

SHOULD WE EXPECT A TRILLION DOLLAR ATLANTIC HURRICANE SEASON BY THE END OF THE 21ST CENTURY?

Kieran Bhatia

ABSTRACT

Economic losses due to tropical cyclone landfalls occur in discrete, random incidents, and therefore can be modelled using a Bayesian compound Poisson process. This model is generated by multiplying two individual distributions, one involving the incident frequency and the other specifying the incident size. This study's Bayesian compound Poisson model is applied to the annual normalized economic damages caused by Atlantic tropical cyclones making landfall in the continental United States. The number of landfalling storms is fit well by the Poisson model and the monetary damage caused by individual storms is fitted by the truncated Pareto I distribution. Predictive Bayesian versions of each of these models are used. The ability of the compound Poisson model to predict future annual tropical cyclone economic damage is tested using twentieth century data. The Atlantic tropical cyclone seasons between 1900 and 1949 are used as training data while the tropical cyclone seasons between 1950 and 1999 are used as verification. After confirming the model's predictive capabilities, it is then applied to late twenty-first century predictions. CMIP5 results from Knutson et al. (2013) are used to adjust the Poisson and Pareto accordingly due to climate projections of tropical cyclone frequency and strength. The adjusted Bayesian compound Poisson model indicates that a trillion dollar North Atlantic hurricane season is within the realm of possibilities. The model represents an approach to evaluating the ramifications of climate projections for tropical cyclones and suggests some mitigation procedures should be considered.

1. INTRODUCTION

Since 1900, hurricanes and tropical storms (tropical cyclones) making landfall in the United States (U.S.) have resulted in over a trillion dollars in economic damage, adjusted to 2005 levels of inflation, wealth, and population distribution (Pielke et al. 2008). These natural disasters clearly have a significant societal impact so it is important to understand how climate change could lessen or increase the influence of these storms. Thus far, there is agreement in the literature that normalized annual losses due to tropical cyclones (TCs) have not shown any significant trend from 1900-2008 (Willoughby 2012a). However, by the end of the twenty-first century, multiple climate models are expecting different distributions for the frequency and strength of TCs. Understanding the financial ramifications for these predicted changes is an area of concern for insurance and reinsurance industries as well as society in general. Future economic damage due to TC landfalls would vary based on both their predicted change in frequency and intensity. Therefore, to analyze the magnitude of future damages, we need to employ a statistical technique that represents both of these distributions realistically and multiply them together to obtain total annual damage.

The Bayesian compound Poisson model is an appropriate technique for forecasting annual economic losses while accounting for uncertainties. The particular compound model used in this study represents the number of landfalling TCs per year using the Poisson distribution and the monetary damage associated with each TC using the truncated Pareto distribution. The Poisson distribution is frequently used to model TC landfall frequency because mean landfall frequency shows no trend during the available historical record, the number of events in each year is independent, and the mean and variance of the annual number of landfalls are both approximately equal to the same parameter λ (Katz 2002).

TC damage has been modelled mainly with the lognormal (Katz 2002), Pareto I (Coia and Huang 2013), truncated Pareto I (Englehardt 1996), and cluster truncated Pareto I distribution (Huang et al. 2013). During the last 100 years, the most damaging 10% of Atlantic hurricane seasons caused roughly 64% of the total damage, which suggests the data are dominated by rare, costly events (Willoughby 2012b). The heavy-tailed nature of the data implies that the Pareto distribution is more appropriate than the log-normal distribution for modeling economic damage associated with TC landfall. The truncated version of the Pareto I is used here because physical laws prevent cyclones from exceeding a certain strength, and they therefore should be fundamentally limited to a threshold value of normalized economic damage (Emanuel 1988). Finally, the truncated Pareto I was selected over the cluster truncated version because it can be altered to account for future climates in a more physically justifiable way.

The skill of the Bayesian compound Poisson model was tested using the twentieth century normalized hurricane economic damage dataset (Pielke et al. 2008). The fifty-year period between 1900 and 1949 served as data inputted into the predictive Bayesian model, and the fifty hurricane seasons between 1950 and 1999 was used as verification for the model. A two-sample Kolmogorov-Smirnov test for the predictive cumulative distribution function (CDF) and the verification CDF reveals the prediction fits the data at a significant level. These results justified using a similar model to predict annual economic damage for hurricane seasons at the end of the twenty-first century.

The model for the late twenty-first century forecast can be adjusted based on the expected changes in the frequency and strength of landfalling hurricanes and tropical storms. To assess how total economic losses due to TCs could change based on future climate projections, results from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) for 2081-2100 presented in Knutson et al. (2013) are used. The exact methodology for changing the distributions is discussed. After updating the frequency and incident size distributions, a CDF for total losses is again computed using the Bayesian compound Poisson model and compared to predictions using the model with no climate change. The potential for a TC season exceeding one trillion dollars in economic damage for the US is then addressed. It is important to note that this question of whether a hurricane season can exceed a trillion dollars has been previously analyzed (Willoughby 2012b). However, the approach in this work distinguishes itself from the previous study because of its more statistically rigorous methodology and use of climate projections.

