Quantitative Impact of Catastrophe Risk Insurance on Community Resilience

Ji Yun Lee
Assistant Professor, Dept. of Civil & Environmental Engineering, Washington State University, Pullman, WA, USA

Jie Zhao
Graduate Student, Dept. of Civil & Environmental Engineering, Washington State University, Pullman, WA, USA

Yue Li
Professor, Dept. of Civil Engineering, Case Western Reserve University, Cleveland, OH, USA

Yue-Jun Yin
Principal Engineer, AIR Worldwide, Boston, MA, USA

ABSTRACT: Catastrophe risk insurance is an important risk management tool that reduces excessive financial burdens of homeowners following a disaster and expedites the recovery of disaster-impacted buildings and the community that they support. This paper proposes a quantitative framework for assessing the effects of catastrophe risk insurance on community resilience. The framework simulates pre- and post-disaster circumstances of a community by explicitly incorporating the characteristics of hazards and properties, individual homeowners' financial availability and risk attitudes, and available insurance plans. A small residential community in Miami-Dade County, Florida, following a scenario hazard event (Hurricane Wilma) is used to test the feasibility of the proposed framework. The quantitative impact of insurance on community resilience will provide guidance on how catastrophe risk insurance can be used in a broad resilience planning to achieve its long-term resilience goals.

1. INTRODUCTION

Catastrophe risk insurance is an important risk management tool to expedite the recovery of disaster-impacted buildings, critical civil infrastructure systems, and in turn, the communities that they support (Field et al., 2012; Kunreuther, 2015). In addition, property insurance helps policy holder transfer risk and avoid substantial financial burdens from repair/reconstruction activities following a hazard event (Kunreuther and Pauly, 2006). However, recent experiences indicate that many buildings and infrastructure systems are not sufficiently insured against natural disasters partly due to building owners' lack of foresight or their limited financial availability (Vasiljevic et al., 2013).

The role of catastrophe risk insurance in disaster risk management strategies has been well investigated in several studies. Kunreuther and Pauly (2006) pointed out the importance of mandatory comprehensive insurance in reducing significant expenditures following a disastrous event. Kunreuther (2008) also showed that the adoption of structural measures can be encouraged by insurance premium reduction (as an economic incentive), and both of them lead to significant reduction in catastrophe losses and excessive financial burdens induced by a disaster. However, most of these studies to date have assessed the role of catastrophe insurance in disaster risk management qualitatively rather than quantitatively.

In recent years, many studies have realized that catastrophe risk insurance may considerably shorten the recovery time and affect the restoration curve of a community following a disaster as it provides much more expedited payments to the insured properties compared to government assistance. HAZUS-MH (FEMA, 2009) implicitly included the time to negotiate with insurance company in the building repair time and loss of function while the REDi™ framework (Almufti and Willford, 2013) explicitly developed the statistical models for the delay due to insurance payment and SBA-backed loans, assigning smaller median values on the former. Moreover, Miles and Chang (2007) incorporated the insurance status of homeowners in the model that simulates the recovery processes of communities following a disaster. Although the reduced delay time due to insurance is now well recognized in community resilience planning, most studies have made restrictive assumptions or utilized simple statistical information to model the insurance status of properties. While individual homeowner's decision on insurance purchase is critical in community resilience modeling, the area of research is still in its infancy.

This paper proposes a quantitative framework for assessing the impact of catastrophe risk insurance on community resilience by explicitly incorporating behaviors of individual homeowners. We begin by investigating the structure of the proposed framework which consists of two parts: pre-disaster individual-level decision model (Part I) and post-disaster community-level recovery model (Part II). Part I describes individual homeowners' decisions on insurance coverage based on the maximum expected utility model. Part II models the recovery processes of individual buildings based on homeowners' pre-disaster and post-disaster actions, and subsequently simulates the recovery process of a community. The proposed framework is applied to a small residential community located in Miami-Dade County, Florida to simulate the insurance coverage of each building prior to a disaster and its post-disaster recovery following a scenario hurricane. Finally, sensitivity analysis is performed to assess the effect of government assistance on the community recovery process.

