Foundation and Development of Natural Catastrophe Modeling

Gonzalo L. Pita, M.ASCE[1]

Abstract: The quantification of damage potential is an essential prerequisite for mitigating the impact of natural hazards on the built environment of a country. Catastrophe models are complex computer programs that allow us to measure damage potentials, investigate the possible effects of climate change, and more. Model-generated information, however, is highly sensitive to the incorporated assumptions, and thus the soundness of our knowledge of risk and the effectiveness of mitigation mechanisms is in direct proportion to how well we understand those assumptions. The history of the development of catastrophe modeling in the last 60 years has much to teach us about these and other important aspects. However, it has been underexamined. This paper aims to trace the origins of modern catastrophe modeling—identifying its roots and rapid progress from World War II until the mid-1960s, when risk assessment approaches grew from empirical data-dependent techniques to physics-based computer simulations, and from the 1960s to early 2000s, when catastrophe models acquired an important role in policy analysis. The role of Don G. Friedman, a scientist not yet properly recognized in the risk modeling community although arguably the chief pioneer of catastrophe modeling, is highlighted. The sources used to construct this account include relatively unexplored ones as well as interviews with key pioneers of catastrophe modeling. **DOI: 10.1061/(ASCE)NH.1527-6996.0000567.**

Introduction

The welfare and prosperity of countries affected by natural hazards are achieved not only through a robust economy and a resilient built infrastructure, but also through a suitable risk management strategy. This strategy is a research and action cycle of four operations: assessment of the occurrence and effects of natural disasters, design of risk control mechanisms, implementation of the selected mechanisms, and evaluation of their performance.

Catastrophe models are the most comprehensive tools to quantify the effects of natural hazards on the built infrastructure and population. These are complex computer models that simulate the mechanisms by which recurrent hazards exert damages on built inventory with recursive algorithms that overlap layers of data.

Nowadays, catastrophe model-generated information is used as input in several regulatory processes. For example, the Disaster Mitigation Act of 2000 (PL 106-390.S322) requires jurisdictions to develop mitigation plans with projections made with catastrophe models for eligibility in Federal Emergency Management Agency (FEMA) grant programs. The Florida Office of Insurance Regulation requires insurers to submit rate filings with projected hurricane losses estimated with certified models [F.S. 627.062(2)(b)11]. The National Flood Insurance Program (NFIP) relies on them to develop rate maps (FEMA 2018), and the United States basic wind map of the American Society of Civil Engineers standard (ASCE-SEI 2016) is developed with a hazard model.

Over time, the predictive skill of catastrophe models has improved considerably thanks to the incorporation of richer scientific theories, engineering methods, and additional data (Pita et al. 2013). Concurrently, the uncertainty of the predictions was affected by the several assumptions about the nature of the problem that were incorporated. Consequently, modelers and decision-makers must be familiar with these aspects to better understand the implications of acting on the outputs of catastrophe models.

While not exhaustive, this paper presents an account of the main developments and actors in the progress of methods for assessing natural risk, from the heuristic techniques of the early 1900s to the complex catastrophe models of the 2000s, dwelling particularly on the contributions of Don G. Friedman, the scientist who established the first models, a fact that has not been addressed in sufficient detail until now (Foster 1980; Walker 1997; Collier 2008; Scawthorn 2008). The history of natural risk-assessment tools herein is organized as follows: predecessors of catastrophe models (1914–1941), advances during World War II (1941–1945), advances in applied climatology (1945–1955), foundation of modern catastrophe modeling (1955–1965), use of catastrophe models in national policy analysis and formulation (1965–1975), multiplication and growth of catastrophe modeling endeavors (1975–1995), and establishment of open models, modeling firms, and the regulation of catastrophe models (1990s–mid 2000s).

Predecessors of Catastrophe Models (1914–1941)

The predecessors of the first catastrophe model, whose origin dates to 1955 as subsequently discussed, were flood damage assessment techniques developed by USACE and the Department of Agriculture prior to World War II (WWII). These techniques, developed from the 1900s to the 1930s, were in turn rooted in efforts started in the 1850s to evaluate the economic feasibility of engineering projects and in efforts to price insurance coverage.

During the 1800s the merit of flood-control structures regarding their projected economic benefits (e.g., averted property and agricultural losses, as well as new economic opportunities) was evaluated with heuristic cost-benefit analyses. One of the first, and most important, flood prevention studies was conducted by Humphreys and Abbot (1861) from the US Army Corps of Topographical Engineers for the lower Mississippi River (Reuss 1985). Future losses

[1]Associate Scientist and Director of the MSE in Systems Engineering Program, Dept. of Civil and Systems Engineering, Johns Hopkins Univ., Baltimore, MD 21218. Email: gpita@jhu.edu

Note. This manuscript was submitted on August 18, 2021; approved on March 18, 2022; published online on August 2, 2022. Discussion period open until January 2, 2023; separate discussions must be submitted for individual papers. This paper is part of the ***Natural Hazards Review***, © ASCE, ISSN 1527-6988.

were estimated by averaging previous flood losses, as was done in the thorough Pittsburgh flood study (Flood Commission of Pittsburgh 1912, pp. 66–67).

As part of these studies, large amounts of river flow data were collected, including the surveying of "danger lines," predecessors of the damage functions. These efforts continued and were expanded nationwide by the US Army, which began to systematically tabulate storm occurrences and wind speed measurements around 1870 (USASC 1874).

Fire insurers, on the other hand, began averaging annual loss claim data to conduct ratemaking around the 1890s, when sufficient consistent data was accumulated (Baranoff 2005). The idea that underlined this approach was that a sufficiently long damage series could adequately characterize risk and remained as the main standard framework in the industry until the 1950s. Insurers also began at this time to survey building inventory and classify it according to its structural characteristics.

Prediction of Damage and of River Flow Intensity and Frequency

A groundbreaking boost for flood assessment was introduced in 1913 by the renowned engineer H. Allen Hazen (Hazen 1914), who developed a probabilistic framework to characterize river flow frequency to overcome the limitations of the deterministic method in use (Jarvis 1936). He also created a technique to extend synthetically the length of available data to overcome the paucity of river flow observations.

Another more direct boost to damage assessment techniques was introduced by Hazen's associate Weston Fuller, who developed the return period concept to characterize the frequency of river discharges associated with unobserved events (Fuller 1914, pp. 596–598). He proposed that instead of averaging losses over time to estimate annual average loss, as commonly done, this could be better accomplished using river discharge frequencies, assessed with the new approach, along with observed associated damages using the expression for annual expected value

$$A = p \cdot D \tag{1}$$

where A is the annual cost of flood risk, and D is the damages caused by flood heights of annual frequency of exceedance p.

This new loss estimation approach formulated the loss-generating mechanism into two independent processes. One is the hazard frequency, estimated with Hazen's and Fuller's methods, and the other process is the building damage production, consisting at this point only of recorded aggregates. The premise was that the accuracy of assessments would improve with access to more and better data.

Better representations of the hazard process (frequency, time of occurrence, flood area) and of the damage-producing process (extent of development of flood plain, damage functions), were soon developed, for instance by Meyer (1921), who related damage to river stages, and in studies of the USACE (e.g., 1928 Tennessee Valley River study, 1932 Missouri River studies, and the "308 Program" from 1929 to 1948).

First Earthquake and Weather Damage Estimation Techniques

In the late 1920s, the aforementioned flood damage estimation technique was repurposed, it may seem, to assess earthquake damages. Motivated by the "unsatisfactory conditions" posed by the lack of sound engineering design criteria after the Santa Barbara earthquake of 1925, John R. Freeman developed a similar method for earthquake damages (Freeman 1932). Unlike the technique for floods, however, the description of the earthquake damage-producing process was specified more granularly—in terms of physical variables instead of claim data. In his influential study, Freeman, who was a hydraulics engineer by training, split the damage term D of Eq. (1) into a point average of areal building vulnerability V, corresponding to an earthquake of high Rossi–Forel intensity of annual probability p, and the buildings' cost C

$$A = p \cdot V \cdot C \tag{2}$$

Even though the term V was empirical, it allowed differentiating building typologies explicitly. This idea was used to assess annual average earthquake losses until the mid-1960s.

Studies for assessing the impact of weather on business activities before WWII used essentially the same statistical technique of Eq. (1). For instance, for assessing rainfall and frost effects on agriculture, accounting probability of plant damage by growing season (Spillman et al. 1916; Reed and Tolley 1916), flood effects (Meyer 1921), effects of weather on transportation (van Cleef 1917), and for economic decision-making (Bilham 1922; Angstrom 1922).

These techniques were relatively less developed than those for floods or earthquakes. For this very reason, however, they received significant attention from researchers during WWII, and the ensuing developments prepared the way for the creation of the first catastrophe model. To better portray this situation, some attending historical circumstances and people involved are referred to at some length next.

