Distributions and Trends of Death and Destruction from Hurricanes in the United States, 1900–2008

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Abstract: Because annual death and destruction from hurricanes in the United States can vary by > 4 orders of magnitude, common logarithms are convenient measures. If the data are stratified into years when at least one major hurricane (maximum winds > 49 m/s) made landfall and those without a major-hurricane-landfall, logarithmic mortality and damage in both subsets appear to be normally distributed. Combined log-normal distributions accurately represent the data. From 1900 through 2008, total hurricane mortality decreased with a halving time of 26 years. Consistent with previous analyses, historical damage normalized for population growth, increasing individual wealth, and inflation did not exhibit significant trends in either subset. Comparison between the complete 1900–2008 record and a truncated version spanning 1900–2000 shows that the effects of hurricanes since 2000, especially Katrina, doubled the expected loss of life and increased the expected damage by 10%, consistent with the relatively large statistical uncertainty in estimation of the model parameters. In the context of the model, the expected frequency of disasters that cause $> \$100$ billion in damage is approximately three times a century and for those that claim $> 1{,}000$ lives is approximately once a century. **DOI: 10.1061/(ASCE)NH.1527-6996.0000046.**

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Author keywords: Hurricane; Damage; Mortality; Climate; Statistics.

Introduction

Since 1900, tropical cyclones (TCs) making landfall in the United States ended 18,000 lives prematurely and destroyed US$400 billion in property, corrected for inflation to 2005 (Blake et al. 2007; Pielke et al. 2008). Normalization of historical damage for increasing population and individual wealth, and for inflation (Pielke and Landsea 1998; Pielke et al. 2008), shows that historical storms would have inflicted $>$ US$1,200 billion in damage from 1900 through 2008 with constant early 21st century coastal development. Thus, the cost of hurricane damage is a significant economic misfortune. Indeed, Galbraith (1954) traces the roots of the Great Depression, in part, to collapse of the southeast Florida real estate bubble and subsequent loss of bank deposits and liquidity after the 1926 Miami Hurricane. Conversion of the deaths to a dollar figure by using late 20th century "Statistical Value of Life" (US$5 million; Fisher et al. 1989) yields a total US$90 billion in economic effect for 1900–2008 hurricane mortality.

Quantitative assessments of TC effects are essential to rational policy and planning. The insurance industry, for example, estimates windstorm risk with Monte Carlo, "catastrophe models" that convolute winds from climatologically realistic virtual hurricanes with the spatial distributions of insured properties (Vickery et al. 2000; Grossi and Kunrather 2005). By using a less elaborate approach, Katz (2002) modeled annual hurricane damage by using a compound statistical distribution. He represented the frequency of hurricane landfalls with a Poisson distribution, and the normalized damage for each occurrence with a log-normal-distribution. In this formulation, only 15% of the variance arose from random landfall occurrence, whereas most of the variance stemmed from differences in effects of individual landfalls. Damage during most seasons was dominated by single events. Exceptions to this generalization include 1915, 1954–1955, and 2004–2005.

This paper analyzes annually aggregated damage and mortality. This approach is appropriate because governments and corporations have annual budget cycles. Primary insurers set rates and negotiate reinsurance contracts every year. Moreover, potential climate signals will appear as year-to-year variations of effects. Alternative analyses that treat individual landfalls can be used to validate catastrophe models (Pielke et al. 1999) and to provide vital input for social-science research, but definition of systematic climate changes and measurement of effects on the economy as a whole require annually aggregated statistics.

The HURDAT climatology (Jarvinen et al. 1984) shows that from 1900 through 2008, 182 hurricanes crossed the U.S. coastline. Of these, 71 were major hurricanes in Saffir-Simpson categories 3, 4, and 5, with maximum wind ($V_{\max}$) > 49 m/s (111 miles per hour). Major hurricanes account for $> 80\%$ of U.S. tropical-cyclone property damage (Pielke and Landsea 1998). Landfall incidence varied on a multidecadal time scale. Early in the 20th century, hurricane landfalls were more frequent than the long-term average. Then through the mid-1920s, landfalls occurred at a somewhat below average rate. A prolonged period of above-average landfalls began in approximately 1926 and continued through 1970. From 1971 through 2003, landfalls averaged slightly more than one per year; although this respite was interrupted in 1985 when six landfalls occurred, tying the record set in 1916. The number of observed Atlantic TCs increased dramatically after 1995, but the increase did not reach U.S. shores until 2004 and 2005, when a total of nine landfalls occurred.