2. Data and Methodology

Pielke et al. (2008) normalizes U.S. hurricane damage from 1900-2005 to 2005 values using two methodologies (data available at http://sciencepolicy.colorado.edu/publications/special/normalized_hurricane_damages.html). The methodology proposed by Pielke and Landsea (1998) is more mathematically rigorous than the Collins and Lowe (2001) technique, so it is used to produce all normalized losses for TCs in this study. Pielke and Landsea's (1998) dataset focuses on total economic damage related to direct losses from hurricane landfalls and not indirect damage and longer-term macroeconomic effects. The normalization procedure adjusts for changes in inflation and wealth at the national level and changes in population at the coastal county level. The normalized data provides an estimate of the economic damage that would occur if storms from the past made landfall under the 2005 societal conditions. The most damaging single storm in their record is the 1926 Great Miami storm, with 157 billion dollars in normalized damage. The estimated damages of past TCs under 2005 conditions confirm that society is becoming increasingly vulnerable to hurricane impacts (i.e. Hurricane Andrew resulted in 26.5 billion dollars in economic losses in 1992 and normalized to 2005 levels, the losses would exceed 58 billion dollars).

Both Bayesian compound Poisson models, the hindcast for the second half of the twentieth century and the forecast for the late twenty-first century, are created following the same general procedure. As previously mentioned, the Poisson distribution is selected to describe the probability of experiencing different number events over a planning period. The Poisson distribution is defined by one parameter, λ , equal to the mean of the distribution as well as the variance. However, λ has some uncertainty so the gamma prior distribution is used to quantify the uncertainty. The gamma distribution probability density function (PDF) for λ is described by the following equation:

$$f(\lambda) = \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\beta\lambda} \quad (1)$$

where the α controls the shape of the gamma distribution and β controls the scale of the distribution. For a well-behaved gamma distribution,

$$\beta = \alpha / \text{Ex}(\lambda) \quad (2)$$

The larger the α , the more confidence shown in the expected value of α . Smaller values of β result in broader gamma distributions. After deciding on the appropriate gamma prior, the marginal distribution of the gamma prior can be multiplied by the Poisson sampling distribution and then integrated over all possible values of λ to obtain the predictive distribution of the annual number of landfalling TCs. The predictive distribution is a version of the negative binomial distribution which accurately conveys the uncertainty in λ :

$$p(n \mid \alpha, \beta, n_1, n_2, \dots, n_I) = \frac{(\beta + I)^{\alpha + I \bar{n}_i} \Gamma(n + \alpha + I \bar{n}_i)}{n! \Gamma(\alpha + I \bar{n}_i) (\beta + I + 1)^{n + \alpha + I \bar{n}_i}}, \quad n = 1, 2, \dots, \infty \quad (3)$$

where n is the number of landfalling hurricanes during a year, α and β are the parameters from the gamma prior distribution, \bar{n} is the average of the available data, and I is the number of data points. After inputting the appropriate parameter estimates based on inferred prior information and data, random variables from the negative binomial distribution shown in equation 3 can be generated using a Monte Carlo simulation. For the entirety of this paper, 10,000 simulations were used because the parameters changed negligibly when more simulations were added.

The second component of the compound Poisson model is the Bayesian Truncated Pareto I distribution, which describes the economic damages associated with each landfalling TC. The scale parameter ϕ for the Pareto distribution is not known precisely so a gamma prior distribution is used. The same interpretation of α and β from the prior distribution for λ applies except now they convey the uncertainty in ϕ . If there is no information in the literature, ϕ can be determined from historical data using this equation:

$$\phi = \left(\frac{1}{J} \right) \sum_{j=1}^J \left(\frac{z_j}{Z_0} \right) \quad (4)$$

where J is the number of observations, z_j is the cost of the j th TC landfall, and Z_0 is the realistic minimum cost of a TC landfall. After deciding on the appropriate parameters in the gamma prior distribution (equation 1) for ϕ , the predictive Bayesian version of the Truncated Pareto I distribution can be determined:

$$F(z) = \frac{1 - \left[\frac{\beta + J \overline{\ln(z_j)} - J \ln Z_0}{\ln z + \beta + J \overline{\ln(z_j)} - (J+1) \ln Z_0} \right]^{J+\alpha}}{F(Z_{\max})} \quad (5)$$

in which z is the economic damage associated with a TC landfall, Z_{\max} is the maximum economic damage that could result from one TC landfall, and z_j , Z_0 , and J are the same as in equation 4. After carefully selecting the parameters based on professional expertise and academic sources, random variables from the predictive Bayesian Truncated Pareto I distribution shown in equation 5 can be generated using a Monte Carlo simulation. Random variables between 0 and 1 are inputted into $F(z)$, and the equation is solved for z to get incident sizes. The product of the 10,000 simulated values of the annual number of landfalling TCs can then be multiplied by the 10,000 simulated values of the economic damage of TCs to produce 10,000

data points for annual total damage. These datapoints can be then binned using a preferred method¹ and the PDF and CDF can be created. This total damage data can provide information on the expected cost for an individual hurricane season as well the median and 95% exceedance cost.

