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Billion-Dollar Natural Disasters: What Does the Future Look Like?

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Abstract

The average cost of natural disasters and damage to the U.S. economy has increased each year from approximately $35 billion in 1980 to $300 billion in 2017. This increase in the cost of natural disasters could be due to an increase in the strength and frequency of natural disasters and/or growth in the U.S. economy. We forecast the cost of natural disasters by fitting probability distributions to the historical cost of billion-dollar disasters. We model the cost of natural disasters based on all weather-related natural disasters that cost more than $1 billion since 1980 and based only on those natural disasters that cost more than $1 billion that occurred in the past 20 years. Using the data from 1980 to 2018, the model forecasts the annual expected cost to be $52 billion. However, if only the recent disaster data is used to the fit the model, we forecast the expected annual cost to be $93 billion.

Keywords
Natural disasters, economic impacts, probabilistic forecast, Monte Carlo simulation.

1. Introduction
The United States has sustained 250 weather and climate disasters from 1980 to 2018 with a cost of $1 billion or more. The total cost of all the billion-dollar natural disasters in these 38 years exceeds $1.7 trillion [1]. These costs are adjusted for inflation using the 2018 Consumer Price Index. The average cost of billion-dollar natural disasters and damage to the U.S. economy have increased from $35 billion in 1980 to $300 billion in 2017. This increase could be due to an increase in the strength and frequency of natural disasters and/or the increase in the U.S. real gross domestic product (GDP). The frequency of billion-dollar natural disasters has increased by 2.5 times from 1980 to 2018. Twenty billion-dollar disasters occurred in the United States from 1980 to 1985, and 72 billion-dollar natural disasters occurred from 2013 to 2018. The real U.S. GDP was $6.95 trillion in 1980 and $18.93 trillion in 2018 [2]. GDP increased by more than 172% from 1980 to 2018, but the average cost of billion-dollar disasters increased by more than 750%. The economic cost of natural disasters in the United States has increased faster than the nation's GDP.

Modeling the historical data of billion-dollar disasters can provide an understanding of the past and provide a means to forecast the cost of future disasters. This data could be modeled by time series methods, regression analysis, causal analysis, and simulations. It is difficult to understand the underlying factors that might affect the cost of billion-dollar disasters. Multiple factors such as the U.S. GDP, increasing population, climate change, and more frequent and more dangerous disasters can affect the overall cost of disasters. It is hard to understand and use all these factors in a model. See [3] for a good review of previous studies that estimate the costs of natural disasters.

This paper uses probabilistic models to forecast billion-dollar disasters in the future. The billion-dollar natural disasters are recorded and published by the National Oceanic and Atmospheric Administration (NOAA) [1]. NOAA categorizes these disasters into seven types: drought, flood, freeze, severe storm, tropical cyclone, wildfire, and winter storm. This paper models each type of disaster separately and fits a probability distribution for the frequency and the cost for each type of disaster. We simulate each type of disaster and combine the simulation of each type of disaster to generate an annual cost of billion-dollar disasters in the United States. Fitting probability distributions to all the data from 1980 to 2018 assume that the frequency and costs of these disasters have remained constant in the preceding 38 years. Since that might be an unrealistic assumption, we also fit probability distributions to only the most recent data for each type of disaster (approximately 20 years' worth of data). This paper presents the simulated results in the form of a risk curve (or probability of exceedance) to present a picture of risk that the United States faces from natural disasters. A probabilistic forecast of the costs of billion-dollar disasters provides insights into the risks the United States faces due to natural disasters. Policymakers can use these types of models to develop strategies and allocate resources for how to prepare for these large-scale disasters.

This paper is divided into four sections. Section 2 presents the methodology and the steps taken to model the billion-dollar disasters. The analysis includes two models to estimate the cost to the U.S. economy. Section 3 discusses the results of fitting distributions to the data and running the Monte Carlo simulation. The conclusion highlights the risk of natural disasters expressed in costs in order to understand the benefits of increasing the country's preparedness to natural disasters and enhancing the resilience of the nation.