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Multidecadal variations in hurricane activity throughout the Atlantic basin may be influenced by the Atlantic multidecadal oscillation (AMO), a 50–70 year episodic change in the Atlantic oceanic thermohaline circulation (Goldenberg et al. 2001; Kerr 2005). The AMO is hypothesized to modulate the inhibiting effect of vertical wind shear in the eastern tropical Atlantic. Apparent century-scale increases in Atlantic-basin-wide intensities and numbers have been attributed to anthropogenic global warming (Emanuel 2005; Webster et al. 2005). Although these increases seem qualitatively consistent with the model of hurricanes as classical heat engines running between the warm sea surface and cold upper troposphere (Emanuel 1991), they also may be attributable to better detection (Landsea et al. 2010). Downscaled global climate model results show that the increase in intensity of the strongest TCs should be evident above random variation only after the late 21st century (Bender et al. 2010). Even as the intensities of hurricanes in Saffir-Simpson categories 3–5 ($V_{\max} > 49$ m/s) become stronger and more common, the number of hurricanes in general will probably decrease. An emerging international consensus based upon this view (Knutson et al. 2010) promises to reconcile the competing explanations for the apparent increase in Atlantic-basin hurricanes since 1970 (Vecchi et al. 2008).

Apart from multidecadal variation that seems weakly correlated with basinwide activity, the numbers of U.S. landfalls do not show statistically significant trends over the 109-year record (Landsea 2005, 2007; Holland 2007; Wang and Lee 2008), and year-to-year serial correlation is not strong.

Landfall occurrences stratified by nonmajor and major hurricanes are reasonably well modeled by using Poisson distributions with means of 1.02 and 0.65 (Elsner et al. 2001; Katz 2002). The combined landfall total is described by a Poisson distribution with a mean of 1.67. The corresponding variances are 0.93, 0.65, and 1.67. Chi-square tests of yearly landfall counts against Poisson distributions with these means yield p-values of 0.4 to 0.9, so that there is no reason to reject Poisson models.

In this paper, statistical trends and probability density functions (PDFs) are derived for hurricanes' human and economic effects. Key limitations are that the time series are imperfectly measured, nonstationary, and probably too short to resolve long-term variations. The analysis focuses primarily on the years 1900–2008, but also considers a truncated interval, 1900–2000, of the same time series to assess the stability of trends and PDFs.

Data

The mortality data (Blake et al. 2007) are both nonstationary and variable (Fig. 1). The range is from several years with no deaths or single deaths to > 8,000 deaths in 1900. Three spectacularly fatal hurricanes that dominate the record (Galveston in 1900, Lake Okeechobee in 1928, and Katrina in 2005) claimed a total of 12,000 lives. Two of these hurricanes and 11 of the other deadly (> 100 deaths) seasons struck before 1970. From 1970 through 2004, the annual average loss of life was 21.

Fitting trends to these data can present problems, because the fitting algorithms often track extreme values and produce negative values near the beginning or end of the period. The large dynamic range and a hint of a concave-upward curve suggest exponentials. A nonlinear, minimum-variance fitting algorithm with a weak Lagrange multiplier constraint that minimizes the square of the fitted function's first derivative controls overly sensitive responses. Both the linear and exponential fits are approximations to the time-varying arithmetic mean. An alternative approach fits linear trends to the logarithm of the number of deaths in years with nonzero mortality. The logarithmic fits track time-varying geometric means, which are usually smaller than the arithmetic means and do not have the mean-value property. That is, the area under the logarithmically fitted curve is not the total of the quantity being described. Nevertheless, because of the large range of values, logarithmic transformations simplify the analysis. The halving time of the exponential nonlinearly fitted to nonlogarithmic hurricane mortality is 25.8 years. It decreases from 478 deaths annually in 1900 to 26 in 2008. This decrease in mortality as a result of better forecasts and warnings (Sheets 1990) is a significant achievement in the face of a growing population at risk.

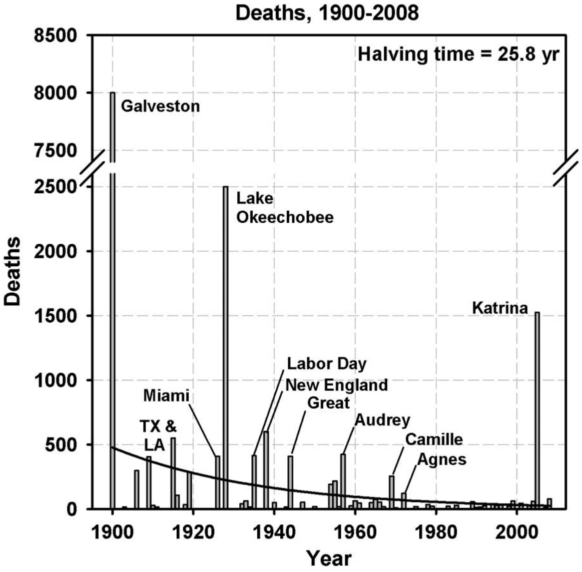

Fig. 1. U.S. annual deaths attributable to hurricanes, 1900–2008 (data from Blake et al. 2007); the solid curve is a fitted exponential trend that approximates the time-varying arithmetic mean

Inflation-adjusted hurricane damage (not shown) has a range even greater than for deaths, 4 orders of magnitude, from US $12 million dollars in 1962 and 1987 (excluding years with zero damage) to US$121,000 million in 2005. In contrast with mortality, it grew exponentially with a doubling time of 13.7 years during the interval 1900–2008.