3. Results and Discussion

a. 1950-1999 Hindcast

The procedure for creating the Bayesian compound Poisson model for the hindcast of 1950-1999 annual TC economic damage is discussed first. Following the procedure outlined in section 2, the gamma prior distribution for the Poisson variable λ needs to be determined. Based on the long-term mean in the number of U.S. landfalls per year, an appropriate expected value for λ is 2 TCs. An α of 30 was selected to show high confidence in the expected value of λ because of the published work documenting the long-term mean in the number of landfalling storms per year (Landsea 2007). Using equation 2, β is equal to 15. Potential α values with the appropriate β values from equation 2 are shown in Figure 1. Clearly, the larger α values demonstrate higher confidence in the expected λ value.

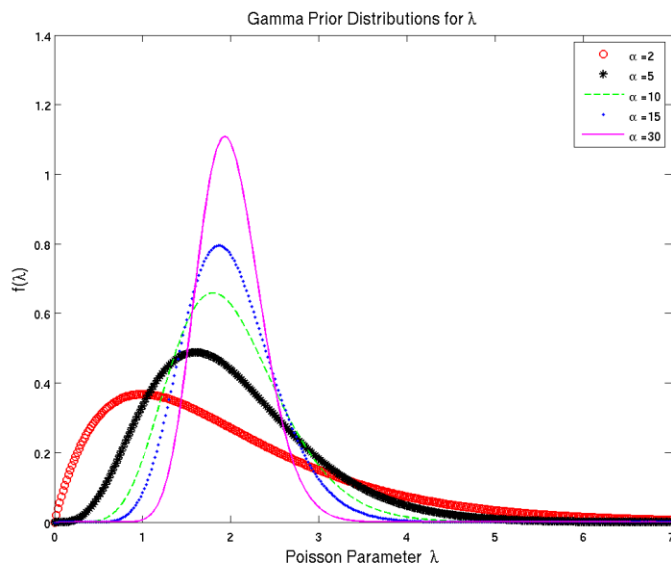


Fig. 1. Gamma prior distributions for λ using different α values (with β changing according to equation 2).

The hurricane seasons between 1900 and 1949 are treated as data inputted into equation 3. It is statistically robust to use incident frequency information from these years even though they are separate from the 1950-1999 period because of the lack of a temporal trend in TC landfall frequency in the twentieth century. As a result, the parameters I equals 50 and \bar{n} equals the number of landfalling storms over the number of years, or 65/50. However, this \bar{n} is undoubtedly too low, and both Mann et al. (2007) and Landsea (2007) documented the low bias

¹ Method 2 from Englehardt (2013) handout on plotting empirical incident size densities used for the entirety of this study.

in TC reporting in the first half the twentieth century. Based on these two papers, the low bias ranges from 0.5 to 2 landfalling TCs per year. Therefore, \bar{n} was increased by 1.5 to 2.8 landfalling TCs per year. The PDF for number of TC landfalls generated by the predictive Bayesian version of the Poisson distribution is shown in Figure 2. Using the mentioned parameter estimates, 10,000 random values from the negative binomial distribution shown in equation 3 were generated using a Monte Carlo simulation.

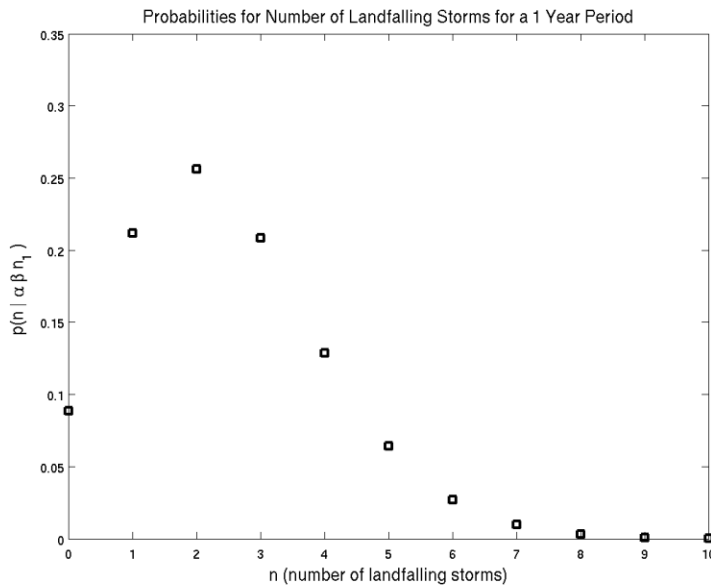


Fig. 2. Predictive Bayesian version of the Poisson distribution used to show the probability of different numbers of landfalling storms per year during the period 1950-1999.

The second component of the compound Poisson model is the Bayesian Truncated Pareto I distribution which describes the economic damage associated with each landfalling TC. The expected value of 0.6 for the Pareto variable ϕ is obtained from a study by Coia and Huang (2013). Their ϕ was calculated using a dataset that is almost independent from the information used here. An α value of 3 was selected because there is considerable uncertainty that Coia and Huang's (2013) data gives an accurate estimate of ϕ for the 1950-1999 data. From equation 2, $\beta = 5$. Using these parameters, the gamma prior PDF for ϕ is created and shown in Figure 3.