2. MODEL STRUCTURE

This section illustrates the structure of the proposed framework that quantitatively assesses the impact of catastrophe risk insurance on community resilience. The proposed framework consists of two sequentially linked parts: pre-disaster individual-level decision model (Part I) and post-disaster community-level recovery model (Part II). In Part I, individual homeowners decide what insurance coverage might be optimal based on their locations, building types, financial availability, and risk perception. Insurance coverage of each household (the result from Part I) determines the delay time of individual buildings and the number of bankruptcies in the community in Part II. After a scenario hazard occurs, the damage state and the associated economic losses sustained by each building are recorded, and coupled with possible impeding factors and the results from Part I, the total recovery time and trajectory of each building are computed. The recovery process of the community can be obtained by aggregating the recovery states of individual buildings at every time step. More detailed information on each part will be provided in the following subsections.

2.1. PART I: PRE-DISASTER INDIVIDUAL HOMEOWNERS' DECISION MODEL

Individual risk transfer decisions on one's property depend not only on one's expectation of the likelihood and consequences (i.e. financial losses in this study) of a disastrous event, but also on one's risk attitudes, budget constraints, and post-disaster aid provided by the federal or local government. Let's assume that the mth homeowner determines the optimal property insurance plan (with a coverage C and the premium zC for a given amount of the coverage) to protect the kth type of building based on the expected utility model:

$$\mathrm{E}[U_m(C,k)] = \sum_{i=1}^{n} p_i U\big[W_m - E[L_k|IM_i] + CP\big(IM_i, L_k, D(V_m)\big) - zC + GA(IM_i, L_k, CP, GA_{max})\big] + \left(1 - \sum_{i=1}^{n} pi\right) U[W_m - zC]$$
$$m \in M, k \in K \quad (1)$$

where M = the set of households in a community, K = the set of building types considered, n = the total number of intensity levels of a disastrous event, p_i = the annual probability of occurrence of an event with the ith level of intensity (IM_i), $U(.)$ = the utility function, W_m = the initial wealth of the mth household, $\mathrm{E}[L_k|IM_i]$ = the expected economic losses of the kth type of building induced by an event with the ith level of intensity (IM_i), CP = the claim payment received from an insurance company following a disaster, D = the deductible, V_m = the value of the mth property, z = the insurance premium per dollar coverage, C = insurance coverage, and GA = the amount of federal or local government assistance following a disaster.

Based on the assumption that all individuals have the same level of probabilistic information on the likelihood and consequences of a disastrous event, an individual would determine the optimal amount of insurance coverage (C_{opt}) and the associated premium by finding the value where $\frac{dE[U_m(C,k)]}{dC} = 0$. C_{opt} is the actual amount of coverage of the insurance plan the individual would purchase.

Claim payment (CP) in the expected utilities is the amount paid by an insurance company to the insured when covered damage occurs. CP is defined as:

$$CP = \begin{cases} 0, & E[L_k|IM_i] \le D(V_m) \\ E[L_k|IM_i] - D(V_m), & D(V_m) < E[L_k|IM_i] \le C \\ C - D(V_m), & E[L_k|IM_i] > C \end{cases} \quad (2)$$

If the expected financial losses ($\mathrm{E}[L_k|IM_i]$) of the insured property are less than the deductible (D), the property owner is responsible for paying such losses and the insurance claim would not be initiated. If the financial losses exceed the deductible but are within the limit of the insurance plan (C), the insurance claim would be initiated and the insurance company covers the financial losses except the deductible. If the financial losses are greater than the coverage, the owner would receive the amount of money that is equal to the policy limit except the deductible.