2. Methodology

NOAA annually records and publishes natural disasters where the cost exceeds $1 billion. Figure 1 shows substantial variation from year-to-year in the costs of billion-dollar disasters from 1980 to 2018. As seen in Figure 1, the total cost of all disasters in 2005, 2011, and 2017 are significantly higher than the other years. This is largely due to a few extreme events. The abrupt increase in total cost up to nearly $221 billion dollars in the year 2005 is largely due to Hurricane Katrina. The high cost in 2011 is due to Hurricane Irene. Several droughts, Hurricane Harvey, and Hurricane Maria generate large costs in 2017. We initially attempted to fit a probability distribution to this entire data set, but no distribution fit well to the observed data or provided good predictions.

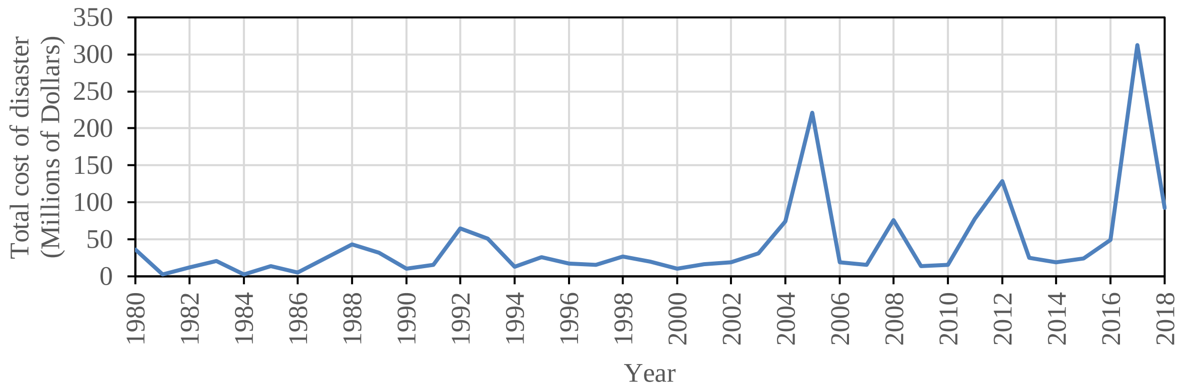

Figure 1: Total cost of billion-dollar natural disasters from the year 1980 up to the year 2018

A better approach than fitting a model to all the data is to fit separate models to each type of disaster. Analyzing each type of disaster also provides a better understanding of billion-dollar disasters. Modeling each type of disaster separately can make the model more robust to changes in the data. Using probabilistic models rather than deterministic models reflects the uncertainty that is inherent in forecasting future economic costs from natural disasters.

We use the billion-dollar disaster data for each type of disaster. First, we model the distributions of each type of billion-dollar natural disasters separately: drought, flood, freeze, severe storm, tropical cyclone, wildfire, and winter storm. Second, we fit a discrete distribution to the annual frequency of each type of disaster. This analysis also tests to see if the frequency of any of these disasters is correlated. If the frequencies are highly correlated, the model will incorporate this correlation. We assume the cost for each type of a billion-dollar disaster is identically and independently distributed. Third, we fit a probability distribution for each type of billion-dollar disaster. We use the Akaike information criterion (AIC) and the loglikelihood to assess the goodness of fit and choose a distribution. We also attempt to use common distributions across many of the disasters. If a single distribution rates highly in the AIC and loglikelihood metrics for many different disasters, we attempt to use that same distribution for each type of disaster.

JMP Statistical Software is used to fit a continuous random variable for each type of disaster. We fit the costs for each type of disaster to the following continuous distributions: Johnson with a lower bound, sinh-arcsinh (SHASH), lognormal, generalized log, gamma, normal mixtures (2 and 3), Weibull, extreme value, exponential, and normal. Model 1 uses all the historical data from 1980 to 2018 to model the costs of natural disasters.