Normalization for inflation, population of the counties affected, and nationwide index of wealth (Pielke and Landsea 1998; Pielke et al. 2008), makes the damage data nearly stationary in time (Fig. 2). Again, three hurricanes (Galveston in 1900, Miami in 1926, and Katrina in 2005) accounted for a disproportionate share of the damage, US$395 billion. For the 1900–2008 data, the halving time between 1900 and 2008 is 1,210 years, but the rate of change is not significantly different from zero. The constant mean normalized damage is US$11,048 million. Because the normalization appears to remove trends in damage, the subsequent analysis will focus on normalized damage and unadjusted mortality.

Examination of normalized damage in more detail hints at a multidecadal pattern that parallels the one described for landfalls. Few large effects occurred in the early 20th century, apart from the Galveston Hurricane of 1900 and the Texas and Louisiana Hurricanes of 1915. From the middle 1920s through 1969, 13 devastating hurricanes stuck the United States. Then from 1970 though 2003, the United States experienced a respite from deadly or devastating hurricanes, punctuated by Agnes in 1972, Hugo in 1989, and Andrew in 1992.

The one-year lagged serial correlation coefficients for logarithmic mortality and normalized damage are 0.012 and −0.040,

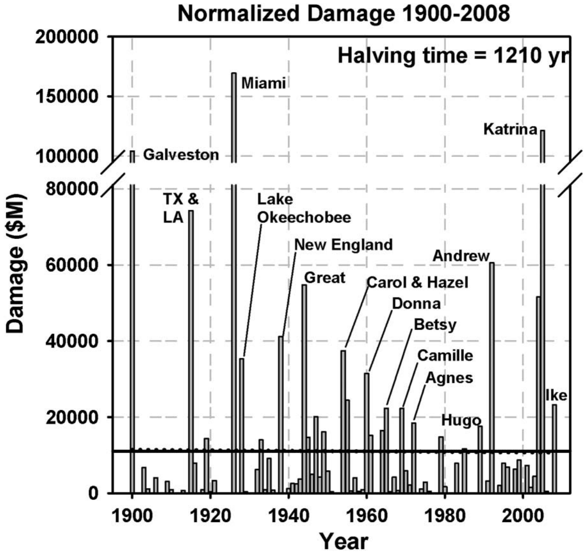

Fig. 2. U.S. normalized annual damage in millions of dollars attributable to hurricanes, 1900–2008 (data from Pielke et al. 2008); the dotted line is the trend, which is not significantly different from zero; the solid black line is the 109-year mean

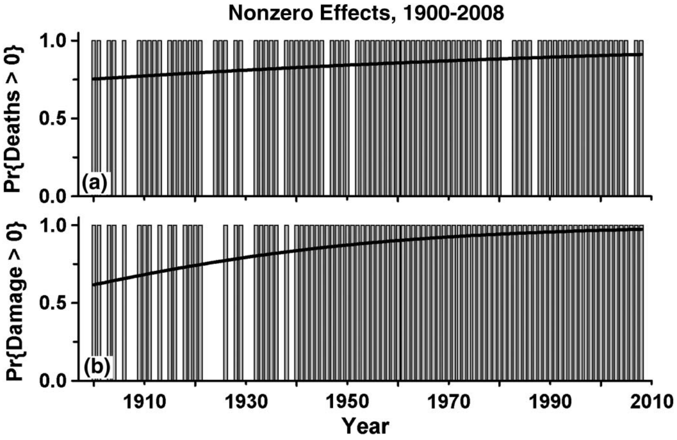

Fig. 3. Time-varying probability of hurricane effects greater than zero, 1900–2008: (a) deaths; (b) damage; bar-graph values of one indicate years with effects > 0

respectively. Thus, there appears to be little year-to-year serial correlation of effects, despite the multidecadal variation. In analysis of meteorological time series, the presence of serial correlation or red noise usually requires reduction of the number of degrees of freedom used in significance testing (Shapiro and Chelton 1986). Not making this correction introduces a bias toward accepting chance correlations as significant. Because the serial correlations are so small, the degrees of freedom are calculated in this study without reduction.

The 109-year record contains 17 years with no deaths and 16 years with zero damage. The zero values are an obstacle to analyzing logarithmic hurricane effects. A solution to this difficulty is to approximate the time-varying probability of effects > 0 and to represent the PDF, $f(d)$, as the product of $\Pr\{d > 0\}$ with $g(d)$, the contingent PDF computed only from years with effects $> 0, f(d) = \Pr\{d > 0\}g(d)$.

$\Pr\{d > 0\}$ is estimated by using a discriminant analysis in which years with $d > 0$ are assigned values of unity and those with $d = 0$ are assigned zero. The probability is modeled as a logistic curve fitted to the series of ones and zeros by using a conventional logistic regression algorithm (Fig. 3). Between 1900 to 2008, the fitted probability of nonzero damage increases from 40 to $> 99\%$, and the probability of at least one death increases from 70 to 93%. Thus, although the number of U.S. landfalls has remained sensibly constant since 1900, the proportion that kills someone or destroy property has increased.