Another factor affecting homeowners' decisions on insurance coverage is government assistance (GA) following a disaster. In the aftermath of a major disaster, the federal or local government provides the owners of non-insured and under-insured properties with financial assistance through grants, low-interest loans, or tax benefits to aid their post-disaster recovery. Some of empirical studies, however, have suggested that many individual homeowners do not anticipate receiving any federal disaster assistance prior to an event (Kunreuther et al., 1978; Burby et al., 1991). Thus, it is assumed in this study that homeowners are not aware of federal assistance prior to an event and may not take it into account in making decisions while government assistance is considered in the post-disaster recovery model that will be introduced in the next subsection.

After determining the amount of insurance coverage of all properties in a community, their recovery processes can be modeled and aggregated in the post-disaster community-level recovery model.

2.2. Post-Disaster Community-Level Recovery Model

Following an extreme natural hazard event, the post-disaster recovery of a residential community (measured in terms of housing capacity) depends on the restoration activities of individual houses and is determined by their aggregated effects (Miles and Chang, 2007; Burton et al., 2018). The post-disaster recovery process of an individual house is affected by (a) its damage and economic

losses induced by a hazard event, (b) the property insurance plan purchased prior to an event as described in Section 2.1, (c) the ex-post government disaster assistance, (d) the household's financial resources at hand, and (e) other variables. This subsection illustrates the Monte Carlo Simulation process that captures the temporal evolution of the recovery processes of individual houses with different pre-disaster and post-disaster situations and their aggregated effects on community resilience. This model places a particular focus on the role of catastrophe risk insurance in individuals' financial resources following a disaster, recovery time determined based on their financial availability, as well as community resilience.

The model begins by estimating the extent of damage and economic losses of individual buildings induced by an extreme event that occurs at $t = t_0$. The damage states (DS) are divided into five states, namely, no damage (DS_0), minor damage (DS_1), moderate damage (DS_2), severe damage (DS_3), and destruction (DS_4), that are consistent with those in HAZUS-MH (FEMA, 2009). Economic losses associated with building damage states can be obtained from the relationship between damage and loss functions. The total repair time, T_{repair}, of a building is defined as the time to achieve the pre-event damage state (DS_0 is assumed here) from the damage state (DS_i) at t_0.

The time to initiate recovery activities is not immediately after the time of occurrence of an event (t_0) but may be delayed due to several "impeding factors" defined in the REDi™ framework (Almufti and Willford, 2013). These factors include: (a) post-disaster inspection; (b) engineering mobilization and review/re-design; (c) financing; (d) contractor mobilization and bid process; (e) permitting; and (f) procurement of long-lead time components. The last impeding factor is not considered in this study because most of residential buildings do not require the procurement of long-lead time components, such as custom-made structural, mechanical, or architectural components. The detailed description of each impeding factor can be found in Almufti and Willford (2013).

As introduced in the REDi™ framework, this paper considers three delay sequences of a damaged building due to different combinations of impeding factors. Each sequence provides its expected delay time ($T_{delay,i}$) as follows:

- Delay Sequence 1: inspection → financing ($T_{delay,1} = T_{insp} + T_{financing}$)
- Delay Sequence 2: inspection → engineering mobilization and review/redesign → permitting ($T_{delay,2} = T_{insp} + T_{eng} + T_{permitting}$)
- Delay Sequence 3: inspection → contractor mobilization ($T_{delay,3} = T_{insp} + T_{mob}$)

The longest delay sequence controls the overall delay time. Thus, the total expected delay time is:

$$T_{delay} = \max_i(T_{delay,i}), i = 1,2,3 \qquad (3)$$

This paper focuses on the Delay Sequence 1 which is primarily triggered by the financing delay as it is closely associated with the pre-disaster individual homeowners' decisions about catastrophe insurance modeled in Section 2.1. As presented in Figure 1, if the owner has financial resources enough to repair his/her damaged property, there is no need to wait for insurance claim payment, and thus no "financing delay" is expected. If not, the owner should wait until the insurance company provides CP. Note that, in this stage, the expected financial losses ($E[L_k|IM_i]$) can be replaced with the actual losses (L) induced by the hazard event by removing the associated uncertainties. If the owner has sufficient funds to cover the rest of the repair costs ($L - CP$), the delay time due to financing ($T_{financing}$) is governed by insurance claim delay ($T_{insurance}$). If the available funds are insufficient to cover the remaining repair costs, the owner should wait until the government assistance becomes available. It is assumed that disaster assistance is provided to aid the recovery of properties only when they are damaged as a result of a presidentially-declared disaster. Government assistance (GA) is calculated as:

$$\mathrm{GA} = \begin{cases} \mathrm{L-CP}, & \mathrm{L-CP} < GA_{max} \\ GA_{max}, & \mathrm{L-CP} \geq GA_{max} \end{cases} \quad (4)$$

Significant delays can occur in processing *GA* compensation as compared to the time that private/public insurance claim is paid. This delay ($T_{financing}$) is determined by the delay due to government assistance (T_{GA}) and is substantially longer than $T_{insurance}$ in most cases. If the owner cannot guarantee financial availability to cover the remaining costs necessary to repair damaged properties at any point in time during this process, he/she would file for bankruptcy. It should be noted that, in this study, loan is not considered as an additional source of funding due to the complexity in incorporating individual's credit history, market conditions, and different loan qualifications into the analysis.

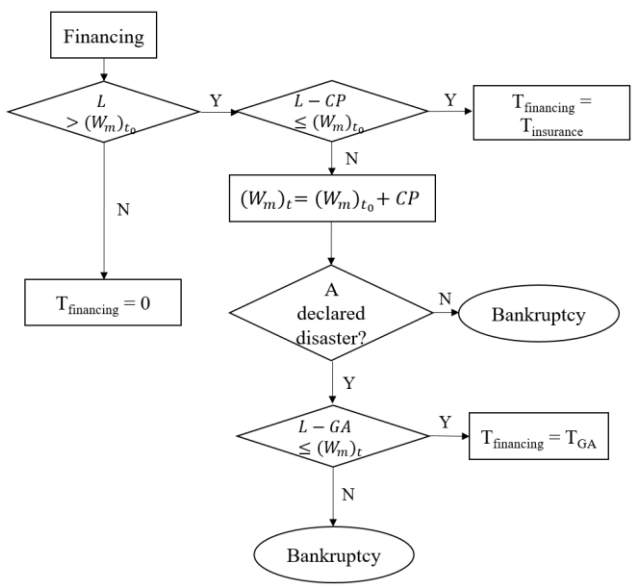

Figure 1. Financing delay sequence of a damaged building and the associated delay time

The total recovery time of a building ($T_{recovery}$) is the sum of the total delay time (T_{delay}) and the total repair time (T_{repair}). The total recovery times of all buildings are assumed to start immediately following a disaster at t_0. As described in this subsection, each residential building has its own distinctive $T_{recovery,m}$ value, which is dependent on the type of the building, the extent of damage sustained by the building and the associated economic losses, the financial availability and pre-disaster decisions about insurance coverage of an individual homeowner, and economic/political circumstances that may affect the amount and terms of the disaster assistance (Almufti and Willford, 2013). Since the post-disaster recovery of a residential community is measured in terms of housing capacity in this study, the recovery states of individual houses are aggregated at each point in time to capture the recovery process of the community.

3. CASE STUDY

3.1. Study region

To assess quantitative impact of catastrophe risk insurance on the recovery processes of individual houses and subsequently on the resilience of a residential community, the framework introduced in the previous section is applied to seven census tracts located in Miami-Dade County, Florida. This site is selected for the application because (a) it is located in a hurricane-prone area and catastrophe insurance policy purchased prior to a disastrous event may play a significant role in the community resilience; and (b) it consists mostly of residential buildings (i.e., one-, two- and more-story single-family and multi-unit dwellings).