The TC landfall costs between 1900 and 1949 are treated as data inputted into equation 5. There were 65 U.S. landfalls during this 50 year period so J equals 65. The minimum economic damage from a TC landfall was 17 million dollars which is a reasonable estimate for Z_0 . Z_{max} is set to 200 billion dollars because the highest normalized TC damage incident was 160 billion dollars, and with little trend expected in the normalized data, it is unreasonable to expect one storm to produce a much higher total. These parameter values, along with α and β , are inputted into equation 5 to obtain the predictive Bayesian version of the Truncated Pareto distribution. Random entries from this distribution are selected by entering random real numbers between 0 and 1 into $F(z)$ in equation 5, and then solving the equation z to calculate incident sizes.

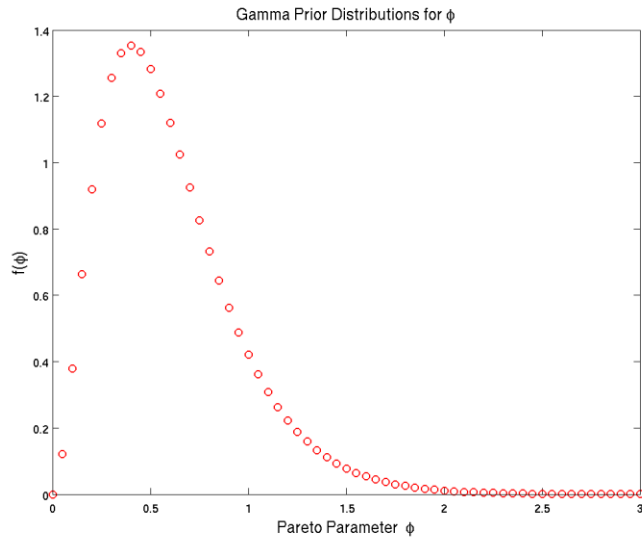


Fig. 3. Gamma prior distribution for ϕ using $\alpha=3$ and $\beta=5$.

The product of the 10,000 simulated values of the annual number of landfalling TCs can then be multiplied by the 10,000 simulated values of the economic damage of landfalling TCs to produce 10,000 data points for total annual damage. Figure 4 shows the PDF of the ten thousand simulated years of annual TC damage for the 1950-1999 planning period. The corresponding CDF is shown in Figure 5 along with the 50 true values of annual economic damage during 1950-1999. A two-sample Kolmogorov-Smirnov test is used to compare the predictive distribution and verification data. The p-value of 0.76 indicates the null hypothesis that the predictive distribution and the data are from the same continuous distribution is accepted. As a result, the predictive Bayesian compound Poisson model appears skillful at anticipating future annual TC economic damages.

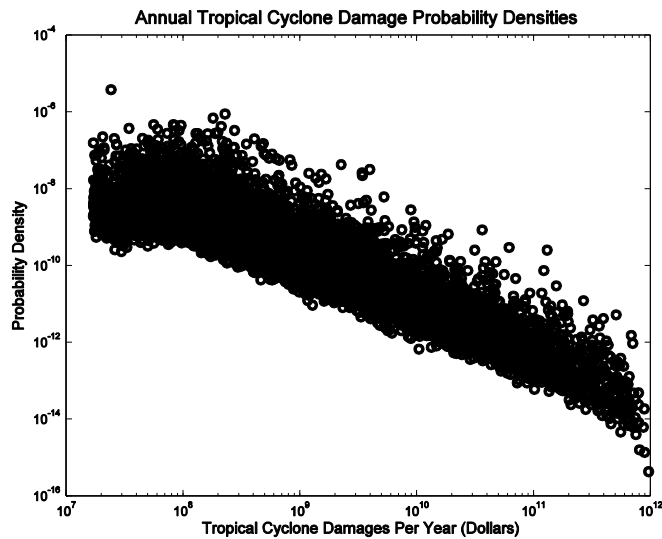


Fig. 4. PDF for the predictive Bayesian compound Poisson Model for 1950-1999. Monte Carlo methods are used to produce the 10,000 entries. Each TC economic damage value on the x-axis was normalized to 2005 conditions.

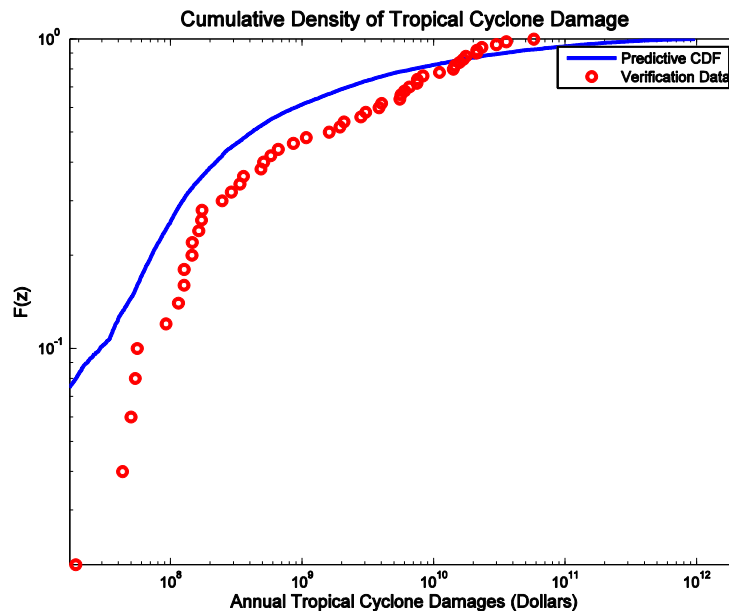


Fig. 5. CDF for the predictive Bayesian compound Poisson model for 1950-1999 shown as the blue line. The red circles indicate the fifty actual values for normalized annual economic damages from TC landfall during the 1950-1999 period.