Analysis

The damage figures from Pielke et al. (2008) normalized to 2005, with the addition of then-year damage from 2006–2008 and mortality data from (Blake et al. 2007), with the additions of deaths at sea during the Great Hurricane of 1944, plus those in 2008, constitute a homogeneous record of hurricane effects over the 109 years of reliable reporting. As argued above, logarithmic transformations simplify the analysis. Common logarithms offer a significant advantage because they readily convert to actual values, much as with the decibel notation used in signal processing. For example, the common logarithm of 8,000, the number of deaths from the 1900 Galveston hurricane, is ~3.9. The logarithm of 50, the number of lives lost in hurricane Donna of 1960, is ~1.7. Even after the logarithmic transformation, a scatter diagram of the 91 years with nonzero deaths (Fig. 4) still exhibits large year-to-year variation combined with the same downward trend that appeared in Fig. 1.

Fig. 4 shows least-squares lines fitted to subsets of the 1900–2008 logarithmic data: *M*08, major-hurricane-landfall years with nonzero deaths; *A*08, all years with nonzero deaths; and *N*08, nonmajor-hurricane landfall years with at least one death. It also displays tendencies computed for *M*00 and *N*00, the

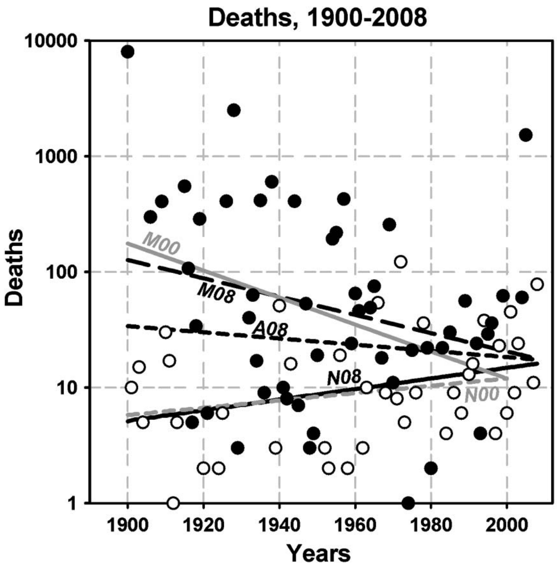

Fig. 4. Scatter diagram of the common logarithm of annual hurricane-related deaths, 1900–2008; filled circles indicate years when at least one major hurricane struck the United States, and open circles indicate years with no major-hurricane landfalls; black lines fit 1900–2008 major-hurricane years (*M*08), all years (*A*08), and non-major-hurricane-landfall years (*N*08); grey lines (*M*00 and *N*00) fit major- and nonmajor-hurricane years in the truncated 1900–2000 data; slopes of the solid lines (*M*00 and *N*08) are significantly different from zero at 5%, whereas the slopes of the short-dashed lines (*A*08 and *N*00) are not; the slope of the long dashed line (*M*08) is marginally significant ($p = 0.057$)

major-hurricane and nonmajor-hurricane subsets of a truncated record that spans 1900–2000. The trend for the $N08$ subset shows a significant (F-test, $p = 0.045$) increase with a doubling time of 66 years. Many of the deaths in nonmajor hurricane landfalls occur singly or in small clusters through misadventure, often by drowning in inland floodwaters because of torrential TC rains (Rappaport 2000). Prevention of this pattern of death is more difficult than evacuation of large populations en-masse, even given the too-frequent disappointingly poor compliance with evacuation orders.

The decreasing trend of $M08$ mortality was significantly different from zero at the 5.7% level. Thus, whereas it is not significantly different from zero at 5%, it is clearly different from zero with 10% significance. The $M08$ halving time is 38 years. The $A08$ time-varying geometric mean exhibits no significant change. It has an apparent halving time of 112 years—in contrast with the ~26-year halving time of the arithmetic mean described in Fig. 1.

The tendencies in the truncated record are similar, but with different statistical significances. Exclusion of the Katrina disaster makes the decrease in $M00$ mortality statistically significant ($p = 0.008$) with a halving time of 25.8 years. In contrast, exclusion of the relatively deadly nonmajor-hurricane seasons after 2000 makes the upward $N00$ trend not significant ($p = 0.23$).

The deadly landfalls in the early 21st century may call into question the continuation of the 100-year decline in hurricane mortality attributable to improved forecasting. This concern is particularly relevant to the $N08$ curve in which better reporting after the mid-20th Century and filling of unpopulated gaps on the coastline are plausibly driving the increase of recorded mortality. The marginal significance of the decrease in $M08$ mortality is almost entirely attributable to Katrina. A sequence of more years like 2006–2008 could gradually restore significance to the decline. The significant $M00$ decrease stemmed from cessation of hurricanes that took more than 100 lives after Camille in 1969 and Agnes in 1972. If increasing population and continued low compliance with evacuation orders overwhelms the effects of better forecasts, more deadly disasters will occur during the 21st century.