Model 2 follows the same steps as Model 1 with one important difference—Model 2 only uses the most recent disaster data as opposed to using all of the data from 1980 to 2018 as in Model 1. Figure 2 depicts the number of each billion-dollar disaster by year. There appears to be an increase in the number of billion-dollar disasters beginning in 1998. We examine each disaster separately and identify a year in which the annual frequency appears to change. After identifying the year in which the annual frequency changes, we follow all of the above steps to fit a probability distribution for the frequency and the cost for each type of disaster, but we use the data from that year until 2018 to fit the distributions.

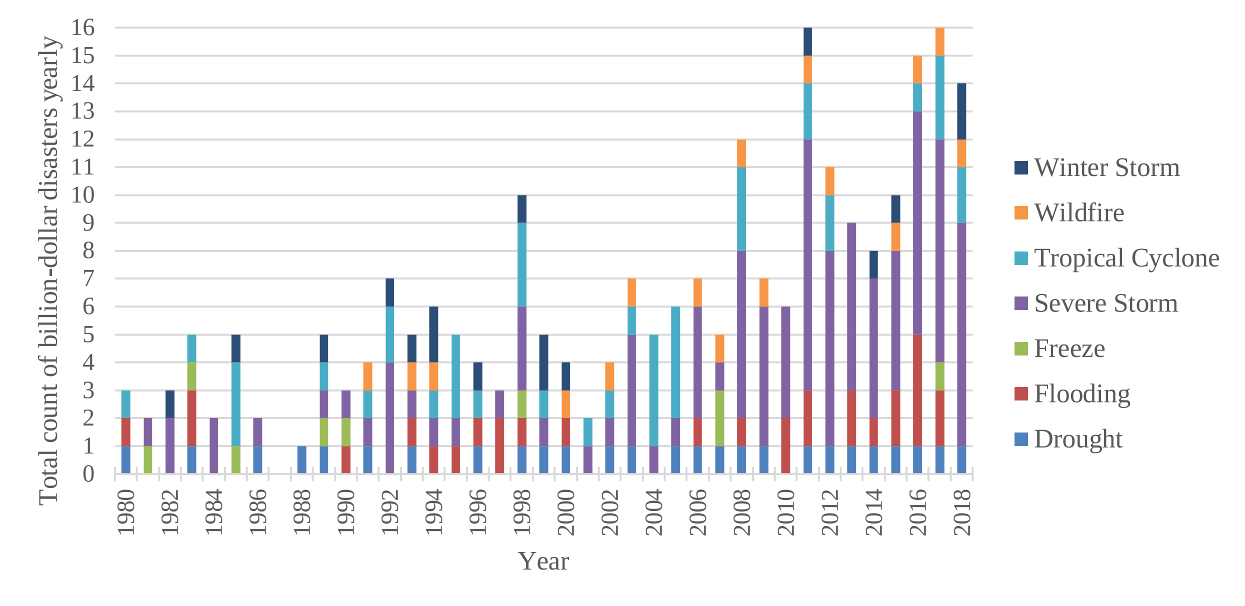

Figure 2: Frequency of each type of billion-dollar natural disasters from 1980-2018

A single trial in the Monte Carlo simulation begins by randomly generating the number of billion-dollar disasters that occurs in a single year for each of the seven disasters. For each simulated disaster, we randomly generate the cost of that disaster from the probability distribution that best fits that type of disaster. We calculate the total cost of billion-dollar disasters in a single trial by adding up all of the costs of individual disasters. This process is repeated 100,000 times to generate a simulated probability distribution of the annual costs of billion-dollar disasters.