b. Late Twenty-First Century (2081-2100) Forecast With and Without Climate Change

The Pielke and Landsea (1998) normalized TC damages data are used differently in the determination of the predictive Bayesian version of the Poisson for the late twenty-first century forecasts compared to the hindcast of the second half of the twentieth century. The data is used to inform the expected value of λ for the gamma prior distribution. It is not prudent to use the data to update the prior because late twenty-first century hurricane seasons are expected to have a different number of TC landfalls. An abbreviated version of the Pielke and Landsea (1998) data is used because of the underreporting of TC landfalls in the first part of the twentieth century. Rather than doing a bias correction, it is more statistically robust to use a reliable dataset. Aircraft reconnaissance started in 1944, and data after this year is considered significantly more accurate (Hagen 2012). Therefore, the expected value of λ is calculated by dividing the total number of landfalling TCs from 1944-2005 by the number of years. There are 159 storms during the 62 year period of interest which yields 2.56 storms per year. To calculate an expected value of λ for the climate change scenario, the task is more intensive.

The downscaled CMIP5 ensemble results for the 2081-2100 period from Knutson et al. (2013) are used for the late twenty-first century climate projections of TC landfalls. The details of the CMIP5 ensemble are available in Knutson et al. (2013), and only the main results for forecasted percent change in TCs are reported here. CMIP5 projects 13.1% less tropical storms, 43.5% less category 1 hurricanes, 18.4% less category 2 hurricanes, 30.4% less category 3 hurricanes, 30.0% more category 4 hurricanes, and 300% more category 5 hurricanes by the end of the twenty-first century. Knutson et al. (2013) only reports the change in the frequency of storms, and these numbers need to be translated into a change in frequency of landfalling storms.

During the 1944-2005 period, 23% of tropical storms and hurricanes made landfall. Therefore, making the assumption that the ratio of total storms to landfalling storms will remain the same, the predicted percent change in landfalling TCs becomes 3.0% less tropical storms, 9.9% less category 1 hurricanes, 4.2% less category 2 hurricanes, 7.0% less category 3 hurricanes, 6.9% more category 4 hurricanes, and 69% more category 5 hurricanes. It is important to acknowledge that there is considerable uncertainty in these projections but it is still useful to understand the economic ramifications of this potential future climate. Therefore, the expected value of λ for the climate change Poisson model is adjusted to reflect these forecasted changes in TC landfall frequency; the climate change expected λ is 2.42.

In both cases, there is a sizable dataset used to estimate λ and the agreement with the long-term mean in U.S landfall frequency indicates significant confidence should be placed in this expected value of λ . For the no climate change predictive model, the assumption is that there will be no trend in frequency or strength of landfalling TCs. As a result, a high α value of 30 was selected and the corresponding β is 12.7. Due to the assumptions made to adjust the expected value of λ for the climate change predictive model, a smaller α value of 15 is used with β equal to 6.2. In both models, there is nothing that can be used as data to update the prior so I equals 0 and \bar{n} equals 0. By plugging these parameter values into equation 3, the PDFs for the predictive Bayesian version of the Poisson distribution for the climate change and no climate change projections are obtained. The PDFs are respectively shown in Figures 6 and 7. Using the mentioned parameter estimates, 10,000 random values representing potential annual numbers of TCs making landfall from each PDF were generated using a Monte Carlo simulation.

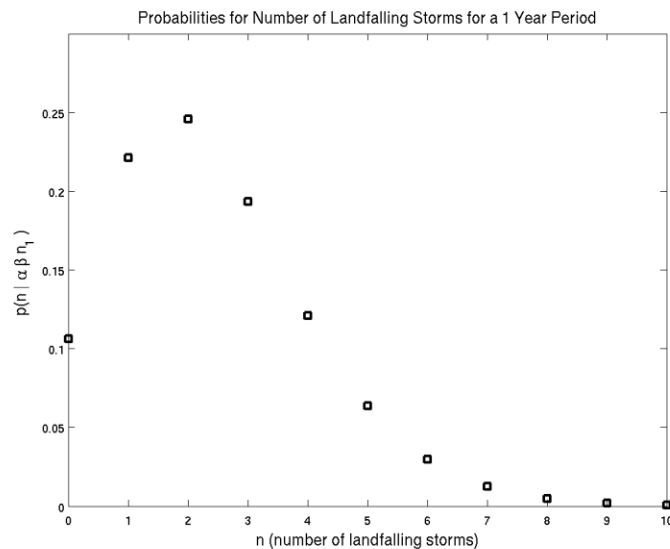


Fig. 6. Predictive Bayesian version of the Poisson distribution used to show the probability of different numbers of landfalling storms per year during the period 2081-2100. This distribution accounts for CMIP5 projections from Knutson et al. (2013).