Of the 51 major-hurricane-landfall years between 1900 and 2008, only 17 fall below the $A08$ trend line; of the 40 nonmajor landfall years, only nine fall above the $A08$ line. Despite the convergence of the means toward the end of the period, these characteristics point to a combined distribution in which seasons with major- and nonmajor-hurricane landfalls have distinct PDFs.

The scatter diagram showing partitioning of logarithmic normalized damage as a function of time (Fig. 5) further illustrates the dichotomies between mortality and damage statistics and between effects in seasons dominated by major- and nonmajor-hurricane landfalls. The separation of the $M08$ and $N08$ data by the $A08$ trend line is more marked than for deaths. Only 13 of the 50 major-hurricane landfall years fall below the geometric mean, and only 12 of the 43 nonmajor-hurricane landfall years fall above it. The $M08$ damage shows no significant trend. It has a constant geometric mean of US\$8,671 million. Although the $A08$ subset has a noticeable decreasing trend, neither it nor that of $N08$ is significant (p-values 0.15 and 0.75). The 1900–2000 trends are consistent with this pattern. None of the trends is significant; $p = 0.12$ and 0.52 for $N00$ and $M00$, respectively. The decreasing $N00$ trend seems to stem from a cluster of years with damage $<$ US\$100 M after 1950. Indeed, only seven of the 37 $N00$ years happened before 1950. A consistent explanation of this pattern is that in the early years of the 20th century, hurricanes often struck gaps between developed segments of coast. If they were not major hurricanes, they either caused no damage or the damage went unreported. As coastal development progressed and communications improved after World War II, more damage occurred and it was more likely to be reported. More damaging, nonmajor-hurricane years after 2000 account for the flattening of the $N08$ trend.

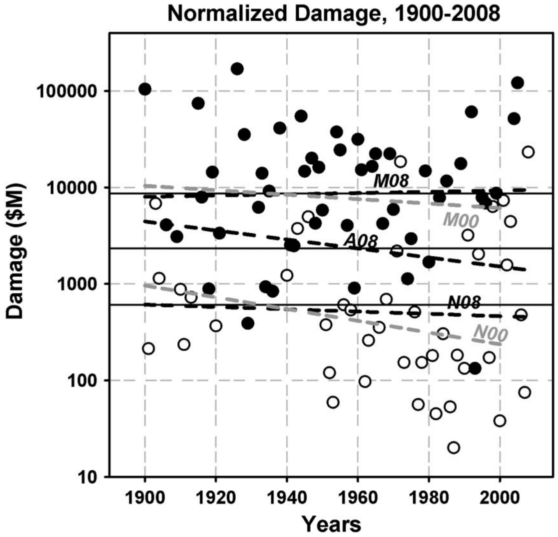

Fig. 5. As in Fig. 4, but for normalized damage 1900–2008; none of the trends is significantly different from zero at the 5% level for either the full or truncated data; solid reference lines indicate geometric means of the $M08$, $A08$, and $N08$ stratifications

Frequency histograms for the $M08$ and $N08$ data extrapolated along the trend line to 2005 appear to be normal [Fig. 6(a)]. Chi-square and Shapiro-Wilk (Shapiro and Wilk 1965) tests offer no justification for rejecting null hypotheses that these data are (common) log-normally distributed. The antilog of logarithmic mean is the geometric mean. The ± 1 standard deviation range is the antilog of the geometric mean divided and multiplied by one plus the antilog of the logarithmic standard deviation. The geometric mean of the extrapolated $M08$ data (logarithmic $\mu = 1.25$, $\sigma = 0.81$) is 17.7 deaths annually; the standard deviation ($\pm\sigma$) interval is 2.7 to 114 deaths. The $N08$ ($\mu = 1.25$, $1\sigma = 0.46$) geometric mean is 16.1, with $\pm\sigma$ range 5.5 to 47 deaths.

Because the $M08$ geometric mean is only approximately 10% more than the $N08$ mean, the combined PDF exhibits only a single peak (Fig. 6(b)). Because the $\pm\sigma$ range of the $M08$ subset is more than twice that of the $N08$ subset, the combined PDF has long tails on both sides of the mean. The converging means of the subsets reflects an increasing ability to prevent catastrophic loss of life, rarer landfalls after 1970 (apart from 2004 and 2005), and the disappearance of unpopulated coastal gaps. The combined PDF for the years with nonzero effects is

$$g(\log d) = \Pr\{N08\} n(\log d; \mu_{N08}, \sigma_{N08}) + \Pr\{M08\} n(\log d; \mu_{M08}, \sigma_{M08}) \quad (1)$$

in which $n(\_; \mu, \sigma)$ = normal PDF with logarithmic mean, μ, and standard deviation, σ; d = number of deaths; $\Pr\{N08\} = 44.6\%$ is the probability of a hurricane season that caused at least one death without a major-hurricane landfall; $\Pr\{M08\} = 55.4\%$ is the probability of a deadly season with at least one major-hurricane landfall. This expression requires multiplication by $\Pr\{d > 0\}$ to calculate $f(\log d)$, the actual PDF. Despite the convergence of μ, the different detrending and disparity in standard deviations indicates that the data cannot be represented with a single log-normal-distribution (Chi-square and Shapiro-Wilk $p = 0.018$, 0.046).