Natural Risk Assessment during World War II (1941–1945)

During WWII, several important advances were achieved in atmospheric sciences prompted by the strong reliance on them for planning military operations (Fuller 1990; Fleming 2016), especially on the prediction of climatological and weather conditions. Available information for the prediction of wind speed, temperature, and rainfall mostly consisted of average climatological data over large geographic areas, and as such, it did not describe the attendant surface weather. To overcome this deficiency, the climatologist Woodrow Jacobs developed a synoptic climatology technique to predict surface weather conditions over the coming 6 h, based on previous pressure patterns at high altitudes (Jacobs 1947). This was a useful and important improvement over previous methods, but had a limited applicability because pressure patterns were not quantified. In 1942, the Army Air Force Weather Service (AAFWS) contracted with George Wadsworth, a mathematician of the Massachusetts Institute of Technology (MIT) who eventually pioneered applications of mathematical methods to important geophysical problems, to work on long-range forecasting with statistical techniques (Wadsworth 1948; Pardo, personal communication, 2017). He and statistician Joseph Bryan quantified the atmospheric pressure fields at high-altitude and correlated them with surface weather time-series of temperature and pressure applying the findings of Norbert Wiener (Wiener 1942; Robinson 2015). After the war, however, the technique did not find practical applications due to lack of good data and the time-consuming calculations.

On the practical side, several projects used atmospheric information, for example in the assessment of trafficability of vehicles, airfield designs, dispersal of smokes, assessment of airplane's fuel consumptions, specifications of equipment and supplies, location and operations of facilities and personnel, and in the detection of preconditions for forest fires (Jacobs 1947). People involved in these studies included Thomas Malone, Herbert Thom (Thom 1952), Helmut Landsberg (Henderson 2016), and Heinz Lettau, all of whom will be subsequently referred to.

Advances in Applied Climatology at the MIT Department of Meteorology (1945–1954)

The period between the end of WWII and 1955 saw a great deal of activity in the economic and social analysis of weather influence (Maunder 1970; Bates 1949), which led to the foundation of catastrophe modeling. Tom Malone and the men mentioned earlier, initiated research collaborations on weather prediction and applications to economic decision-making. The development of the computer, however, changed the panorama completely and widened the modeling possibilities as never before (Perry 1988; Droessler 1989).

The circumstances that sparked these collaborations began around 1949, when Malone edited the *Compendium of Meteorology* (Doel 1995). It may seem that to start discussions about collaborations, Malone invited Jacobs and Landsberg, arguably the two most influential applied climatologists, and Lettau, renowned micrometeorologist, to teach in a summer program organized in 1950 by the MIT departments of Meteorology and Mathematics. Conversations with Wadsworth and Bryan also started around this time (Doel 1995). The program, aimed at training operators in the assessment of climatology and weather impacts on agricultural and industrial activities, was attended by several students, including Don G. Friedman, a meteorology graduate from the University of California, Los Angeles (UCLA), who developed the first modern catastrophe models less than a decade later. Among the several topics covered, particularly interesting was a damage assessment technique for agricultural land planning that Jacobs taught in his course (Friedman 1950; Landsberg and Jacobs 1951; Jacobs and Spreen 1953). The risk of annual crop losses caused by frost was determined by superimposing temperature data from several stations and damage susceptibility functions. Perhaps Friedman was later influenced by this technique to develop the first catastrophe model. At any rate, he continued as a master's student advised by Lettau and later began his doctorate advised by Malone, working in the Synoptic Climatology Project (SCP).

The SCP, launched in October of 1952, was planned to improve statistical weather prediction based on the previous work of Jacobs and Wadsworth. The MIT-developed computer, Whirlwind I, significantly facilitated the task, especially expediting the solution of prediction equations, which until then had been addressed with Marchant calculators. Friedman and the other students researched statistical weather forecasting using Whirlwind I advised by Malone, Wadsworth, and other researchers (Sellers 1956). The chief intended applications of the project were in the forecasting and military fields, but natural disasters soon presented the opportunity to apply them for risk assessment in the insurance industry.

The Foundation of Modern Catastrophe Modeling (1955–1965)

In 1954 and 1955, five hurricanes battered most of the eastern United States, a situation that greatly affected the insurance industry because it was ill-prepared to price rates for the rise in demand for coverage against natural perils. At the time, the risk assessment technique used by insurers consisted of averaging claim data to price the peril. However, the period covered by the statistics dated back only to 1949 (Finnegan 1956), and so some insurers commissioned technical studies. One such study, which received wide circulation in the industry, was from MIT meteorologist Hurd Willett, who estimated long-term trends in hurricane frequency and destructivity in the Atlantic and Gulf Coasts using information of climatology, solar cycles, and damage surveys (Willett 1955).

Nevertheless, the industry at large did not abandon the averaging approach; the prevalent impression was that the estimates would improve with the accumulation of more damage data, an attitude that largely persisted until the 1990s. Clearly, there was no firm suspicion of the statistical flaws inherent in the assumptions of this technique, tailored to describe fire peril, but inadequate for hurricanes and earthquakes.

The Travelers Weather Research Center

The notable exception to this sentiment was the Travelers Insurance Company in Hartford, CT, which decided to develop in-house methods to price atmospheric perils instead of relying on loss data alone (Weatherwise 1954). In 1954, the Travelers Weather Research Center (TWRC) was formed to conduct research on the effect of atmospheric hazards on the company's portfolio. Tom Malone was established as first director, and several of his collaborators in the SCP project, including Don G. Friedman, joined him.

From its inception, the TWRC became a sort of scientific think tank addressing private and government projects. By providing the funds and freedom to explore different scientific approaches to tackle several problems, Travelers created the environment for the birth of the first catastrophe model.

Problems with the Risk Assessment Technique in Use

In 1955, Travelers' actuaries were tasked with measuring the windstorm loss potential of an insured regional portfolio for which few years of claim data were available, and so, the problem was intractable. Consequently, the project was passed to the TWRC, where it became apparent that loss data were unsuited to that task (Friedman and Hendrick 1960). Besides the data shortage, several other problems compromised the loss averaging approach. Loss data series—even long ones—imply a single realization of a stochastic climatological process, meaning that the averaging approach assumes the hazard to be constant. Also, the very question of how long the data series should be to adequately measure risk sits on a dilemma: to comprise the most infrequent storms, the longer the series the better; conversely, to capture an accurate static picture of the inventory's spatial spread and vulnerability, a shorter loss data series is preferred. Lastly, loss data are a one-time conjunction of a storm and a building array, which will not occur again (Friedman 1975). For mitigation purposes, empirical loss data was not an aid for risk control, because causal relationships were masked.

Characteristics of the First Catastrophe Model

Having recognized that additional quantities of empirical data would not alone improve the estimates of loss potential, Friedman proposed that a better risk assessment method was needed. He saw that, for having a more dependable means of loss potential quantification, the damage-producing mechanism had to be broken down into its parts and their interactions, and that a physics-based construct of the interplay between natural phenomena and building array could provide just that.

Consequently, Friedman started developing a computational framework to assess natural disaster risk (Friedman 1956). The technique was essentially a modular approach that represented separately the hazard process—in whose modeling he had considerable expertise from the SCP days—and the damage-producing process driven by a wind field traversing an array of buildings. Synthetic damage estimates were computed for each simulated year overlapping mathematically both processes. The loss data, used before as a direct measure of annual risk, was repurposed in Friedman's model for building and calibrating damage functions, and for validating model-generated information. An obvious benefit, if only a future one, was that the approach allowed improving the hazard, exposure, and vulnerability modules independently as scientific knowledge became available for any of them. In addition, and also in the future, the approach was suitable for studying the effectivity of alternative risk control mechanisms.

The centerpiece of this model was an equation that represented the constituent components of a windstorm's damage-producing mechanism. The damages caused by the occurrence of storms of daily wind speed maxima v_l were computed with a causal relation provided by the damage function $D(v_l)$. These first functions were developed for wind risk assessment, hand-digitizing into punch cards tens of thousands of claim records from Travelers (Friedman, personal communication, 2012–2017). The frequency of windstorms $p(v_l)$ was retrieved from Weather Bureau tabulations. Aggregating daily damages rendered the annual average damage A_i at year i typified by the expression

$$A_i = \sum_{v_l} p(v_l) \cdot D(v_l) \tag{3}$$

The first model was built to hindcast previous losses over the company's portfolio in a region. An advantage of this technique was its modular structure that permitted adjusting the configuration of the potential loss simulation. Thus, variations of hazard severity and frequency, building inventory, and vulnerability could be hypothesized to examine events that could have occurred.

The model was simple—it resembled the earlier ones, especially the technique from Jacobs—in that it used input data of limited representativity, and had simplified wind field model (defined over multiple county regions) as well as building inventory (which was assumed homogeneous). However, subsequent versions made the representation of the hazard and damage-generating processes more accurate; the description of wind hazard improved (with the inclusion of thunderstorm, nonthunderstorm, hail, and tornado), and better damage functions were built.

Shortly after, the model was reframed to estimate loss potentials caused by future weather. Estimates of future wind speeds replaced observed ones in order to produce a long record of synthetic future loss experience. The algorithmic detailedness of the hazard and damage-generating mechanisms was enhanced. The hazard description was specified in more detail in its spatiotemporal aspects (dissipation of a hurricane's intensity after landfall, granularity of wind field was downscaled to substate level, and a probabilistic law of hurricane arrivals) (Thom 1960). The granularity of the building inventory was increased, including potential growth patterns. To estimate annual expected loss A, the risk equation was adapted for the greater descriptive details

$$A = \sum_j \sum_i p_i g(h_i) z_j \tag{4}$$

where p_i represents the probabilities of varying intensities of the hazard event h_i, the vulnerability functions $g(h_i)$ represents the inventory's extent and its typologies, and z_j is the array of building typologies in the jth region.

In parallel to this work on loss modeling, the TWRC initiated collaborations with federal agencies and academia in several research projects to better characterize the frequency and intensity of several hazards, (a practice that was continued) including studies of rainfall frequency, drought, hailstorm frequency, extreme wind speeds, thunderstorm frequency and severity, frost, hurricane damage to crops, hurricane hazard (e.g., Friedman and Janes 1957), and pioneering efforts in the predictions of hurricane motion (Spiegler 1996).

