. *Behavioral foundations of policy, Princeton University Press, Princeton*, 398-413.

Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke (2012). Physically based assessment of hurricane surge threat under climate change. Nat. Clim. Change 2(6): 462-467. DOI: 10.1038/Nclimate1389.

Malmstadt, J., K. Scheitlin, J. Elsner, 2009: Florida hurricanes and damage costs. Southeastern Geographer, 49, 108–131. Available at: http://fsu.academia.edu/JillMalmstadt/Papers

Mendelsohn, R., Emanuel, K., Chonabayashi, S., and L. Bakkensen 2012: The Impact of Climate Change on Global Tropical Storm Damages. Nature Climate Change 2, 205–209 (2012) doi:10.1038/nclimate1357

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.

Meyer, R. J., Baker, E. J., Broad, K. F., Czajkowski, J., & Orlove, B. (2014). The dynamics of hurricane risk perception: Real-Time Evidence from the 2012 Atlantic Hurricane Season. *American Meteorological Society*.

Mileti, D., Bandy, R., Bourque, L., Johnson, A., Kano, M., Peek, L., Sutton, J., and Wood, M. 2006. Annotated Bibliography for Public Risk Communication on Warnings for Public Protective Action Response and Public Education. Available at http://www.colorado.edu/hazards/publications/informer/infrmr2/pubhazbibann.pdf

Murnane, R. J. and J. B. Elsner (2012), Maximum wind speeds and US hurricane losses, Geophys. Res. Lett., 39, L16707, doi:10.1029/2012GL052740.

Murphy, A., Strobl E., 2010 The Impact of Hurricanes on Housing Prices: Evidence from US Coastal Cities. Federal Reserve Bank of Dallas Research Department Working Paper 1009

Morss RE, Wilhelmi O, Meehl G and Dilling L (2011) Improving societal outcomes of extreme weather in a changing climate: an integrated perspective. Annual Review of Environment and Resources 36(1): 1–25.

National Research Council (NRC). (2010). *When Weather Matters: Science and Service to Meet Critical Societal Needs*. National Academies Press.

NOAA, 2015. Risk Communication and Behavior Assessment: Findings and Recommendations. Internal Report

Nordhaus, W, 2006. The Economics of Hurricanes in the United States. NBER Working Paper 12813, http://www.nber.org/papers/w12813

Nordhaus, W, 2010. The Economics of Hurricanes and Implications of Global Warming. Climate Change Economics. 1:1:1-20

NWS (National Weather Service) 2015. Impact Based Warnings available at http://www.weather.gov/impacts/#.Va_h5flViko accessed July 2015.

Rappaport, E. N. (2000). Loss of life in the United States associated with recent Atlantic tropical cyclones. *Bulletin of the American Meteorological Society*, *81*(9), 2065-2073.

Rappaport, E. N. (2014) Fatalities in the United States from Atlantic Tropical Cyclones: New Data and Interpretation. Bull. Amer. Meteor. Soc., 95, 341–346.RMS, 2008, *A Guide to Catastrophe Modelling*, The Review: Worldwide Insurance, London, 23 pp.

Schmidt, S., Kemfert, C., Hoppe, P. 2009. Simulation of Economic Losses from Tropical Cyclones in the Years 2015 and 2050: The Effects of Anthropogenic Climate Change and Growing Wealth. DIW Discussion Paper 914.

Schmidt, S., Kemfert, C., Hoppe, P. 2010. The Impact of Socio-Economics and Climate Change on Tropical Cyclone Losses in the USA. Regional Environmental Change 10:13-26

Strobl, E., 2011. The Economic Growth Impact of Hurricanes: Evidence from U.S. Coastal Counties. The Review of Economics and Statistics. 93:2:575-589.

Tye, M. R., Holland, G. J., & Done, J. M. (2014). Rethinking failure: time for closer engineer–scientist collaborations on design. Proceedings of the Institution of Civil Engineers. DOI: 10.1680/feng.14.00004

UNISDR (2013) From Shared Risk to Shared Value –The Business Case for Disaster Risk Reduction. Global Assessment Report on Disaster Risk Reduction. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction (UNISDR).

UNISDR (2015). Making Development Sustainable: The Future of Disaster Risk Management. Global Assessment Report on Disaster Risk Reduction. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction (UNISDR)

Zhai, A. R., & Jiang, J. H. (2014). Dependence of US hurricane economic loss on maximum wind speed and storm size. *Environmental Research Letters*,*9*(6), 064019.