3. Results

3.1 Fitting distributions

This paper analyzes, fits distributions, and simulates all the billion-dollar natural disasters in the U.S. economy from 1980 to 2018. When all the data is included, the annual frequencies of drought and wildfire have a correlation equal to 0.43, and the annual frequencies of flood and severe storm have a correlation equal to 0.48. These are the only two correlations greater than 0.4. It is reasonable that these disasters are correlated because hot and dry weather can lead to more droughts and wildfires, and rainy weather can lead to more severe storms and floods. If just the recent disasters are analyzed, the correlation between droughts and wildfires increases to 0.64, and the correlation between floods and severe storms is 0.37. Both Model 1 and Model 2 incorporate the correlation between drought and wildfire and between flood and severe storm so that the simulated number of disasters for these four types of disasters exhibit these correlations. The annual frequency of each of the other three disasters (freeze, tropical cyclone, and winter storm) is treated as independent of the frequency of the other types of disasters.

Table 1 depicts the distribution for the annual frequency for each distribution, the year in which data for Model 2 begins (i.e., the year in which the annual frequency changes), and the parameters for each distribution for both Model 1 and Model 2. These parameters are based on the data visualized in Figure 2. The Poisson distribution is used to model the number of events for freeze, tropical cyclone, winter storm, severe storm, and flood. The parameter λ (average number of annual events) for the Poisson distribution is given in Table 1 for these disasters. The number of droughts or wildfires never exceeded 1 in any given year from 1980 to 2018, and the frequency of each of these two disasters is modeled as a Bernoulli random variable with the probability p. The annual frequency of all the disasters except for freeze increases, and the year in which the annual frequency changes are depicted in Table 2. Since the annual frequency of freeze appears to remain constant, we use the data for freeze from 1980 to 2018 in Model 2.

Table 1: Distributions on the annual frequency

Disaster type	Type of distribution	Model 1 parameter	Year Model 2 begins	Model 2 parameter
Freeze	Poisson	$\lambda = 0.23$	1980	$\lambda = 0.23$
Tropical cyclone	Poisson	$\lambda = 1.07$	2004	$\lambda = 1.4$
Winter storm	Poisson	$\lambda = 0.44$	2009	$\lambda = 0.5$
Drought	Bernoulli, correlated with wildfire	$p = 0.67$	2000	$p = 0.84$
Wildfire	Bernoulli, correlated with drought	$p = 0.41$	2000	$p = 0.68$
Severe storm	Poisson, correlated with flood	$\lambda = 2.7$	2006	$\lambda = 5.85$
Flood	Poisson, correlated with severe storm	$\lambda = 0.74$	2006	$\lambda = 1.3$

Figure 3 shows the Johnson distribution fitted to the histogram of the costs of severe storms. Table 2 shows the loglikelihood and AIC for the distributions for the severe storm based on JMP. The Johnson distribution (with a lower bound) fits the best to the historical data of severe storm. The SHASH distribution's AIC and loglikelihood values are very similar to that of the Johnson distribution. The two distributions look very similar and using either of these two distributions to model the costs of severe storms is reasonable. The Johnson distribution perhaps underestimates the likelihood of extreme costs, and three severe storms cost more than \$9 billion, which the Johnson distribution has trouble capturing. Despite this deficiency, the Johnson distribution provides a good fit for every type of disaster except for the costs of recent winter storms. We prefer to use the same type of distribution for as many disasters as possible and we select the Johnson distribution to model the cost of each type of disaster except for winter storm. The Weibull distribution provides the best fit for the cost of recent winter storms.