Catastrophe Models in Public Policy Analysis and Formulation (1965–1975)

By 1964, the catastrophe model of the Travelers' Natural Hazards Research Program was an integral component to inform company operations, but a turning point came about that year-the model was requested by the federal government to conduct a national policy study.

The circumstance that prompted the reorientation of the Travelers model was the concurrence during the 1950s and 1960s of severe floods across the country and of the several unsuccessful attempts of government agencies to mitigate flood damage. The situation not only demonstrated that the flood management strategy was inadequate, but also that the empirical loss estimation technique was ineffective. It poorly represented the damage potential, it overrelied on empirical data, and was not a guide to possible nonstructural mitigation mechanisms. Until then, the chief defense against flood losses had been structures built by USACE, but critics argued that this approach was part of the problem rather than a solution because, despite the escalating Federal and State spending on relief and protection, flood losses and social disruptions were increasing (White 1945; Maass 1951; Hoyt and Langbein 1955; Kates 1962). A sounder risk management strategy, they claimed, should incorporate a wider variety of nonstructural policy tools, including a national flood insurance program.

The other triggering circumstance was that neither the government agencies nor the insurance industry had a risk assessment methodology to design such recommended interventions. In fact, insurers until then had refrained from writing flood insurance because the peril was considered uninsurable due to adverse selection (Roy, personal communication, 2019). Meanwhile, some of them sought sounder techniques to price flood insurance coverage and commissioned a study by the engineering consulting firm Parsons, Brinkerhoff, Hall & McDonald in 1951. This study, which used a method of the USACE, discouraged flood insurance (Foster 1952; AIA 1955). On the government side, another assessment was conducted in 1956, as part of the Federal Flood Insurance Act (PL 84-1016) (Overman 1957) using a hybrid actuarial statistical technique, but distrust of that methodology led Congress to refuse to authorize funds (Kaplan 1972).

The National Flood Insurance Program Study

As a result of this situation, because of the widespread devastation caused by Hurricane Betsy in 1965 and the Alaska Earthquake in 1964, and in part due to the recent performance of the Travelers model (Collier 2014; Friedman 1965), the government and the insurance industry changed their attitude toward the viability of a federal insurance program. In response, and encouraged by the Great Society plan, Congress passed the Southeast Hurricane Disaster Relief Act of 1965 (PL 89-339) which marked the birth of disaster politics (Davies 2017). This was a decisive moment in the history of catastrophe risk modeling: models were used for the first time in national policymaking.

For floods, the Department of Housing and Urban Development (HUD) required two simulations, one from Travelers and the other from Harvard University's Division of Engineering and Applied Physics. Both models turned out to be instrumental for the passing of the National Flood Insurance Act of 1968 (PL 90-448, title XIII).

Nat. Hazards Rev., 2022, 23(4): 04022025

For the second study, HUD also required a simulation approach for an earthquake insurance program, which although not approved by Congress in 1971 (HUD 1971), it was also a milestone for the earthquake risk-modeling community as discussed below.

The Catastrophe Simulations in the HUD Flood Study

In the first phase of the flood study, agencies with responsibilities over the construction of control and abatement works—USACE, US Geological Survey, Tennessee Valley Authority, and Soil Conservation Service—determined the flood risk faced by individual homeowners (HUD 1966). The damage assessment technique used, known at the time as the "hydrologic method" (Foster 1952), was the same one used by USACE.

On the other hand, the computer simulation from Travelers assessed the viability of the flood insurance program quantifying the potential magnitude of flood losses and simulating complex policy scenarios to define initial fund-reserve requirements, rate estimation, and reinsurance issues. Friedman and operations researcher Tapan Roy developed a physics-based simulation to characterize unobserved river stages and resulting damages (Friedman and Roy 1966).

In comparison with Eq. (4), Friedman and Roy's simulation formulated a more detailed representation of the hazards and damage-generating processes. The inventory was decomposed at the subcity resolution in over a thousand cities across the main river basins and coastal areas. The wind field model was made to account for frictional dissipation over different terrains using radar scan images (Cosnett, personal communication, 2017). The hazard module had two flood sources: rivers and cyclone-caused storm surge. The depth and extent of both were represented in terms of varying return periods, and for coastal areas, cyclone landfall was simulated. A chief simplification introduced was that spatiotemporal correlation between river levels was accounted for indirectly by statistical factors from rough empirical data. The core equation of the simulation was

$$A = \sum_{j=1}^{J} T_j \sum_{i=1}^{I} p_i \sum_{k=1}^{i} n_{kj} D(h_k^i) V_{kj} \tag{5}$$

where T_j is the number of cities of size j, p_i is the probability of flood severity I (associated to a certain return period), n is the number of dwellings in city zone k, D is the damage function, h is the water height, and V represents building value.

Notably, another important conceptual innovation was incorporated, the casting of the simulation within a probabilistic Monte Carlo framework—the first instance of the application of this technique in catastrophe modeling. Aside from the obvious benefits of representing the stochastic nature of the problem, this approach, developed during WWII (Metropolis and Ulam 1949), was adopted to better capture the multilevel nature of the operation. The first modeling level estimated direct flood damage. The next level contained the workings of a damage mitigation mechanism, an insurance operation. Finally, there were the interlevel's upward and downward linkages between damage variability and the behavior of the insurance operation parameters in contrast with the previous single-level models of Eqs. (3) and (4).

The other computer simulation was developed by a team from Harvard to check out the results of the Travelers' model. This team was composed by Myron Fiering (lead), John Schaake and Herbert Winokur, and was related to the Harvard Water Program (Reuss 2003; Maass et al. 1962). This simulation essentially had the same structure as Friedman and Roy's simulation represented in Eq. (5) (Schaake, personal communication, 2019; Schaake and Fiering 1967; Winokur 1967). It was a physics-based Monte Carlo simulation of the interaction between the natural and socioeconomic systems (Winokur, personal communication, 2017). One significant difference in the hazard module, however, was that the Fiering–Schaake–Winokur simulation explicitly preserved the multisite spatiotemporal statistical structure of the river flow series. This was accomplished by simulating 3,000 years of synthetic simultaneous correlated streamflows with a Markov autoregressive model

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t + \mathbf{B}\boldsymbol{\varepsilon}_{t+1}, \quad \mathbf{A}, \mathbf{B} \in (m \times m) \tag{6}$$

where $\mathbf{x}$ has the flows series at times t and $t+1$, matrices $\mathbf{A}$ and $\mathbf{B}$ specify the spatiotemporal interdependence of flows at different times at m sites, and $\boldsymbol{\varepsilon}$ is a vector of random components. Despite this difference, an intercomparison of both simulations exhibited remarkably similar outputs, indicating that the empirically estimated spatiotemporal correlation of river levels in the Friedman–Roy model was somewhat valid. This lent decisive support to the reliability of both models' estimates for the design and aspects of the insurance operation (Kaplan 1972).

The exigencies from the HUD flood study posed modeling questions, which effected an expansion of Friedman's model. Its scope was broadened, and the hazard and damage-production processes modules were further specified. Access to more data from the aforementioned agencies allowed the calibration of vulnerability functions and the validation of model estimates.

It is instructive to briefly examine the confirmatory paradigm, which was laid out in considerable detail to highlight the limitations of the models (Friedman and Roy 1966; Schaake and Fiering 1967; and even in P.L. 89-339), a practice that, unfortunately, seems uncommon today. In general terms the confirmatory paradigm provides the criteria to validate the degree of success of a model's outputs with respect to real-world data, assuming that the model's logical structure resembles the dynamics of the natural–sociotechnical system. In catastrophe models, two types of validations are performed: of the components' workings (i.e. of the natural hazard, inventory, and vulnerability components) and of the model-generated information. Validations of the model components involve verifying that modeled hazard adequately resembles the real spatiotemporal geophysical variables, that the building array is accurately represented in the model, and that building vulnerability functions convincingly reflect real damage mechanisms. On the other hand, validation of the model-generated damage estimates requires that damage data is reproduced by the model to an acceptable degree of similarity. The level of success of both types of validations provides evidence to the credibility that should be attributed to the model's outputs.

The model's caveats were disclosed stating that the data needed for calibration and validation were insufficient, that the model structure was simple, and the assumptions were fraught with limiting simplifications and subjectivity. As a result, the overall verdict was that the model results were only "very rough guide lines [sic]" indicative of order-of-magnitude estimates (Friedman and Roy 1966). However, it was acknowledged that these simulations were the most rational way to combine the available information to attain useful actionable knowledge. Moreover, upon the availability of more data, the estimates could be refined.

In addressing the confirmatory paradigm, Friedman ended his case inviting the decision-makers' thoughtful consideration, for acceptance or rejection of the results depended on the users' willingness to accept, or reject, the (exhaustively enumerated and discussed on the official record) assumptions (Friedman and Roy 1966).

The National Earthquake Insurance Study

To evaluate the feasibility of a potential national earthquake insurance program the Coast and Geodetic Survey (CGS) conducted a study from 1967 to 1969. Modelers included Karl Steinbrugge, Theodore Algermissen, Frank McClure, and Don G. Friedman (Kaplan 1972).