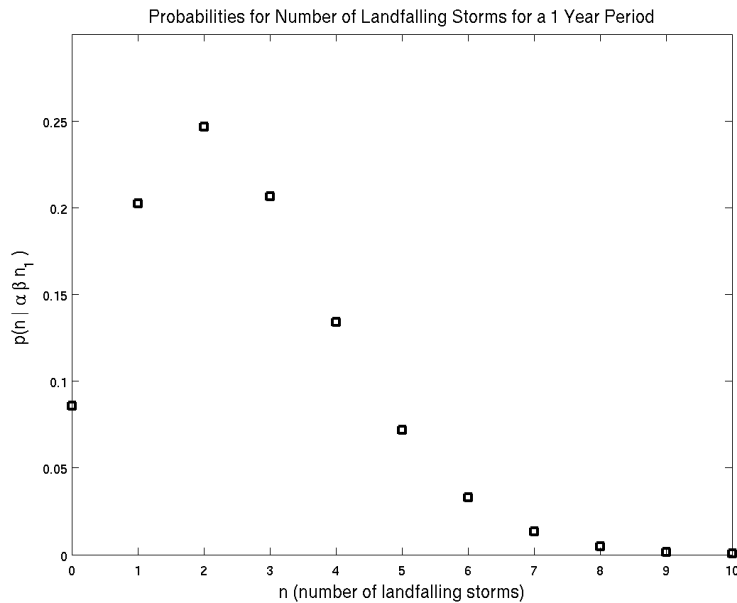


Fig. 7. Predictive Bayesian version of the Poisson distribution used to show the probability of different numbers of landfalling storms per year during the period 2081-2100. This distribution does not take into account climate change projections.

Similar to the approach with the Poisson distribution, the Pielke and Landsea (1998) data is used to inform the gamma prior for the Pareto I distribution rather than update it. The expected value of the Pareto variable ϕ is calculated by applying equation 4 to the 1944-2005 data. As mentioned, there are 159 landfalling TCs from 1944-2005 for the no climate change scenario, which corresponds to J , and economic damage from each TC is inputted into z_j . The parameter Z_0 does not equal the minimum incident size but instead is set to 2 million dollars. There are two storms in the 1944-2005 period that did not exceed 2 million dollars in economic damage. Landfalling TCs with less than 2 million dollars in normalized economic damage are highly unlikely, and it is hypothesized there was potentially some underreporting error for the TCs that did not surpass this value. Using these parameter values, ϕ equals 0.18.

For the climate change scenario, ϕ needs to be adjusted to compensate for the change in the expected costs of landfalling TCs. With less weak and more strong TCs making landfall under the CMIP5 projections, the expected value of ϕ needs to be altered so higher incident sizes (economic damages) are more probable. The procedure for changing the gamma prior distribution for ϕ involves first finding the monetary values that correspond to the average economic damages associated with each category of TC. These six datapoints (one for tropical storms and five for categories of hurricanes) are then increased or decreased according to the predicted percent change in landfall frequency of the respective storm categories. A new ϕ is then determined from the slope of the best fit regression line of the six adjusted datapoints. Using the CMIP5 predicted changes in TC landfalls, ϕ approximately equals 0.12. Figure 8 shows how the adjustment in ϕ changes the slope of the truncated Pareto PDF. As expected, the red truncated Pareto curve corresponding to the climate change scenario clearly has larger probabilities for the higher annual TC economic damage amounts than the blue curve corresponding to the no climate change scenario.

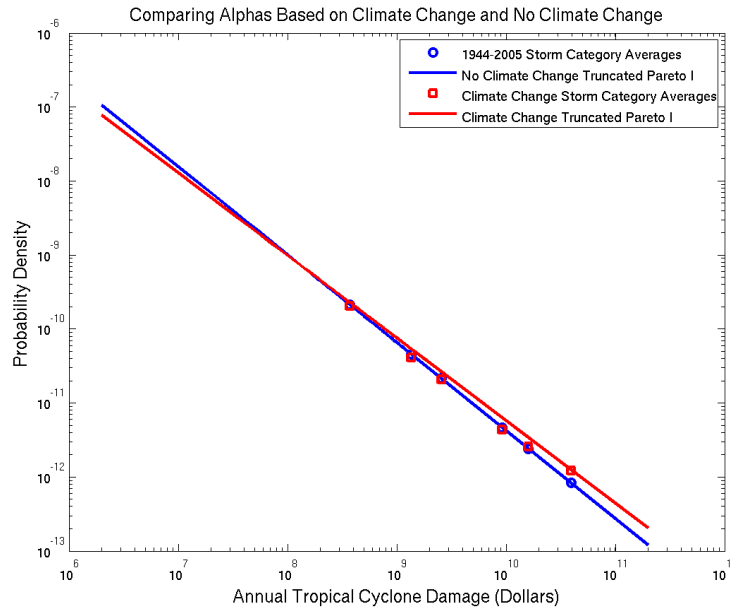


Fig. 8. The blue circles represent the average economic damage and probability of the different TC categories based on the 1944-2005 data. The blue line corresponds to the truncated Pareto PDF fitting the 1944-2005 data ($\phi=0.18$). The red squares represent the probabilities adjusted for climate change for the different TC categories at the end of the twenty-first century. The red line is the best fit regression line for the TC category values in the climate change scenario ($\phi=0.12$).