The individual PDFs for normalized damage are farther apart than those for mortality [Fig. 7(a)]. For $M08$ data ($\mu = 3.94$,

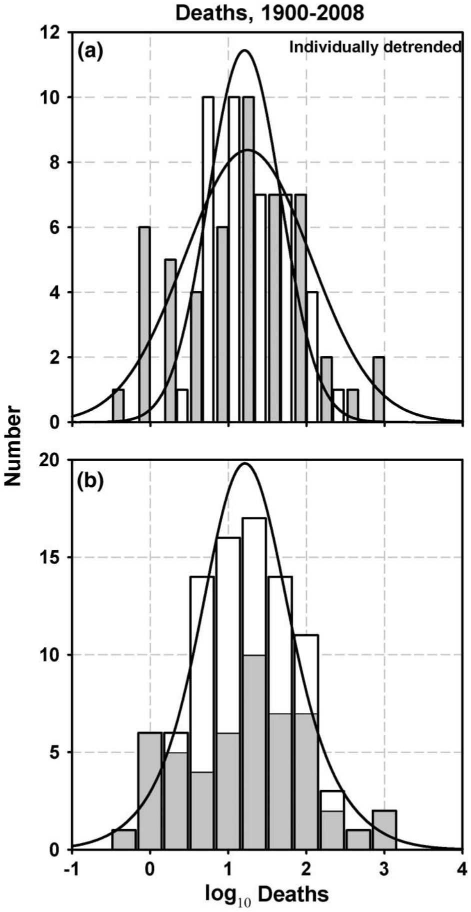

Fig. 6. Histograms of deaths, 1900–2008: (a) histograms of detrended annual deaths in the *M*08 (grey) and *N*08 (white) stratifications with corresponding log-normal PDFs superimposed; (b) combined histogram and PDF for the same data

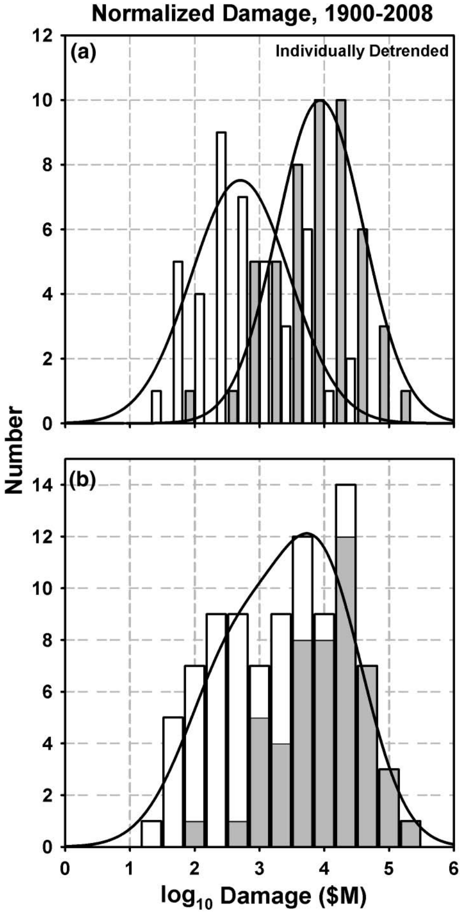

Fig. 7. Normalized damage, 1900–2008: (a) histograms of annual normalized damage in *M*08 (grey) and *H*08 (white) seasons, with log-normal PDFs; (b) combined histogram and PDFs for the same data; none of these data are detrended

$\sigma = 0.66$), the geometric mean was US\$8,671 million with $\pm\sigma =$ US\$1,872 to \$40,146 million. For *N*08 data ($\mu = 2.71$, $\sigma = 0.76$), geometric mean was US\$507 million with $\pm\sigma =$ US\$88 million to \$2,920 million. The *M*08 geometric mean is a factor of 17 larger than the *N*08 geometric mean. This ratio is equivalent to 1.7 logarithmic standard deviations. Chi-square and Shapiro-Wilk goodness-of-fit tests offer no reasons to reject log-normal distributions for either partition.

A combined distribution, as described, produces a combined PDF [Fig. 7(b)] that is noticeably skewed to the left as a result of the low-effect, nonmajor-landfall seasons in the latter half of the 20th century. A single combined log-normal-distribution of the *A*08 data (not shown) passes the Chi-square test ($p = 0.66$) but is marginal ($p = 0.105$) in the Shapiro-Wilk test because of the skewness. Because the means are so different, the combined characterization is retained instead of projecting the difference between stratifications onto the variance of a single log-normal distribution.