Mirroring the flood study, the earthquake study computed damage potentials only for California, using the expected value statistical technique (ESSA 1967a, b). A test simulation was developed by Friedman and Roy (1969) to quantify earthquake direct damages on infrastructure. Like the model that preceded it, the earthquake simulation, replicated the earthquake damage–generating mechanism with a physics-based approach. The simulation's hazard module description was especially elaborate; it modeled earthquake intensity by reproducing the causal chain initiated by the occurrence of events of different severities at random hypocenters and focal depths, considering fault type and orientation, and local site effects with attenuation functions (Friedman 1972, 1973). Dozens of historic earthquakes were simulated for the San Francisco Bay area, and the intensity was estimated. Annual average damages to the inventory and damages of different return periods were computed.

At about the same time, another innovative technique to quantify earthquake damages called the Spectral Matrix Method (SMM) was also in the making. The technique, developed by earthquake engineer John Blume (ESSA 1967b), computed total building damage D_z at zone z with the expression

$$D_z = \sum_b E_b \sum_i P(i|b) F(b,i) \quad (7)$$

where E is the exposure in dollars, the probabilistic structural response intensity i is a function of the building period of vibration b for earthquake severity at the site $P(i|b)$, and the damage function was represented with a spectral damage factor $F(b,i)$.

In comparison with Friedman's simulation, the first versions of the SMM hinged on a simpler, more local seismic hazard module. However, it contained a more detailed representation of the building damage mechanism. Seismic intensity at a site was taken as an input in $P(i|b)$ without considering the causal links. As regards the building damage estimation, the SMM posited a physics-based description of the building damage mechanism in terms of the fundamental period of vibrations of structures, instead of empirical damage functions. This type of mechanistic description of damage allowed better specification of building typologies in the inventory by structural characteristics. It also invited the analysis of building vulnerability from an engineering perspective.

The SMM continued being developed and became a predecessor of more sophisticated future earthquake catastrophe models. Other models were developed about the same time, including a computer model to map the distribution of intensities of historical earthquakes by means of a detailed account of the seismic mechanism (Evernden et al. 1973), a simulation of earthquake intensity and building damages (ESSA 1969), among several other efforts (Veneziano 1975).

The Assessment of Research on Natural Hazards Project (1972–1975)

The next shaping episode for catastrophe modeling was brought about by a project conducted from 1972 to 1975 in which catastrophe models were used to investigate public policy issues (White 1974).

Prompted by the NFIP and the exploratory national earthquake insurance program studies, the Assessment of Research on Natural Hazards (ARNH) at the University of Colorado-Boulder was a 26-month project led by Gilbert White—one of the most influential natural hazards policy researchers and advocates in the country—that disseminated catastrophe simulations to a broader audience. The project gathered people from industry, federal officials, and researchers to identify natural hazards research needs and opportunities (Hinshaw 2006). White (Friedman, personal communication 2012–2017 based on a letter from White to G. Hinckley VP of Travelers on September 29, 1972), for whom Travelers' models had achieved the "most solid work of this sort in the United States," considered them a better tool than statistical analyses of damage data because they allowed working with what-if cases and enacting mitigation measures (White and Haas 1975). Don G. Friedman was invited to join the project early on.

In the ARNH, catastrophe modeling simulations were used for computing direct damages caused by several hazards: floods (White 1975), hurricanes (Brinkmann 1975), and earthquakes (Ayre 1975), and were also used in scenario studies (Ericksen 1975), in a study of hazard distributive effects (Cochrane 1975), drought studies (Warrick 1975), in a study of warning systems (Mileti 1975), and the investigation of the effects of damage mitigation interventions on risk-reduction strategies. The simulations were refined in the hazards, exposure, and vulnerability modules to accommodate the needs of the researchers (Muskatallo, personal communication, 2017; Boccaccino, personal communication, 2017). Furthermore, the interaction of researchers and catastrophe modelers helped to disseminate the technical possibilities of the simulations broadly.

As part of the project, the structure of the simulations was detailed in a report that became widely referenced by modelers in the coming years (Friedman 1975). In that report there was also a candid assessment of the accuracy that should be realistically expected from catastrophe models, as if to temper any premature haste from new modelers and users. Drawing from experience of the previous 20 years, Friedman discussed a series of opportunities and challenges associated with catastrophe models. Among the latter, a poignant question was posed that is still relevant today: in model development, how good is good enough? On the one hand and resuming the discussion about the confirmatory paradigm as in the NFIP study, it was proposed that the then present state of knowledge and lack of input data did not warrant building very complicated models. In addition, the intended use of the model-generated information should also be pondered in answering how elaborate a model should be. Finally, even though resources to feed models may be scarce, real-world applications usually cannot be postponed until better models are developed. But, as Friedman asserted, "decisions must still be made, if only on order of magnitude estimates." A trade-off between what-ought-to-be and what-is-needed-and-affordable, would determine on a case-by-case basis the answer to the question of how good is good enough.

In retrospect, the significance of the ARNH lies in several accomplishments that greatly influenced the progress of catastrophe modeling efforts in the intervening years. First, with a clear understanding of the progress and challenges facing the nation in relation to natural disasters, Gilbert White and the other organizers strategically brought together the most influential decision-makers, researchers, and modelers, who had worked until then separately, to discuss potential areas of need and synergy. They also secured from the National Science Foundation (NSF) leadership both, the endorsement for the ARNH project and the commitment to fund research suggestions arising from it. Many of the NSF-funded supported projects are listed in the next section. Finally, from a methodological perspective, the use and development of catastrophe model computer simulations, instead of more heuristic approaches, was influentially advocated and encouraged, as will also be discussed.

Growth of Catastrophe Modeling Endeavors and Maturation (1975–1995)

In the two decades that followed, the number of catastrophe models grew considerably, and the discipline reached a stage of maturation by the mid-1980s. Key developments from 1975 to 1995 included better characterizations of hazards, vulnerability, and exposure by researchers in academia, government agencies, and consulting firms across the United States; the Travelers' models, the most advanced at the time, were sought by national and international agencies. Catastrophe models began gradually displacing the actuarial methods to quantify loss potentials, and modeling firms were established in the late 1980s. Finally, after the disasters of Hurricane Andrew and the Northridge earthquake in 1992 and 1994, respectively, catastrophe models became the sole risk-assessment tools, which eventually brought the topic of their influence and accountability into focus.

Advances in Hazard, Vulnerability, and Exposure Studies

Several efforts were established to study hazard, building inventory, and vulnerability (Tubessing 1979). These provided better understanding of both the hazard and damage-producing processes, and also supplied data for calibration and validation purposes. Some salient endeavors are listed next without claiming to be exhaustive.

On the development of models, FEMA considered that it was "imperative to utilize computer simulation techniques" in damage assessments (Moore et al. 1985), and several models were developed: mapping platforms (Tubbesing 1979), economic impact models (NRC 1989; Vogt and Jackson 1993), and emergency management information systems (Jaske 1985). Universities also launched catastrophe modeling efforts (Lesso and Heine 1978; Guidi 1979; Berke et al. 1984; French and Isaacson 1984; Walker 1997).

As for practical applications of catastrophe models, comprehensive regional loss studies were conducted (NOAA-USGS studies started in 1972; NRC 1989; SWFRPC 1982; PBCDEM 1987). There were several efforts in the private sector, in meteorology (Spiegler 1996), and at engineering consulting firms, which conducted risk assessments, many of them funded by the NSF, especially John H. Wiggins Co.; John A. Blume & Associates; Jack R. Benjamin and Associates, Inc.; Dames & Moore; H. J. Degenkolb Engineers; and others.

As for catastrophe modeling components, advances were achieved in the characterization of hurricanes [NWS 15 (Ho et al. 1975), NWS 23 (Schwerdt et al. 1979), and NWS 38 (Ho et al. 1987); Holland 1980]; in probabilistic seismic hazard assessment (Esteva 1963, 1967; Cornell 1968), which led to the creation of the influential probabilistic seismic hazard analysis around 1974 (McGuire 1978), in earthquake ground-motion intensity prediction (Evernden et al. 1981); and in the creation of the first probabilistic seismic hazard maps (Kiremidjian 1976). Advances were also made in in flood-hazards modeling—USACE Hydrologic Engineering Center (HEC) created the HEC-1 and HEC-2 models (Beard 1967; Willey 1989), and storm surge models were developed (Jelesnianski 1972).

Also, better damage functions were developed for earthquakes (Whitman 1973; Vanmarcke and Whitman 1971), including the comprehensive Applied Technology Council's (ATC) ATC-13 (Rojahn et al. 1986), and for floods (Friedman et al. 1981); earthquake damage modeling efforts, in general, grew rapidly by the mid-1980s (Reitherman 1985). Similarly, for wind engineering, vulnerability functions were created (Hart 1976; Leicester and Reardon 1976) and improved quickly (Pita et al. 2015). Building inventory studies also progressed significantly (Algermissen and Steinbrugge 1984; Rojahn et al. 1986).

Advances in the Travelers' Catastrophe Models

Between the late 1970s and early 1980s, Travelers models continued to be enhanced, all the while being requested for national and international risk assessment projects. Improvements included upgrades in the hazard modules (the storm surge model and sampling of the Gutenberg–Richter law of earthquake occurrence were improved) and the exposure module (zip code geocoding became the standard way to locate exposure elements), as well as the development of more precise vulnerability functions (Mangano, personal communication, 2018).