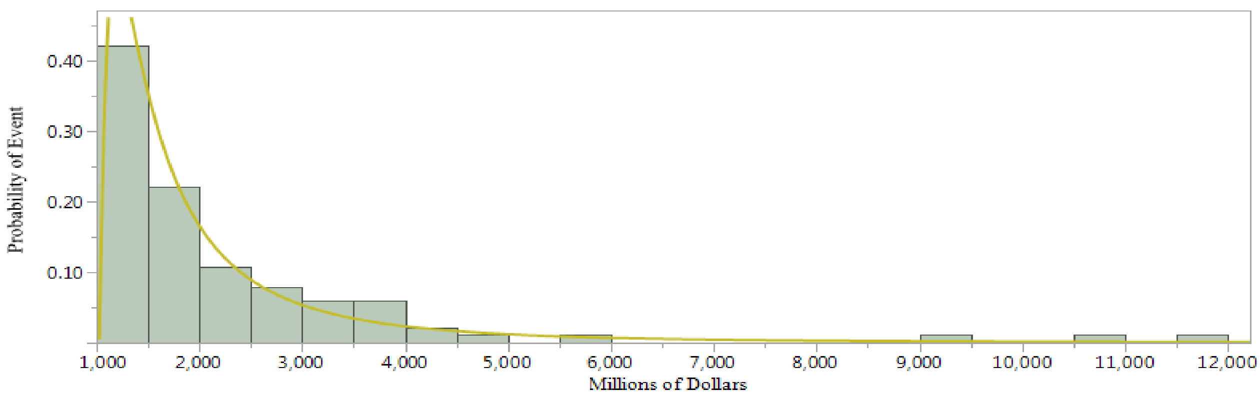

Figure 3: Fitted Johnson distribution to severe storm dollar value during the period 1980-2018.

Table 2: Distributions comparison for severe storm, 1980-2018

Distribution	-2*LogLikelihood	AICc
Johnson	1680	1688
SHASH	1682	1691
Lognormal	1735	1739
Generalized log	1735	1741
Gamma	1766	1770
Normal 2 mixture	1762	1772

Normal 3 mixture	1762	1779
Weibull	1793	1797
Extreme value	1793	1797
Exponential	1828	1830
Normal	1861	1865

3.2 Simulating economic costs

Figure 4 shows a histogram of the simulated annual costs for all billion-dollar disasters for Model 1, which is based on all the data from 1980 to 2018. The expected cost is $52 billion with a standard deviation of $95 billion. There is a 10% chance that the total annual cost will exceed $100 billion. Figure 4 shows that the distribution is very skewed to the right. The vast majority of the simulations result in costs less than $80 billion. However, some simulations result in costs of $200, $300, or even $400 billion. The chance of costs exceeding $300 billion is very small, however.

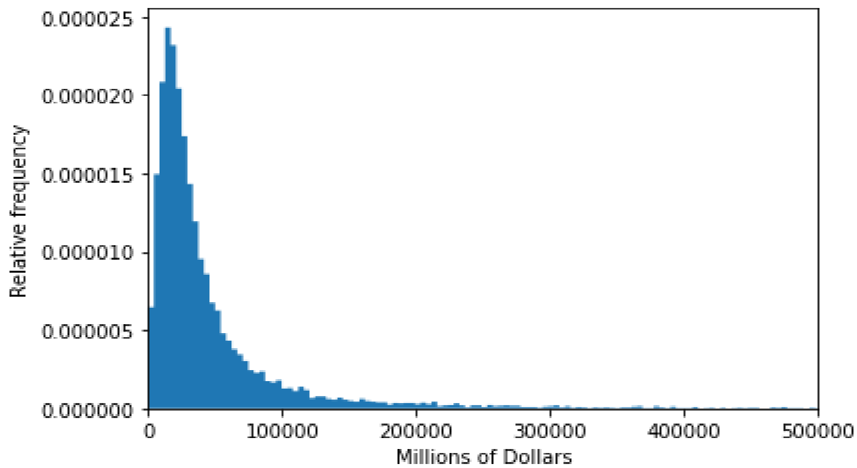

Figure 4: Histogram of annual costs based on Model 1 (all data, 1980-2018)

Figure 5 shows a risk curve or probability of exceedance for the annual costs. This figure shows how bad the annual costs could be. The median annual cost is about $30 billion, and there is an 80% chance the cost will exceed $20 billion. There is a 10% chance that the cost of billion-dollar disasters will exceed $100 billion and about a 5% chance that the cost will exceed $150 billion. Model 1 suggests that the United States should plan for $20 to $100 billion in economic losses from billion-dollar disasters, but the losses could be as large as $200 to $300 billion.