For both the climate and no climate change scenario, an α of 60 was selected with the corresponding β value derived from equation 2. There are two main reasons that a large α was selected. First, the sample size for fitting the truncated Pareto is large and the data follow the distribution very closely. Second, it is important that the gamma prior distributions for ϕ in the climate change and no climate change scenarios do not overlap. In other words, the probability of the Pareto parameter ϕ in the climate change scenario equaling ϕ in the no climate change scenario should be very low. This narrow gamma prior will ensure the climate change scenario has a TC annual economic damage distribution that is significantly different from the no climate change scenario. Figure 9 captures the effect of the high α values.

In both the climate change and no climate change scenario, there is nothing that can be used as data to update the prior for ϕ so in equation 5, J equals 0 and $\ln z_j$ equals 0. In each case, Z_{\max} is set to 300 billion dollars to allow the possibility of stronger TCs by the end of the twenty-first century. By inputting these parameters along with α and β for the respective scenarios into equation 5, the predictive Bayesian version of the truncated Pareto distribution for the two versions of the late twenty-first century are calculated. Random entries from these distributions are selected by entering a random real number between 0 and 1 into $F(z)$ in equation 5 and solving the equation for z . The product of the 10,000 simulated values of the annual number of landfalling TCs can then be multiplied by the 10,000 simulated values of the economic damage of TCs to produce 10,000 data points for total annual TC damage. After binning this data, the predictive Bayesian compound Poisson CDF for normalized annual TC damage (at 2005 levels of national inflation and wealth and coastal population structure) at the

end of the twenty-first century can be produced. Figure 10 shows the CDF for both the climate change and no climate change scenarios. Table 1 summarizes the results for these two scenarios.

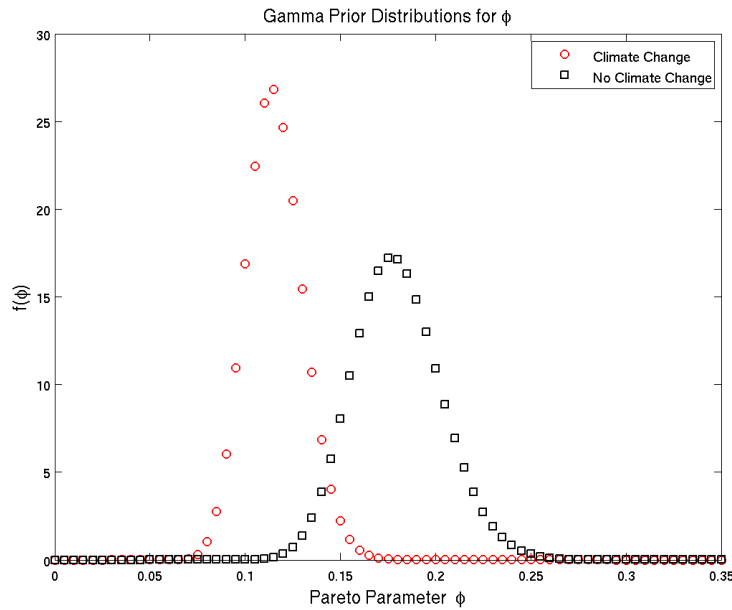


Fig. 9. The black squares represent the gamma prior distribution for the Pareto parameter ϕ in the no climate change scenario. The red circles indicate the gamma prior distribution for the Pareto parameter ϕ in the climate change scenario. Note the center of each distribution is in the tail of the other distribution, indicating a very low probability of having the same ϕ .

Clearly, the CDFs show higher annual TC damage is more likely under the climate change scenario. Table 1 confirms this observation: the predicted mean annual TC damage is over 10 billion dollars higher for the climate change scenario compared to the no climate change scenario. Although with climate change, it is more likely that there will be a hurricane season with no landfalling TCs. The most alarming statistic in Table 1 is the 99% exceedance value. The 100-year event represented by the 99% exceedance value is 160 billion dollars higher if the CMIP5 projections are realized. If this 100-year event occurs during the forecasted 2081-2100 period, it will undoubtedly cost over a trillion dollars under that year’s societal conditions. This statement is justified assuming a paltry 0.5% inflation rate; the 660 billion dollar event (in 2005 conditions) would cost over a trillion dollars in late twenty-first century dollars. Obviously, larger coastal populations and wealthier individuals would increase this estimate substantially.

Table 1. The summary statistics for the predictive Bayesian compound Poisson models under the climate change and no climate change scenario. All values are in units of annual U.S. dollars caused by TC economic damages under 2005 conditions.