Besides this, an innovative measure of catastrophe-producing potential was developed (Friedman 1975). This metric measured maximum expected damage that was potentially realizable by combinations of hurricane parameters at landfall to various degrees of building exposure area on the coast. As such, the index was a continuous envelope function derived by the joint deterministic variation of maximum credible hurricanes, exposure, and vulnerability parameters that elicited the maximum's breadth of the damage potential from Texas to Maine. The intent of this metric is better understood in the context of the confirmatory paradigm discussed earlier. Given the ramifications that the scarcity of sufficient data to perform calibrations and validations have on the credibility of model outputs, this metric was an attempt to gauge the maximum anticipated extent of hurricane-caused losses in current or hypothesized circumstances independently of probabilities. Among the motivations for this measure were the need to circumvent the lack of data, and especially, avoid the pitfalls associated with the incorrect application of statistical techniques, including the Monte Carlo, to enlarge the catalog of natural events when the sample of occurrences was deficient (Friedman 1995a, b).

Computer operations were also expedited significantly. John Mangano, a meteorologist who joined Travelers in 1981, rewrote the model codes in Visual Basic for a PC. Simulations were also used in international projects, for example, a study to model effects of earthquakes in Montenegro from 1981 to 1983 sponsored by the United Nations (Friedman and Mangano 1983), and contributions for the launch of a model in Australia (Oliver 1983).

Interestingly, knowledge and expertise gained from model development were not kept locked by Travelers. The company had assumed a generous open-door policy from its inception and held technical trainings in which knowledge was shared with academics, planners, federal agencies, and catastrophe modelers (Friedman, personal communication, 2012–2017; Mangano, personal communication, 2018; Shorr, personal communication, 2018). Also, the outreach efforts continued in conferences, publications, and participation in several expert committees (NRC 1983, 1992).

At the same time, since the mid-1970s, thanks to the projects, a distressing insight became increasingly clear. The unchecked growth in the number of exposed properties in risk-prone areas in the country had effectuated a significant if yet unknown amplification of the catastrophe potential of those regions. In consequence, the alarm was sounded for more than a decade about the plausibility of impending monumental losses to the insurance industry and

Nat. Hazards Rev., 2022, 23(4): 04022025

society in general, caused by hurricanes impacting large cities such as Houston, Miami, and others (AIRAC 1986; Friedman 1979, 1980, 1987, 1990) or earthquake occurrences in Los Angeles (Friedman 1988, 1991), and San Francisco where damages could reach $24B in 1980 (Wiggins 1978). Unfortunately, these warnings appear to have been voiced in the wilderness, as the response from policymakers to implement mitigation techniques was insufficient (Friedman, personal communication, 2012–2017), and the insurance industry did not see the necessity of moving toward simulation models to better price their perils. In fact, up until 1992 when Hurricane Andrew sent several insurers into insolvency, the industry was still relying on techniques based on historical data to quantify their risk (Chernick 1998). Admittedly, the catastrophe models were imperfect, and even some scholars harbored some reservations about their usefulness (NRC 1978), but arguably they were the best tools available.

Nevertheless, the tide for the adoption of catastrophe models slowly started to change in the mid-1980s. Travelers, as the only company that had modeling capabilities, created the Natural Hazards Research Services (NHRS)-Constitution State Management Company in the mid-1980s, a separate modeling company that provided loss modeling services on portfolios of those external companies (Mangano, personal communication, 2018).

A Public Catastrophe Model for State and Local Governments

In 1992, prompted by the need to provide a tool to state and local governments to conduct loss assessments for risk mitigation planning, FEMA (which, by the mid-1980s, had amassed significant expertise and information; Moore et al. 1985; Jaske 1985; Tetra Tech 1981) and the National Institute of Building Sciences (NIBS) sponsored the creation of the nationally applicable open catastrophe model HAZard US (HAZUS) (Kircher et al. 2006). HAZUS for earthquakes was released in 1997, and the multihazard version (hurricanes and floods) in 2004 (Schneider and Schauer 2006). The creation of HAZUS marked a new phase in catastrophe modeling, in that it was the first large open model, and also led to the creation of a community of practice active until this day.

Further Reflections. Modeling Firms, the Florida Public Model, and Regulation (Mid-1990s–Mid-2000s)

By the early 1990s, two decades had already elapsed since the ARNH in Colorado and its recommendations. Great strides had been made in data availability and knowledge about the physical and societal systems, which allowed developing better and more complex models. Former challenges had been turned into new opportunities. At the same time, new challenges had arisen that joined ranks with the old ones. Friedman discussed these in several articles, published until after his retirement in the early 1990s (CRN 1999). Among the new/old challenges was the question of model accuracy and credibility. Admittedly, there was now a data largesse, but this was mostly applicable to calibrate and validate the modeled damage generation process (i.e., damage produced by individual events). In contrast, the body of data to calibrate and validate the hazard simulations had not grown at the same pace, did not have enough spatiotemporal representativity to afford an equivalent degree of credibility to the modeled frequencies and locations of events, even with the help of Monte Carlo sampling techniques. Consequently, Friedman (1995c) stated that the credibility of both modeled processes should not be considered equivalent especially when formulating interventions that depended on model-generated information. As a corollary, modelers should also be alert against overpromising about accuracy of the models, and users should not expect more from the models than what is warranted.

Other sobering reflections were made by White et al. (2001) from the perspective of policy analysis. Assessing the progress of natural hazard management 20 years after the ARNH they pointed out that, thankfully, loss of life from natural hazards had been declining, but how come, they lamented, that despite the significant knowledge increase the current loss of life levels had not been achieved more rapidly. On the other hand, property losses were steadily increasing despite the increase in knowledge. The best intentions had met with the disconnect between knowledge and policy formulation and implementation.

It was not all bad news, however. Catastrophe models had become the most skilled tools to tie disparate information, and even with the less-than-optimal information they provided, it was possible to find courses of action that would produce "good enough" results.

In the mid to late 1980s, some insurers and reinsurers eventually came to terms with the reality that a switch to catastrophe models was necessary sooner rather than later and that the recent developments in simulation models made it a viable option. Some companies ran loss assessments on their portfolios in the Travelers' NHRS. Others developed their own catastrophe models (BI 1987); and several modeling firms were established (Grossi and Kunreuther 2005; Dong et al. 1988) that drew upon the existing work of Friedman, Steinbrugge, Algermissen, Esteva, Cornell, Blume, and others. The private catastrophe models achieved wide acceptance mostly with (re)insurers after the Loma Prieta earthquake in 1989, but especially after Hurricane Andrew in 1992.

It appears that the private modeling industry quickly became successful, due in some part to the high demand, but also due to the access to proprietary portfolio data. Inventory information and large amounts of damage data spanning long periods of time were made available to modelers by the (re)insurance industry for calibration and validation of their models. With the quick growth of the industry and competition, however, the firms also started to withhold giving information about the details of their models, which constituted a departure from the common open-door approach prevalent in the small modeling community until the early 1990s.

As the popularity and amount of work performed by private models for the insurance and reinsurance industry steadily increased, their applications soon reached the public sector. Insurers began requesting raises of insurance rates based on model projections. However, the idea of using computer models with undisclosed assumptions to determine public matters did not sit well with many lawmakers and government officials (Niedzielski 1996). Moreover, it was not evident that models which may have been useful for characterizing risk over the relatively small and well-defined portfolios of insurers would perform equally well on a state-wide basis. As a result, by 1995, government officials began voicing concerns in Florida, New York, and California (Trigaux 1995; Beller 1995; Ceniceros 1995; Best 1997). These concerns led the State of Florida to establish in 1995 the Florida Commission on Hurricane Loss Projection Methodology (F.S. 627.0628) to evaluate the soundness of the methodology of the catastrophe models, according to modeling standards, while keeping proprietary information confidential. Also, in 2001 a bill was passed to develop a taxpayer-funded open catastrophe model built by Florida universities, the Florida Public Hurricane Loss Model (HB 2145-2000), which was released in 2006.

Today, the number of proprietary and open catastrophe models as well as academic efforts keeps growing, and their outcomes continue to be scrutinized (Weinkle and Pielke 2017). At any rate, policy analysis for natural hazards simply cannot be done without the input of catastrophe simulations as they are the only tools that can model damage potential and its uncertainty.

Closing Remarks

Catastrophe models are the latest and most advanced in a long line of risk assessment tools established over half a century. The first model was developed primarily between 1955 and 1975 in the United States by atmospheric scientist Don G. Friedman. The context that surrounded its creation was shaped by advances in the methods to characterize atmospheric phenomena achieved during WWII, the absence of a suitable tool to ascertain the impact of geophysical events on society, and the availability of the first high-speed computers.

The predictive power of risk assessment tools grew in accordance with the complexity of the problems set before them: from rudimentary averaging of damage data, and the simulation of the national flood insurance program, to the assessment of complex effects of climate change on a global scale. Initially, a purely data archival approach was used; later, the catastrophe model introduced the specification of the damage mechanism as a physics-based probabilistic computer simulation. Subsequent advances continued breaking the processes down into increasingly detailed depictions of the causal links of the modeled natural and sociotechnical systems.

Besides discussing the development of the discipline, this paper reveals some challenges that the early catastrophe model developers encountered and lessons they learned that can be useful today. Modelers, in their quest to enhance the accuracy of risk estimates, achieved remarkable improvements in supplying more intervening variables to increase the descriptive fidelity of catastrophe models. At the same time, tradeoffs emerged, such as the question of how good is good enough in model development. For one, a more granular model does not necessarily imply an enhancement in the accuracy and precision of risk estimations. Some reasons for this include that more comprehensive theories may necessitate additional assumptions to fill the theoretical gaps, which in turn may grow the uncertainty of the model outputs. Also, more data become necessary to calibrate new variables (and resources to get the data), which in turn may also increase the uncertainty of the outputs. Finally, increases in software complexity may lead to defects in the algorithms that also impact the outputs.