Application of conventional normal-distribution confidence interval estimates to the 1900–2008 parameters shows that (with two-tailed 95% confidence) the logarithmic means for mortality are within 10–20% of the values presented in the preceding paragraph, and those for damage are within 5–10%. Across all parameters, the logarithmic standard deviation fell between 10% less than and 25% more than the tabulated parameters. These ranges translate into substantial uncertainties in expected damage and mortality.

Synthesis

Exceedence probability (EP) curves (Grossi and Kunreuther 2005) provide a concise way to summarize and compare probabilities of effects greater than specified levels (Fig. 8) between the 1900–2000 and 1900–2008 periods

$$f(\log d) = \Pr\{d > 0\}[1 - (\Pr\{N\}E(\log d; \mu_H, \sigma_H) + \Pr\{M\}E(\log d; \mu_M, \sigma_M))] \tag{2}$$

The exceedance probability is the probability that effects are nonzero multiplied by one minus the combined cumulative distribution function (CDF); which is, in turn, the weighted sum of Gaussian CDFs, $E(x; \mu, \sigma) = \int_0^x n(x'; \mu, \sigma)dx'$, of logarithmic effects during nonmajor- and major-hurricane years. The ordinate is the probability of effects that exceed the $\log d$ value specified on the abscissa. The exceedance probability decreases from $\Pr\{d > 0\}$ to zero as $\log d$ increases.

The curve for hurricane deaths shifts to the right as a result of Katrina [Fig. 8(a)]. The difference between the curves is substantial, although it seems small because of the logarithmic scale. Inclusion of 21st century data nearly doubles expected mortality at most levels of probability. The magnitude of a disaster with 1% probability increases from 500 to nearly 900 deaths. On the 1900–2008 curve, the probability of $> 1{,}000$ deaths is 0.85%,

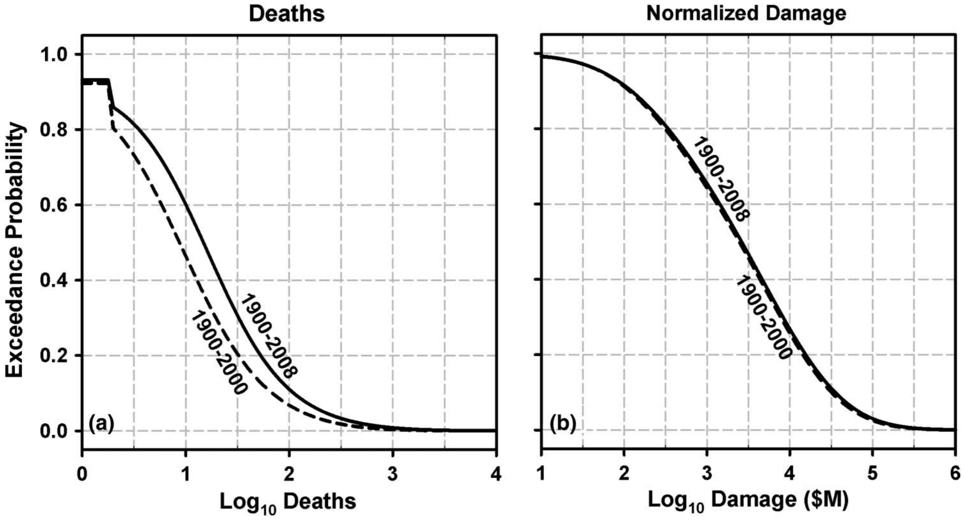

Fig. 8. Exceedance probabilities for hurricane-related deaths and damage: a) deaths; b) damage in millions of dollars; computed with data from 1900–2000 (dashed curves) and 1900–2008 (solid curves)

implying a return period of 123 years, compared with 264 years on the 1900–2000 curve.

The 21st century data have much less effect on normalized damage [Fig. 8(b)]. Over most of the range, expected damage for a given probability increases by ~10%. In the 109-year analysis, the 1% EP event is US$200 billion, and the probability of a $100 billion loss is 3.0%, equivalent to a 33-year return period. In the 101 year analysis, the 1% event would cost US$178 billion and the return period for a $100 billion loss is 40 years. These increases, which are consistent with the wide confidence intervals for μ and σ, stem largely from the 2004 and 2005 seasons.

The early 21st century annual arithmetic mean mortality and damage calculated from the data in Figs. 1 and 2 are 28 deaths and US$10.7 billion. The arithmetic means calculated from the combined log-normal distributions are much larger, 64 deaths and US$16 billion. Essentially identical figures derive from numerical integration of the PDF times the effect, and from use of the standard formula $\mu = \exp\left(\mu_{\ln} + 0.5\sigma_{\ln}^2\right)$ that relates the expectation to the logarithmic mean and standard deviation.

Examination of the partial integrals for the expectation show that the discrepancy between the means of the data and of the distributions arises from the tails of the distributions in which return periods are longer than the quantitative record. Although the combined log-normal PDFs correctly fit the 109-year data, the shapes of the unsampled tails are less certain. Nonetheless, the large expectations raise the somber possibility that the risk from disasters with return periods of several centuries may be larger than one would anticipate from the extant record.