3.2. Simulation process

Florida law requires homeowners living on mortgage to purchase property insurance policy which covers damage caused by wind. Thus, most of homeowners in the study region are assumed to purchase windstorm insurance prior to a disaster and choose coverages based on Eq. (1). While insurance premium discounts may be provided to the homeowners who adopt wind mitigation measures prior to an event or whose properties comply Florida building code, any types of pre-disaster economic incentives or grants are not explicitly incorporated in the utility models. Generally, hurricane causes two types of damage: damage induced by high winds (mostly building damage including exterior components and cladding) which is covered by windstorm insurance and water damage (mostly content

damage) covered by flood insurance. This study focuses on windstorm-related damage and losses as well as windstorm insurance.

Probabilistic descriptions of the variables used in the expected utility model are summarized in Table 1. The power utility function $u(x) = x^{\alpha}$, $0<\alpha\leq 1$, is used in the study based on the assumption that individual homeowners have risk-averse or risk-neutral attitudes (Gollier, 2003). The parameter, α, follows a truncated normal distribution with the mean value of 0.5 and Coefficient of Variation (COV) of 0.3. The annual probability of exceedance of a given wind speed for the site is obtained from FEMA (2009) and ASCE (2016), and is used to construct a site-specific hazard curve. Loss function describing the expected losses of the kth type of building given the ith level of wind speed ($E[L_k|IM_i]$) is modeled by a lognormal distribution with parameters obtained from HAZUS-MH (FEMA, 2009). The annual income of the mth household (I_m) is sampled from the distribution fitted to HAZUS-MH data which shows the percentage of population in each income class and subsequently used to compute the total wealth (W_m) based on their linear relationship. The relationship between annual income and total net wealth (Board of Governors of the Federal Reserve System, 2018) is obtained from linear regression analysis.

Table 1. Probability distributions of the variables of the expected utility model

Variable	*Distribution Type*
α	*Truncated normal*
$W_m = f(I_m)$	*Linear regression*
$E[L_k\|IM_i]$	*Lognormal*
z	*Constant ($8.13)*

Based on data from five private insurance companies collected by Doherty et al. (2008), the range of windstorm insurance coverage (C) in Florida is assumed to be between $5,000 (in 2008 dollars) and building value (which is obtained from HAZUS-MH) and the average premium per $1,000 of coverage, z, is $8.13. Note that most insurance policies do not fully cover the entire repair cost of a building, but require a deductible of 5- 10% of the building value.

Hurricane Wilma in 2005 is selected as a scenario event to simulate the post-disaster recovery process of the study region. The peak gust wind speed during Hurricane Wilma was recorded as 111 mph. Damage state probabilities by building type are obtained from the HAZUS-MH historical storm scenario analysis and then used to generate the damage state of each building and the associated economic losses. Economic losses include the structural and nonstructural repair costs caused by building damage and the costs related to relocation, income, rental and wage. Similar to the approach used in the HAZUS-MH hurricane model, repair time estimates (construction and clean-up time), T_{repair}, are modeled as a function of economic loss ratio, which is the ratio of the economic losses induced by a hazard event to the building value. The repair times corresponding to each building loss ratio (0%, 2%, 10%, 50%, and 100%) are obtained from HAZUS-MH (FEMA, 2003; FEMA 2009) as summarized in Table 2, and the repair time between two adjacent loss ratios can be computed using linear interpolation (FEMA, 2009).

Table 2. Building repair time as a function of loss ratio (Unit: days)

Occupancy Class	*Building Loss Ratio*				
	0%	*2%*	*10%*	*50%*	*100%*
Single family	*0*	*2*	*30*	*90*	*180*
Multi family	*0*	*5*	*30*	*120*	*240*

Three delay sequences of each damaged building are simulated to determine the total expected delay time, T_{delay}. Each impeding factor is assumed to follow a lognormal distribution to incorporate substantial uncertainties in the factors. These lognormal parameters can be found in the REDi™ Framework (Almufti and Willford, 2013). Although those parameters were originally developed for the conditions expected after a seismic event, they are slightly modified and used in this case study with the assumption that post-earthquake delay times are equivalently

applicable to post-hurricane circumstances. As Hurricane Wilma was declared as a major disaster and individual assistance was provided to Miami-Dade County, government assistance (*GA*) is also considered in the simulation process. It is assumed that grants are limited to $31,400 (in 2012 dollars) per household (Kousky and Shabman, 2012). The total recovery time ($T_{recovery}$) is determined by summing the delay time (T_{delay}) and the repair time (T_{repair}) and subsequently used for modeling community recovery process.