From the standpoint of users, the extraordinary complexity of catastrophe models may make it difficult for caveats and limitations to be perceived. To alleviate the possibility of misapplication of model-generated information, the confirmatory paradigm of the model should be disclosed, including the success achieved in validations, and the quality of the data used for validations. For decision-making, users should determine what degree of accuracy is required by the intended application (typical problems for the insurance and reinsurance industries may differ substantially from those of governments), bearing in mind that in the past, increased knowledge did not always result in the desired level of damage reduction. Also, the user should inquire about the potential implications of the model's assumptions, simplifications, and uncertainties on his concrete problem.

Despite these challenges, the role of catastrophe models on important policy decisions around the world remains indispensable. Even though the natural and sociotechnical systems became more difficult to simulate, well used, these models are potent aids to measure and control natural disaster risk. Because of this, consideration of the questions and lessons apparent throughout the history of the discipline, will hopefully contribute to a more robust and meaningful use of these tools in the quest for protecting present day societies from the effects of natural disasters.

Data Availability Statement

No data, models, or code were generated or used during the study.

Acknowledgments

I am very grateful to Don G. Friedman who graciously provided his recollections and information for this paper, as well as to Lori Friedman-Gordon and Matt Friedman whose help was immense. Special thanks to Judy Mitrani-Reiser who was the first to encourage this study. Also, many thanks to all who kindly provided their recollections: Maryellen Bocaccino, Darexa Cosnett, Luis Esteva, Arnoldo Hax, John Mangano, Richard Pfeffer, Anne Wadsworth-Pardo, Anne Kiremidjian, Ron Muskatallo, Enders Robinson, Tapan Roy, John Russo, John Schaake, Bernard Shorr, George Walker, James Wilson, and Herbert Winokur. I am also grateful for help from Philip Berke (UNC-Chapel Hill), Terri Clark (Connecticut Academy of Science & Engineering), Mary Beth Davidson (Travelers Library), Thorleif Kristiansen (Univ. Bergen), Jimi Oke (UMass-Amherst), Elizabeth Pena (Rockefeller Foundation), Marty Reuss (USACE), Graham Village (INFORMA). For any errors, I am alone responsible.

References

AIA (American Insurance Association). 1955. "Report on flood and flood damage of 1955 in the Northeastern States." In *Parsons, Brinkerhoff, Hall & MacDonald engineers*. Shanghai, China: AIA.

AIRAC (All-Industry Research Advisory Council). 1986. *Catastrophe losses: How the insurance system would handle two $7 billion Hurricanes*. Oak Brook, IL: AIRAC.

Algermissen, S. T., and K. V. Steinbrugge. 1984. "Seismic hazard and risk assessment: Some case studies." In *Geneva papers on risk and insurance*, 8–26. Geneva: The Geneva Association.

Angström, A. 1922. "On the effectivity of weather warnings." *Nordisk Statistisk Tidskrift*, 1: 394–408.

ASCE-SEI. 2016. *Minimum design loads and associated criteria for buildings and other structures*. ASCE/SEI 7-16. Reston, VA: ASCE.

Ayre, R. 1975. *Earthquake and tsunami hazards in the United States: A research statement institute of behavioral science*. Boulder, CO: Univ. of Colorado.

Baranoff, D. 2005. "Shaped by risk: The American fire insurance industry, 1790–1920." *Enterprise Soc.* 6 (4): 561–570. https://doi.org/10.1093/es/khi091.

Bates, C. C. 1949. "The status of applied meteorology in the United States in the post-war period." *Bull. Am. Meteorol. Soc.* 30 (6): 199–203. https://doi.org/10.1175/1520-0477-30.6.199.

Beard, L. 1967. *Functional evaluation of water resources system*. Davis, CA: Hydrologic Engineering Center.

Beller, M. 1995. *Insurers, regulators at odds on use of weather-catastrophe models*. New York: Journal of Commerce.

Berke, P., T. Larsen, and C. Ruch. 1984. "A computer system for hurricane hazard assessment." *Comp. Environ. Syst.* 9 (4): 259–269. https://doi.org/10.1016/0198-9715(84)90026-7.

Best. 1997. *Fla. regulator seeks to halt use of hurricane model*. Oldwick, NJ: A.M. Best Company.

BI (Business Insurance). 1987. *E.W.Blanch Co. Spotlight report—Intermediaries. Business Insurance*, 22–24. Wilmington, DE: BI.

Bilham. 1922. "A problem in economics." *Nature* 2733 (109): 341–342.

Brinkmann, W. 1975. *Hurricane hazard in the United States: A research statement institute of behavioral science*. Boulder, CO: Univ. of Colorado.

Ceniceros, R. 1995. *Catastrophe modeling systems sparks controversy in California*. Wilmington, DE: Business Insurance.

Chernick, D. R. 1998. “Pricing the hurricane peril—Change is overdue.” In *Casualty Actuarial Society Forum, Winter*, 23–54. Arlington County, VA: Casualty Actuarial Society.

Cochrane, H. 1975. *Natural hazards and their distributive effects: A research statement institute of behavioral science*. Boulder, CO: Univ. of Colorado.

Collier, S. 2008. “Enacting catastrophe: Preparedness, insurance, budgetary rationalization.” *Econ. Soc.* 37 (2): 224–250. https://doi.org/10.1080/03085140801933280.

Collier, S. 2014. “Neoliberalism and natural disaster: Insurance as political technology of catastrophe.” *J. Cultural Econ.* 7 (3): 273–290. https://doi.org/10.1080/17530350.2013.858064.

Cornell, C. 1968. “Engineering seismic risk analysis.” *Bull. Seismol. Soc. Am.* 58 (5): 1583–1606. https://doi.org/10.1785/BSSA0580051583.

CRN (Catastrophe Reinsurance Newsletter). 1999. *Informa*. London: DYP.

Davies, G. 2017. “The historical presidency: Lyndon Johnson and disaster politics.” *Presidential Studies Q.* 47 (3): 529–551. https://doi.org/10.1111/psq.12384.

Doel, R. 1995. “Interview with Dr. Thomas Malone.” In *Archives American institute of physics*. College Park, MD: Niels Bohr Library.

Dong, W., et al. 1988. “A knowledge-based seismic risk evaluation system for the insurance and investment industries (IRAS).” In *Proc., 9th WCEE Tokio VIII-1083-1088*. Tokyo: Japan Association for Earthquake Disaster Prevention.

Droessler, E. 1989. *Transcript of oral history interview of Thomas F. Malone*. Boulder, CO: Univ. Corporation for Atmospheric Research.

Ericksen, N. 1975. *Scenario methodology in natural hazards research institute of behavioral science*. Boulder, CO: Univ. of Colorado.

ESSA (Environmental Science Services Administration). 1967a. *Studies in seismicity and earthquake damage statistics. Part 1. Environmental science services administration*. Rockville, MD: ESSA.

ESSA (Environmental Science Services Administration). 1967b. *Studies in seismicity and earthquake damage statistics. Part 2. Environmental science services administration*. Rockville, MD: ESSA.

ESSA (Environmental Science Services Administration). 1969. “Studies in seismicity and earthquake damage statistics.” In *Appendix A, and B. environmental science services administration*. Rockville, MD: ESSA.

Esteva, L. 1963. “Regionalizacion sismica de la Republica Mexicana.” *Revista Sociedad Mexicana do Ingenieria Sismica* 1 (1): 31–35.

Esteva, L. 1967. “Criterios para la Construcción de Espectro de Diseño Sísmico.” In *XII Jornadas Sudamericanas de Ingeniería Estructural*, 49–73. Caracas, Venezuela: Instituto de Materiales y Modelos Estructurales.

Evernden, J., R. Hibbard, and J. Schneider. 1973. “Interpretation of seismic intensity data.” *Bull. Seismol. Soc. Am.* 63 (2): 399–422.

Evernden, J., W. Kohler, and G. Clow. 1981. *USGS seismic intensities of earthquakes of conterminous United States*. Washington, DC: USGS.

FEMA. 2018. *Guidance for flood risk analysis and mapping*. Washington, DC: FEMA.

Finnegan, J. 1956. “Statistics of the national board of fire underwriters.” In Vol. XLIII of *Proc., Casualty Actuarial Society*, 82–91. New York: Casualty Actuarial Society.

Fleming, J. R. 2016. *Inventing atmospheric science: Bjerknes, Rossby, Wexler, and the foundations of modern meteorology*. Cambridge, MA: MIT Press.

Flood Commission of Pittsburgh. 1912. *Report of the flood commission of Pittsburgh, Penna*. Pittsburgh: Murdoch, Kerr & Company.

Foster, H. 1952. *Report on floods and flood damage*. New York: Insurance Executives Association.

Foster, H. 1980. “Disaster planning.” In *The preservation of life and property*. Berlin: Springer.

Freeman, J. R. 1932. *Earthquake damage and earthquake insurance*. New York: McGraw-Hill.

French, S. P., and M. S. Isaacson. 1984. “Applying earthquake risk analysis techniques to land use planning.” *J. Am. Plann. Assoc.* 50 (4): 509–522. https://doi.org/10.1080/01944368408976785.