Thus, one can argue that hurricane catastrophes are “Black Swans”—rare, but ruinous, poorly foreseen events (Taleb 2007). To be sure, studies such as this can provide estimates of return periods. But practical decision making is dominated by annual budget cycles, two- or four-year electoral cycles, or tenures in office of professional planners. Because the return period for the “big one” is measured in generations to centuries, long-term planning requires spending of financial or political capital today to prepare for something that will probably happen after the decision maker has passed from the scene. Although regulation and strategic planning can provide longer perspectives, manageable immediate crises too often trump overwhelming eventual ones.

In addition to the effect of hypothetical increases in hurricane numbers and intensity, there are three other possible causes for significant trends of normalized damage. Hardening of buildings against wind damage can reduce expected damage by as much as 75%. Although mitigation demonstrably works, much of the existing U.S. housing stock consists of unhardened, legacy structures. Nonetheless, increasing adoption and enforcement of more rigorous building codes should reduce normalized damage over time (Stewart et al. 2003; Jain et al. 2005). The index of wealth used in the normalization is a nationally aggregated value. It combines generally affluent coasts with less affluent inland locales. Thus, concentration of wealth in coastal counties should cause underestimation of the growth of assets in harms way, leading to increasing normalized damage. During the lull from approximately 1970 through 2003, there were fewer hurricane disasters than would be expected from the long-term average. This lull, which may reflect random fluctuations or the AMO, could help mask an underlying upward trend.

Increasing hurricane activity and underestimation of growth of wealth in coastal communities should lead to increasing normalized damage, whereas structural hardening and aliasing of the late 20th century lull should lead to decreasing normalized damage. These factors may compensate. A consistent interpretation of the present analysis is that their net effect is small compared with the large year-to-year random variation and the growth of assets and population at risk.

Conclusions

Hurricane deaths and destruction in the Unites States are convolutions of numbers and intensities of hurricanes crossing the shoreline, increasing population and development, and measures taken to mitigate effects. None of these factors is necessarily constant over time.

Mortality and damage behave in opposite ways. Mortality decreases with a halving time of ~26 years, despite a 10-fold increase in coastal population since 1900. This decrease is almost certainly the result of better forecasts and warnings and more effective emergency responses (Willoughby et al. 2007). Inflation-adjusted damage increases exponentially with a doubling time of 14 years. If damage is normalized for increasing population and individual wealth, the average annual cost becomes essentially constant. In contrast with loss of life, there is no detectable signal attributable to forecasting or damage mitigation measures. Large random variations from year-to-year and the growth of property at risk also seem to mask effects such as greater concentration of wealth along the coasts, possible century-scale changes in hurricane destructive potential, structural hardening, and reduced late-20th-century high-effect landfalls.

Because the year-to-year variations of human and property casualties can be several orders of magnitude, logarithmic transformations facilitate analysis. Most years with at least one major-hurricane landfall lie above the time-varying geometric means; most years with some effects, but no major-hurricane landfall, lie below the geometric means. Separation of the major-hurricane landfall years from the nonmajor-hurricane landfall years leads to combined log-normal distributions of effects.

Although it seems clear that mortality attributable to hurricanes has declined since 1900, the statistical significance for the decrease in major-hurricane landfall years became marginal as a result of Katrina, and mortality during nonmajor-hurricane seasons actually increased as a result of deadly seasons in that partition after 2000. This change may indicate a bottoming out of the decline in human casualties attributable to better forecasts.

Normalized damage during major hurricane years was constant over time in both records. During the 101-year record, nonmajor hurricane damage seemed to show a (not significant) decrease as a result of small damage during years that would have had zero recorded damage in the early part of the record. By 2000, coastal development had become so dense that this process saturated. The 109-year record shows no significant trend in nonmajor-hurricane damage.

The distributions are skewed. The mean annual number of deaths and amount of damage were 28 and US$11 billion based upon exponential extrapolation of the data to 2005. The corresponding values deduced from the combined logarithmic distributions are 64 deaths and US$16 billion. The differences between these estimates are attributable to large effects with return periods > 100 years on the tails of the distributions.

The changes in mortality tendencies between the 1900–2000 and 1900–2008 records are consistent with growing populations beginning to dominate better forecasts and warnings. Both the modest increase in expected damage and a significant part of the increase in expected mortality reflect better sampling of the high-effect tails of the distributions. Within the well-sampled parts of the PDFs, current coastal development and tropical-cyclone climatology imply that the expected return periods for catastrophes similar to Katrina are approximately a century for $> 1{,}000$ deaths and a third of a century for $>$ US$100 billion in damage. A hurricane season costing $>$ US$200 billion has approximately 1% probability.

This analysis reveals no trend attributable to anthropogenic global warming. It is consistent with the tentative consensus (Bender et al. 2010; Knutson et al. 2010) among TC meteorologists that global warming is a real threat that will ultimately increase numbers and intensities of the strongest hurricanes (if not total numbers of TCs), but the signal is unlikely to be detectible above random variations before the late 21st century.

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