3.3. RESULTS

Following Hurricane Wilma, 67.29% of the buildings in the study area were undamaged (DS_0), while 27.16%, 4.94%, 0.47%, and 0.14% of the buildings were in the damage states of DS_1, DS_2, DS_3, and DS_4, respectively. Figure 2 shows the histogram of the insurance coverages selected using Eq. (1). Based on this distribution and the actual losses sustained by the buildings, *CPs* and homeowners' financial availability to cover the repair costs were determined, and subsequently, the delay times due to financing were computed as described in Section 2.2. The solid curve in Figure 3 represents the community recovery process (which is measured in terms of the number of residential buildings in the damage state of DS_0) following Hurricane Wilma. Since 0.9% (89 out of 9941) of the homeowners file for bankruptcies due to their insufficient financial resources for recovery activities, the fully recovered state of the community is 99.1%.

The sensitivity analysis of government assistance is performed to assess its impact on individual's financial status and community resilience after Hurricane Wilma. If ex-post disaster assistance is not available, 9.65% of the homeowners fail to pay for the repair costs and file for bankruptcy. This number is ten times greater than the number of bankruptcies when *GA* is provided. The recovery process of the community, when *GA* is not provided, is shown by the dashed line in Figure 3. As such, *GA* helps reduce the number of bankruptcies of low-income residents or homeowners whose properties are severely damaged, and thus affects the recovery curve of the community.

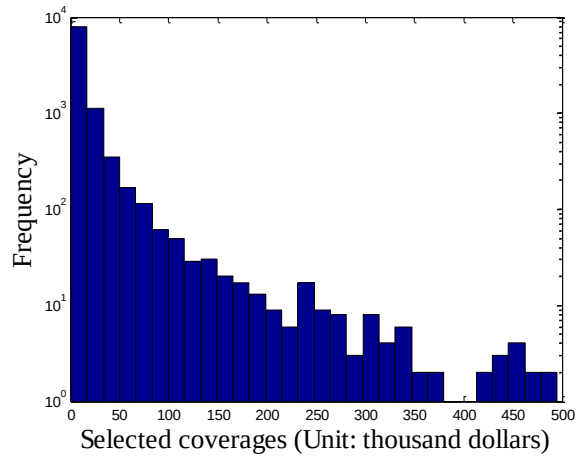

Figure 2. The distribution of selected insurance coverages

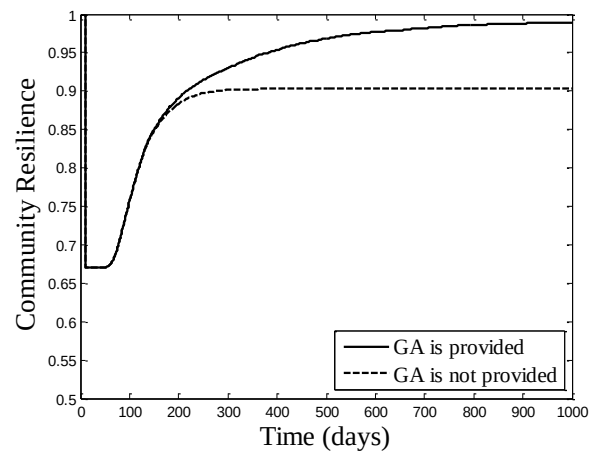

Figure 3. Community recovery processes for two cases: government assistance is provided or not

4. CONCLUSIONS

This paper proposes a framework that quantitatively assesses the impact of catastrophe insurance on community resilience by explicitly incorporating individual homeowner's decisions on insurance coverage. The proposed simulation framework is applied to a small residential community in Miami-Dade County, Florida following Hurricane Wilma. The results indicate that the selected insurance coverage varies widely due to individual's expectation of the likelihood and consequences of a disastrous event, risk

attitudes and budget constraints. Moreover, insurance may play a key role in improving community resilience if ex-post government assistance is not available or if substantial financial losses will occur following a disaster. Thus, providing affordable insurance plan is an important risk management strategy to protect a community and its residents against hazard events.