Friedman, D. 1972. “Insurance and the natural hazards.” *ASTIN Bull.* 7 (1): 4–58. https://doi.org/10.1017/S0515036100005699.

Friedman, D. 1950. *An agricultural land planning operation*. Unpublished Rep. Applied climatology course in the summer program in climatology. Cambridge, MA: Massachusetts Institute of Technology.

Friedman, D. 1956. *Report of a study on windstorm losses in Arizona*. Unpublished Rep. Hartford, CT: Travelers.

Friedman, D. 1965. “The flood damage problem as it relates to dwelling property in the USA.” In *Prepared for the NAIC flood and hurricane committee and the national all-industry flood insurance committee*. Hartford, CT: Travelers.

Friedman, D. 1973. “Analysis for earthquake insurance.” In *Earthquakes and insurance*, 34–72. Pasadena, CA: California Institute of Technology.

Friedman, D. 1975. *Computer simulation in natural hazard assessment*. Boulder, CO: Univ. of Colorado.

Friedman, D. 1979. “What if Hurricane Camille had hit Houston? Science and technology policy—Building toward a hurricane disaster.” In *Proc., 145th Meeting of the American academy for the advancement of science (AAAS)*. Washington, DC: American Academy for the Advancement of Science.

Friedman, D. 1980. “Economic impact of windstorms in the United States.” In *Proc., 5th Int. Conf.: Wind Engineering*, 47–59. New York: Pergamon Press.

Friedman, D. 1987. *U.S. Hurricanes & Windstorms*. London: Insurance & Reinsurance Research Group.

Friedman, D. 1988. *Earthquake losses under workers compensation and general liability estimates for a “Worst Case” event in greater Los Angeles*. Chicago: All-Industry Research Advisory Council.

Friedman, D. 1990. “Is Hugo a forerunner of future great hurricanes?” *J. Soc. Insurance Res.* 3 (3): 1–38.

Friedman, D. 1991. “Estimation of damage-producing potential of future natural disasters in the united states caused by earthquakes and storms.” In *Proc., UCLA Int. Conf. on the Impact of Natural Disasters: Agenda for Future Action*, 1–18. Los Angeles: International Studies and Overseas Program.

Friedman, D. 1995a. “Simulating hurricane loss capabilities and estimating damage.” In *Catastrophe reinsurance newsletter*. London: Informa, DYP.

Friedman, D. 1995b. “Numerical modelling and simulation techniques.” In *Catastrophe reinsurance newsletter*. London: Informa, DYP.

Friedman, D. 1995c. “Selection of a portfolio risk assessment procedure Part II.” In *Catastrophe reinsurance newsletter*. London: Informa, DYP.

Friedman, D., and R. Hendrick. 1960. “The role of a meteorologist in an insurance company.” In Vol. 141 of *Weatherwise*. Boston: American Meteorological Society.

Friedman, D., and B. Janes. 1957. *Estimation of rainfall probabilities*. Storrs, CT: Univ. of Connecticut.

Friedman, D., and J. Mangano. 1983. *Computer simulation of the earthquake hazard in Montenegro*. Podgorica, Montenegro: United Nations Development Program.

Friedman, D., and T. Roy. 1966. *Simulation of total flood loss experience of dwellings on inland and coastal flood plains*. Hartford, CT: The Travelers Insurance Co.

Friedman, D., and T. Roy. 1969. *Computer simulation of earthquake hazard*. Unpublished Rep. Hartford, CT: The Travelers Insurance Co.

Friedman, R., C. Ansell, S. Diamond, and Y. Haimes. 1981. *Use of models for water resources management, planning, and policy*. Washington, DC: US Congress, Office of Technology Assessment.

Fuller, J. 1990. *Thor’s Legions: Weather support to the US air force and army, 1937-1987*. Boston: American Meteorological Society.

Fuller, W. 1914. *Transactions of the American Society of Civil Engineers*. Paper 1293, LXXVII, 564–694. Reston, VA: ASCE.

Grossi, P., and H. Kunreuther. 2005. *Catastrophe modeling: A new approach to managing risk*. Berlin: Springer.

Guidi, G. 1979. *Computer programs for seismic hazard analysis—A user manual*. Stanford, CA: Stanford Univ.

Hart, G. 1976. “Estimation of structural damage due to Tornadoes.” In *Proc., Symp. on Tornadoes: Assessment of knowledge and implications for man*, 645–665. Lubbock, TX: Texas Tech Univ.

Hazen, A. 1914. "The storage to be provided in impounding reservoirs for municipal water supply." *Trans. Am. Soc. Civ. Eng.* 77 (1): 1539–1640. https://doi.org/10.1061/taceat.0002563.

Henderson, G. D. 2016. "Helmut Landsberg and the evolution of 20th century American climatology: Envisioning a climatological renaissance." *Wiley Interdiscip. Rev. Clim. Change* 8 (2): e442. https://doi.org/10.1002/wcc.442.

Hinshaw, R. E. 2006. *Living with nature's extremes: The life of Gilbert fowler white*. Boulder, CO: Big Earth Publishing.

Ho, F., R. Schwerdt, and H. Goodyear. 1975. *Some climatological characteristics of hurricanes and tropical storms, Gulf and East Coasts of the United States*. NOAA Technical Rep. NWS 15. Silver Spring, MD: National Oceanic and Atmospheric Administration.

Ho, F., J. Su, K. Hanevich, R. Smith, and F. Richards. 1987. *Hurricane climatology for the Atlantic and Gulf Coast of the United States*. NOAA Technical Rep. NWS 38. Silver Spring, MD: National Oceanic and Atmospheric Administration.

Holland, G. J. 1980. "An analytic model of the wind and pressure profiles in hurricanes." *Mon. Weather Rev.* 108 (8): 1212–1218. https://doi.org/10.1175/1520-0493(1980)108<1212:AAMOTW>2.0.CO;2.

Hoyt, W., and W. Langbein. 1955. *Floods*. Princeton, NJ: Princeton University Press.

HUD (Housing and Urban Development). 1966. "Insurance and other programs for financial assistance to flood victims." In *Proc., 89th Congress, H.R. 11539 Committee on Banking and Currency.* Washington, DC: Dept. of Housing and Urban Development, US Senate.

HUD (Housing and Urban Development). 1971. *Report on earthquake insurance to the Congress of the United States Pursuant to section five of the Southeast Hurricane Disaster Relief Act of 1965, Nov 23, 1971*. Washington, DC: Dept. of Housing and Urban Development.

Humphreys, A., and H. Abbot. 1861. *Report upon the physics and hydraulics of the Mississippi*. Philadelphia: Lippincott and Co.

Jacobs, W. 1947. "Wartime developments in applied climatology." In *Meteorological monographs*. Boston: American Meteorological Society.

Jacobs, W. C., and W. C. Spreen. 1953. "Some climatological problems associated with assignment of engineering design criteria." *Bull. Am. Meteorol. Soc.* 34 (10): 462–467. https://doi.org/10.1175/1520-0477-34.10.462.

Jarvis, C. S. 1936. *Floods in the United States: Magnitude and frequency.* Washington, DC: US Government Printing Office.

Jaske, R. 1985. "FEMA's computerized aids for accident assessment." In *Proc., Int. Symp. Emergency Planning and Preparedness for Nuclear Facilities*, 1 SI204. Vienna, Austria: International Atomic Energy Agency.

Jelesnianski, C. 1972. *SPLASH (Special Program to List Amplitudes of Surges from Hurricanes) NOAA technical memorandum NWS TDL 46.* Silver Spring, MD: National Oceanic and Atmospheric Administration.

Kaplan, M. 1972. "Actuarial aspects of flood and earthquake insurance." In Vol. XXI of *Proc., Conf. Actuaries in Public Practice*, 474–511. Long Grove, IL: Conference of Consulting Actuaries.

Kates, R. W. 1962. *Hazard and choice perception in flood plain management*. Chicago: Univ. of Chicago.

Kircher, C. A., R. V. Whitman, and W. T. Holmes. 2006. "HAZUS earthquake loss estimation methods." *Nat. Hazards Rev.* 7 (2): 45–59. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(45).

Kiremidjian, A. 1976. "Probabilistic hazard mapping: Development of site dependent seismic load parameters." Ph.D. dissertation, Dept. of Civil Engineering, Stanford Univ.

Landsberg, H. E., and W. C. Jacobs. 1951. "Applied climatology." In *Compendium of meteorology*, edited by T. Malone, 976–992. Boston: American Meteorological Society.

Leicester, R., and G. Reardon. 1976. "A statistical analysis of the structural damage by cyclone Tracy." *Civ. Eng. Trans.* 18 (2): 50–54.

Lesso, W., and M. Heine. 1978. "A hurricane simulation model to evaluate effectiveness of building code standards on reducing wind related damage." *Bull. Am. Meteorol. Soc.* 59 (11): 1543.

Maass, A. 1951. *Muddy waters: The army engineers and the nation's rivers*. Cambridge, MA: Harvard University Press.

Maass, A., M. Hufschmidt, R. Dorfman, H. Thomas, S. Marglin, and G. Fair. 1962. *Design of water-resource systems: New techniques for relating economic objectives, engineering analysis, and governmental planning*. Cambridge, MA: Harvard University Press.

Maunder, W. 1970. *The Value of Weather*. London: Methuen.

McGuire, R. 1978. *FRISK: Computer program for seismic risk analysis using faults as earthquake sources*. Washington, DC: USGS.