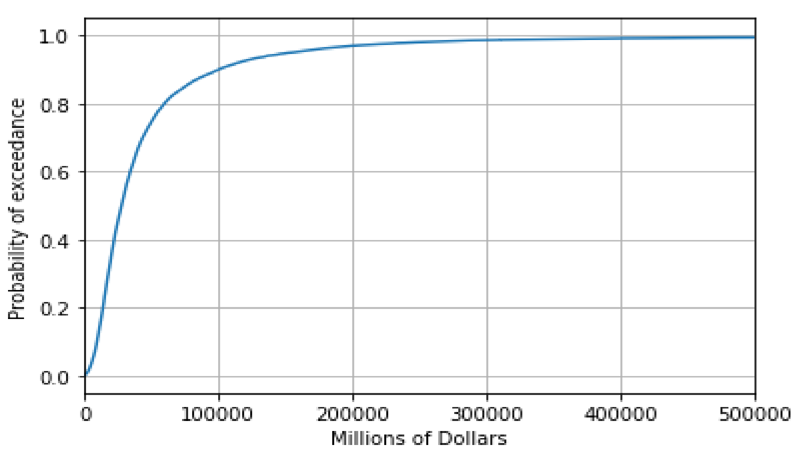

Figure 5: Risk curve for all the billion-dollar natural disasters during the period 1980-2018

The Monte Carlo simulation of Model 2, which is based on the most recent data, results in an expected cost of $93 billion with a standard deviation of $120 billion. There is a 10% chance that the economic costs will exceed $175 billion in a single year. The annual cost of disasters based on using just the recent data is almost twice the annual cost based on using all of the data. Model 2 suggests that the United States should plan for about $40 to $175 billion in economic costs from billion-dollar natural disasters with losses that could be as large as $300 or even $400 billion.

4. Conclusion

This paper forecasts the economic consequences of billion-dollar natural disasters using Monte Carlo simulation. Two models are designed. Model 1 uses all the data from 1980 to 2018, and Model 2 uses only the most recent data. The annual frequency and cost for each of the seven different types of disaster are modeled separately. These separate costs are combined into a single annual cost. Monte Carlo simulation enables us to demonstrate the uncertainty that exists in trying to forecast the annual cost of billion-dollar disasters in the United States.

There is a big difference in costs based on whether all the data is used or only the most recent data is used to forecast the risks of billion-dollar disasters. Recent data captures the change in the frequency of billion-dollar disasters over the last 38 years (1980-2018). The years with five or more billion-dollar disasters include 1983, 1985, 1989, 1992-1995, 1998-1999, and 2003-2018. The costs in Model 2 are almost twice as large as the costs in Model 1. Both models demonstrate that tropical cyclones (i.e., hurricanes) have the most severe impact on the U.S. economy. The cost from tropical cyclones average more than $50 billion in a year. Even though tropical cyclones incur the largest cost to the economy, the most frequent billion-dollar disaster is a severe storm. With an average cost of more than $10 billion per year, severe storms have the second most impact. Droughts, with an average cost of $5 billion, have the third-largest impact. The cost to the U.S. economy by tropical cyclones is approximately 5 times more than severe storms. Extreme disasters like Hurricane Katrina, Hurricane Harvey, and Hurricane Maria have each resulted in $93 billion or more in economic costs.

Since some of the increase in the cost of the billion-dollar disasters is likely due to the growth in GDP, a future extension to this work could include a model of GDP so that the forecast of the cost of natural disasters incorporates the growth in GDP. NOAA also provides the number of fatalities caused by these billion-dollar disasters. Fatalities could also be forecast in a similar way to the economic costs. These types of models can help policymakers understand the risk of large-scale natural disasters and help them better prepared and create more resilient societies.

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