The quantitative impact of insurance will provide guidance on how catastrophe risk insurance should be used in a broad resilience planning to achieve its long-term resilience goals. It will also provide a consistent quantitative measure for its comparison with other risk mitigation strategies (e.g. land use planning, incentives for proactive preventive measure, etc.) in a unified resilience framework.

5. REFERENCES

Almufti, I., and Willford, M. (2013). "REDi™ rating system: Resilience-based earthquake design initiative for the next generation of buildings." *Arup Co*.

ASCE. (2016). "Minimum design loads and associated criteria for buildings and other structures." *American Society of Civil Engineers.*

Board of Governors of the Federal Reserve System. (2018). https://www.federalreserve.gov/econres/scfindex.htm

Burby, R., Cigler, B. A., French, S. P., Kaiser, E. J., Kartez, J., Roenigk, D., et al. (1991). "Sharing Environmental Risks. How to control Governments' Losses in Natural Disasters." *Westview Press*.

Burton, H. V., Miles, S. B., and Kang, H. (2018). "Integrating performance based engineering and urban simulation to model post-earthquake housing recovery." *Earthquake Spectra*.

Doherty, N. A., Grace, M. F., Klein, R. W., Kunreuther, H. C., Michel-Kerjan, E. O., and Pauly, M. V. (2008). "Managing large scale risks in a new era of catastrophes: Insuring, Mitigating and Financing Recovery from Natural Disasters in the United States." *Wharton Risk Management and Decision Processes Center, Pennsylvania University*.

FEMA. (2003). "Multi-hazard loss estimation methodology, earthquake model." *Washington, DC, USA: Federal Emergency Management Agency*.

FEMA. (2009). "Multi-hazard loss estimation methodology—Hurricane model." *HAZUS-MH-MR4 technical manual.*

Field, C.B., Barros, V., Stocker, T.F., and Dahe, Q. (2012). "Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change." *Cambridge University Press*.

Gollier, C. (2003). "To insure or not to insure?: an insurance puzzle." *The Geneva Papers on Risk and Insurance Theory*, *28*(1), 5-24.

Kousky, C., and Shabman, L. (2012). "The realities of federal disaster aid." *RFF Issue Brief. Washington, DC: Resources for the Future*.

Kunreuther, H. (2008). "Reducing losses from catastrophic risks through long-term insurance and mitigation." *Social Research: An International Quarterly*, 75(3), 905-930.

Kunreuther, H. (2015). "The role of insurance in reducing losses from extreme events: The need for public–private partnerships." The Geneva Papers on Risk and Insurance-Issues and Practice, 40(4), 741-762.

Kunreuther, H., and Pauly, M. (2006). "Rules rather than discretion: Lessons from Hurricane Katrina." *Journal of Risk and Uncertainty*, *33*(1-2), 101-116.

Kunreuther, H., Ginsberg, R., Miller, L., Sagi, P., Slovic, P., Borkan, B., and Katz, N. (1978). "Disaster insurance protection: Public policy lessons." *New York: Wiley*.

Miles, S. B., and Chang, S. E. (2007). "A simulation model of urban disaster recovery and resilience: Implementation for the 1994 Northridge earthquake." *MCEER-07-0014 Technical Report*.

Vasiljevic, M., Weick, M., Taylor-Gooby, P., Abrams, D. and Hopthrow, T. (2013). "Reasoning about extreme events: A review of behavioural biases in relation to catastrophe risks." *The Lighthill Risk Network*.