Metropolis, N., and S. Ulam. 1949. "The Monte Carlo method." *J. Am. Stat. Assoc.* 44 (247): 335–341. https://doi.org/10.1080/01621459.1949.10483310.

Meyer, A. 1921. "Report on prevention of floods in Minnesota River Valley." In *First Biennial Report of the Commissioner of drainage and waters*, 31–100. Minneapolis: Syndicate Printing Co.

Mileti, D. 1975. *Natural hazard warning systems in the United States: A research statement*. Boulder, CO: Univ. of Colorado.

Moore, D., et al. 1985. "The FEMA earthquake damage and loss estimation system (FEDLOSS)." In *Proc., Conf. on Emergency Planning*, edited by J. Carroll. La Jolla, CA: Society for Computer Simulation.

Niedzielski, J. 1996. *Cat modelers say usage is growing*. 9. Erlanger, KY: National Underwriter.

NRC (National Academy of Sciences). 1978. "The U.S. government foreign disaster assistance program." In *Commission on sociotechnical systems*. Washington, DC: National Research Council, NRC.

NRC (National Academy of Sciences). 1983. *Evaluation of the FEMA model for estimating potential coastal flooding from Hurricanes and its application to Lee Country, Florida*. Washington, DC: National Academy Press.

NRC (National Academy of Sciences). 1989. *Estimating losses from future earthquakes. Panel on earthquake loss estimation methodology.* Washington, DC: National Research Council.

NRC (National Academy of Sciences). 1992. "The economic consequences of a catastrophic earthquake." In *Proc., Forum*, 49–76. Washington, DC: National Academy Press.

Oliver, J. 1983. *Insurance and natural disaster management*, 49–126. Singapore: James Cook Univ.

Overman, E. S. 1957. "The flood peril and the Federal Flood Insurance Act of 1956." *Ann. Am. Acad. Political Soc. Sci.* 309 (1): 98–106. https://doi.org/10.1177/000271625730900113.

PBCDEM (Palm Beach County Division of Emergency Management). 1987. *A hurricane damage assessment program for real property.* Palm Beach, FL: PBCDEM.

Perry, J. 1988. *Interview of Thomas F. Malone, February 11, 1988*. Boston: American Meteorological Society.

Pita, G., J. P. Pinelli, K. Gurley, and J. Mitrani-Reiser. 2015. "State of the art of hurricane vulnerability estimation methods: A review." *Nat. Hazards Rev.* 16 (2): 04014022. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000153.

Pita, G. L., J. P. Pinelli, K. R. Gurley, and S. Hamid. 2013. "Hurricane vulnerability modeling: Development and future trends." *J. Wind Eng. Ind. Aerodyn.* 114 (12): 96–105. https://doi.org/10.1016/j.jweia.2012.12.004.

Reed, W. G., and H. R. Tolley. 1916. "Weather as a business risk in farming." *Geog. Rev.* 2 (1): 48–53. https://doi.org/10.2307/207461.

Reitherman, R. 1985. "A review of earthquake damage estimation methods." *Earthquake Spectra* 1 (4): 805–847. https://doi.org/10.1193/1.1585293.

Reuss, M. 1985. "Andrew A. Humphreys and the development of hydraulic engineering: Politics and technology in the Army Corps of Engineers, 1850-1950." *Technol. Cult.* 26 (1): 1–33. https://doi.org/10.2307/3104527.

Reuss, M. 2003. "Is it time to resurrect the Harvard water program?" *J. Water Resour. Plann. Manage.* 129 (5): 357–360. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:5(357).

Robinson, E. 2015. *MIT geophysical analysis group*. London: Goose Pond Press.

Rojahn, C., R. Sharpe, R. Scholl, A. Kiremidjian, R. Nutt, and R. Wilson. 1986. "Earthquake damage and loss evaluation for California." *Earthquake Spectra* 2 (4): 767–782. https://doi.org/10.1193/1.1585410.

Scawthorn, C. 2008. "A brief history of seismic risk assessment." In *Risk assessment, modeling, and decision support*, edited by A. Bostrom, S. French, and S. Gottlieb, Berlin: Springer.

Schaake, J., and M. Fiering. 1967. "Simulation of a national flood insurance fund." *Water Resour. Res.* 3 (4): 913–929. https://doi.org/10.1029/WR003i004p00913.

Schneider, P., and B. Schauer. 2006. "HAZUS—Its development and its future." *Nat. Hazards Rev.* 7 (2): 40–44. https://doi.org/10.1061/(ASCE)1527-6988(2006)7:2(40).

Schwerdt, R., F. Ho, and R. Watkins. 1979. *Meteorological criteria for standard project hurricane and probable maximum hurricane windfields, Gulf and East Coasts of the United States*. Technical Rep. NWS 23. Silver Spring, MD: National Oceanic and Atmospheric Administration.

Sellers, W. 1956. *Studies in synoptic climatology.* Arlington, VA: Office of Naval Research.

Spiegler, D. 1996. "A history of private sector meteorology." In *Historical essays on meteorology 1919–1995*, edited by J. Fleming, 417–441. Boston: American Meteorological Society.

Spillman, W. J., H. R. Tolley, and W. G. Reed. 1916. "The average interval curve and its application to meteorological phenomena." *Mon. Weather Rev.* 44 (4): 197–200. https://doi.org/10.1175/1520-0493(1916)44<197:TAICAI>2.0.CO;2.

SWFRPC (Southwest Florida Regional Planning Council). 1982. *Southwest Florida Hurricane loss study.* Fort Myers, FL: SWFRPC.

Tetra Tech. 1981. *Coastal flooding storm surge model. Parts 1, 2, and 3*. Washington, DC: Federal Emergency Management Agency.

Thom, H. 1952. "Seasonal degree-day statistics for the United States." *Mon. Weather Rev.* 80 (9): 143–147.

Thom, H. 1960. "The distribution of annual tropical cyclone frequency." *J. Geophys. Res.* 65 (1): 213–222. https://doi.org/10.1029/JZ065i001p00213.

Trigaux, R. 1995. "Computer models for Hurricane risk raise debate, rates." *St. Petersburg Times*, May 22, 1995.

Tubbesing, S. 1979. *Natural hazards data resources: Uses and needs*. Boulder, CO: Univ. of Colorado.

USASC (United States Army Signal Corps). 1874. "Annual report of the chief signal officer made to the secretary of war for the year." In *United States army signal corps*. Washington, DC: US Government Printing Office.

Van Cleef, E. 1917. "The influence of weather on street-car traffic in Duluth, Minnesota." *Geogr. Rev.* 3 (2): 126–134. https://doi.org/10.2307/207524.

Vanmarcke, E., and R. Whitman. 1971. *Optimum seismic protection for new building construction in eastern metropolitan areas*. NSF-Grant GK-27955X. Cambridge, MA: Massachusetts Institute of Technology.

Veneziano, D. 1975. *Probabilistic and statistical models for seismic risk analysis*. Cambridge, MA: Massachusetts Institute of Technology.

Vogt, D., and W. Jackson. 1993. *National infrastructure information system/regional impact module*. Oak Ridge, TN: Oak Ridge National Laboratory.

Wadsworth, G. 1948. *Short range and extended forecasting by statistical methods*. Technical Rep. No. 105-38. Washington, DC: Air Weather Service.

Walker, G. 1997. *Financial risk management for natural catastrophes*. Edited by N. R. Britton and J. Oliver. Sydney, NSW, Australia: AON Group Australia.

Warrick, R. 1975. *Drought hazard in the United States: A research statement*. Boulder, CO: Univ. of Colorado.

Weatherwise. 1954. *The travelers weather research center.* Boston: American Meteorological Society.

Weinkle, J., and R. Pielke. 2017. "The Truthiness about hurricane catastrophe models." *Sci. Technol. Hum. Values* 42 (4): 547–576. https://doi.org/10.1177/0162243916671201.

White, G. 1945. *Human adjustment to floods*. Chicago: University of Chicago Press.

White, G. 1974. "Natural Hazards Research: Concepts, methods, and policy implications." In *Natural hazards: Local, national, global*, 3–16. Oxford, UK: Oxford University Press.

White, G. 1975. *Flood hazard in the United States: A research assessment*. Boulder, CO: Univ. of Colorado.

White, G., and J. Haass. 1975. *Assessment of research on natural hazards*. Cambridge, MA: MIT Press.

White, G., R. Kates, and I. Burton. 2001. "Knowing better and loosing even more: The use of knowledge in hazards management." *Global Environ. Change Part B: Environ. Hazards* 3 (3): 81–92. https://doi.org/10.3763/ehaz.2001.0308.

Whitman, R. 1973. *Damage probability matrices for prototype buildings*. Structure Publication Rep. No. 38. Cambridge, MA: Massachusetts Institute of Technology.

Wiener, N. 1942. *The extrapolation, interpolation and smoothing of stationary time series with engineering applications*. DIC Contract 6037. Washington, DC: National Defense Research Council.

Wiggins, J. 1978. *Building losses from natural hazards: Yesterday, today and tomorrow.* Alexandria, VA: National Science Foundation.

Willett, H. 1955. "A study of the Tropical Hurricane along the Atlantic and Gulf Coasts of the United States." In *Proc., Inter-Regional Insurance Conf.* New York: Inter-Regional Insurance Conference.

Willey, R. 1989. *Hydrologic engineering center: A quarter century 1965-1989*. Washington, DC: USACE.

Winokur, H. 1967. "Decision-theoretic aspects of time series models." Ph.D. thesis, Div. of Engineering and Applied Physics, Harvard Univ.