	Climate Change	No Climate Change
Mean	$3.19 * 10^{10}$	$2.07 * 10^{10}$
Median	$1.57 * 10^8$	$7.72 * 10^7$
95% exceedance value	$1.89 * 10^{11}$	$1.03 * 10^{11}$
99% exceedance value	$6.62 * 10^{11}$	$5.04 * 10^{11}$

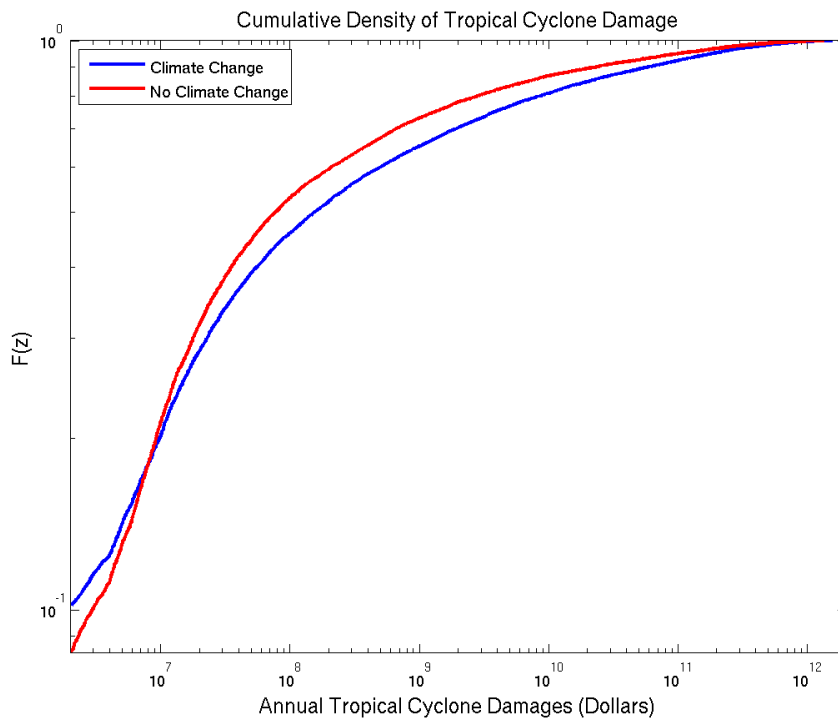


Fig. 10. CDFs for the predictive Bayesian compound Poisson model for the late twenty-first century. The blue line is the CDF created using the climate change scenario and the red line uses data that does not account for climate change.

4. Conclusions

Data from the Pielke et al. (2008) study is used to test if the Bayesian compound Poisson model can predict normalized annual economic damage from landfalling TCs between 1950 and 1999. After confirming the model's predictive capabilities, it is then applied to late twenty-first century predictions. Two scenarios are considered for the future frequency and intensity of TC landfalls. The no climate change scenario hypothesizes that the prior distribution for TC landfall frequency and intensity should be informed only by 1944-2005 data. The climate change scenario uses CMIP5 results from Knutson et al. (2013) to adjust the Poisson and Pareto accordingly due to climate projections of tropical cyclone frequency and strength. The Bayesian compound Poisson model adjusted due to climate change has considerably higher predictions in mean TC annual damage and indicates the 100-year event could be significantly worse if CMIP5 projections are realized.

The potential for significantly larger economic damages due to future TCs suggests that society should consider mitigation procedures. Strengthening buildings against wind damage can lessen the impact of strong TCs. Also, enforcing more rigorous building codes and requiring population growth to move further away from the ocean should reduce normalized damage over time. Funding TC forecasting research can increase the lead times for preparing for TCs and save lives and money. If these preventative measures are realized, the threat of a trillion dollar TC season would likely decrease.

5. References

- Coia V. and M. L. Huang (2013), A sieve model for extreme values. *Journal of Statistical Computation and Simulation*, **83**.
- Emanuel, K.A., 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.*, **45**, 1143-1155.
- Englehardt, J. D. and Peng, C. (1996), A Bayesian Benefit-Risk Model Applied to the South Florida Building Code. *Risk Analysis*, **16**: 81–91.
- Hagen, Andrew B., Christopher W. Landsea, 2012: On the Classification of Extreme Atlantic Hurricanes Utilizing Mid-Twentieth-Century Monitoring Capabilities*. *J. Climate*, **25**, 4461–4475.
- Huang, M. L. and Coauthors (2013), A Cluster Truncated Pareto Distribution and Its Applications. *ISRN Probability and Statistics*, **10**.
- Katz, Richard W., 2002: Stochastic Modeling of Hurricane Damage. *J. Appl. Meteor.*, **41**, 754–762.
- Knutson, Thomas R., and Coauthors, 2013: Dynamical Downscaling Projections of Twenty-First-Century Atlantic Hurricane Activity: CMIP3 and CMIP5 Model-Based Scenarios. *J. Climate*, **26**, 6591–6617.
- Mann, M. E., S. Rutherford, E. Wahl, and C. Ammann (2007), Robustness of proxy-based climate field reconstruction methods, *J. Geophys. Res.*, **112**, D12109.
- Pielke, Jr., R. A., Gratz, J., Landsea, C. W., Collins, D., Saunders, M. A., and Musulin, R., 2008. Normalized Hurricane Damages in the United States: 1900-2005. *Natural Hazards Review*, **9**(1), 29-42.
- Pielke, Roger A., Christopher W. Landsea, 1998: Normalized Hurricane Damages in the United States: 1925–95. *Wea. Forecasting*, **13**, 621–631.
- Willoughby, H. 2012a: Distributions and Trends of Death and Destruction from Hurricanes in the United States, 1900–2008. *Nat. Hazards Rev.*, 13(1), 57–64.
- Willoughby, H. 2012b: Is a Trillion Dollar Hurricane Season Possible. Conference Proceedings. 30th Conference on Hurricanes and Tropical Meteorology.