Global Earthquake Fatalities and Population

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Modern global earthquake fatalities can be separated into two components: (1) fatalities from an approximately constant annual background rate that is independent of world population growth and (2) fatalities caused by earthquakes with large human death tolls, the frequency of which is dependent on world population. Earthquakes with death tolls greater than 100,000 (and 50,000) have increased with world population and obey a nonstationary Poisson distribution with rate proportional to population. We predict that the number of earthquakes with death tolls greater than 100,000 (50,000) will increase in the 21st century to 8.7±3.3 (20.5±4.3) from 4 (7) observed in the 20th century if world population reaches 10.1 billion in 2100. Combining fatalities caused by the background rate with fatalities caused by catastrophic earthquakes (>100,000 fatalities) indicates global fatalities in the 21st century will be 2.57±0.64 million if the average post-1900 death toll for catastrophic earthquakes (193,000) is assumed. [DOI: 10.1193/1.4000106]

INTRODUCTION

From the perspective of global earthquake fatalities, the 21st century began ominously. In 2001, the **M**7.6 Bhuj, India, earthquake killed 20,085 people. In 2003, the **M**6.6 Bam, Iran, earthquake killed 31,000 people. In 2004, the **M**9.3 Sumatra-Andaman, Southeast Asia, earthquake killed 228,000 people, mostly by a tsunami that swept across the Indian Ocean. In 2005, the **M**7.6 Kashmir, Pakistan, earthquake killed 87,351 people. In 2008, the **M**7.9 Wenchuan, China, earthquake killed 88,287 people. And in 2010, the **M**7.0 Haiti earthquake killed 222,570 people. All told, approximately 699,000 people died in earthquakes during the century's first decade. While large losses of life in earthquakes have been observed before, the occurrence of so many very deadly earthquakes within a single decade is unprecedented. These very deadly earthquakes—along with the 2011 Tohoku, Japan, **M**9.0 earthquake, with its 22,626 death toll and huge financial impact—have prompted speculation that the planet is experiencing the consequences of the large urban population growth in the 20th century (e.g., Bilham 2010). (Earthquake fatalities for earthquakes reported here are described at the USGS's world earthquake deaths Web site, http://earthquake.usgs.gov/earthquakes/world/world_deaths.php, as of 26 April 2011. Uncertainty in the Haitian estimated death toll is discussed later.)

The growing world population suggests that earthquakes should become increasingly deadly because the expected number of earthquake deaths is proportional to the exposed population and their vulnerability to earthquakes. This article explores the relation between

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global earthquake fatalities and world population. In addition to examining the relation between global fatalities and world population, we postulate that earthquakes with large death tolls can be represented by a nonstationary Poisson process in which their annual probability of occurrence is proportional to world population. The purpose of our investigation is to use historical trends to predict both global fatalities and the number of catastrophic (>100,000 fatalities) earthquakes in the 21st century.

While a correlation of global fatalities with world population is a reasonable expectation, it assumes that (1) the population of seismically hazardous areas as a proportion of world population has remained approximately constant and that (2) the seismic vulnerability of buildings has remained approximately constant. We tested the first assumption by compiling the aggregate population of the 31 countries that occupy the most seismically hazardous parts of the planet. The population as a percentage of world population of these 31 countries remained remarkably constant from 1500 to 2010, approximately 62%. The countries were selected from the Global Seismic Hazard Map, a probabilistic seismic hazard map, which estimates peak ground accelerations (PGA) with a probability of exceedance of 10% in 50 years (GSHAP 2011). The 31 countries included those where PGA exceeded 0.2 g in part of the country. The 62% compares favorably to Bilham's (2009) estimate that 65% of the world's large cities today may be subject to seismic shaking. The second assumption that building vulnerability has not changed significantly at the global scale is more difficult to evaluate. Some countries, for example, the United States and Japan, have decreased their risk by implementing seismic resistant design while others may have increased theirs. An example of the latter phenomenon was reported by Wyss (2005). He observed a disproportional increase of earthquake fatalities with population growth in an investigation of earthquake fatalities in the front of the Himalaya. He concluded that seismic risk in the region was increasing in part because buildings that were more vulnerable to lethal collapse during shaking were replacing the traditional more seismically resistant wood-frame and bamboo construction. In a more global investigation, Wyss and Trendafiloski (2011) used trends in the ratio of earthquake injuries to fatalities, or the casualty ratio, to infer if newer buildings are less seismically vulnerable. They concluded that the global casualty ratio in the last century had increased as a result of improved building practice, which they interpreted to indicate that newer buildings were less vulnerable or more seismically resistant. The decrease of vulnerability, however, was not very statistically robust, and the investigation was limited to the 20th century. For our investigation, we assume that the seismic vulnerability of new buildings did not, and will not during the 21st century, significantly improve at the global scale.

Only a few investigations have explored the predictive potential of historical trends to forecast future global earthquake fatalities. By excluding earthquakes with large numbers of fatalities, Bilham (2009) fit the underlying residual fatality trends from 1500 to 1999 with curves obeying a power law. His residual curves generally underestimated later fatality rates, which limited their predictive value. In an earlier investigation, Nishenko and Barton (1996), compared the cumulative number of earthquakes to fatalities per earthquake. As pointed out by Bilham (2009), their analysis indicated that one earthquake with a million fatalities may be expected per century if world population reaches 10 billion. Based on statistical regression, Nichols and Beavers (2008) proposed that

the mean annual number of fatal earthquakes for the time period from 1870 to 1999 could be related to world population by simply multiplying world population in billions by a factor of four.

EARTHQUAKE FATALITY CATALOGS

The completeness and reliability of earthquake fatality catalogs presents a significant challenge to investigators of historical trends of earthquake fatalities (e.g., Guidoboni and Ebel 2009, Hough and Bilham 2006). Records of early earthquakes (pre-1900) are incomplete, and the historical fatality count is systemically underestimated (Bilham 2009). Reasons for the incompleteness of historical catalogs include a lack of systematic reporting and the loss of records. Even official estimates of earthquake fatalities in very recent events may be inexact because of imprecise and incomplete record keeping. This uncertainty for modern events is illustrated by reported death tolls for the 2010 Haiti earthquake, which have ranged from 45,000 to 316,000 (Muggah and Kolbe 2011). We use here the 222,570 fatality estimate that was posted on the USGS Web site (cited in the Introduction here) when this manuscript was submitted. This uncertainty can cause fatality estimates for individual earthquakes to vary significantly between catalogs. In addition, seismological aspects—including the location, source parameters, shaking levels, and even the dates—of older earthquakes often are poorly documented. Interpretations are dependent on felt and often incomplete reports of shaking to infer that an earthquake was responsible for fatalities. The poor seismological documentation of some older events is a result of the absence of widespread and systematic instrumental earthquake monitoring. Such monitoring did not begin until the end of the 19th century. In fact, the ability to instrumentally locate earthquakes with magnitudes greater than **M**6.5 dates back only to 1904 (Lee and Brillinger 1979).

To partially compensate for the inherent uncertainty in available earthquake fatality catalogs, the present investigation made use of multiple catalogs. For our analyses of statistical trends, we relied on three multicentury catalogs: Utsu (2002), the National Oceanic and Atmospheric Administration (NOAA) online catalog, and the U.S. Geological Survey (USGS) catalog of the world's most destructive earthquakes. We also used two modern short-term catalogs to highlight some of the characteristics of global earthquake fatalities. We used these latter catalogs for illustrative purposes simply because we suspect that they are more complete. Earthquake fatalities in all of these catalogs are typically total fatalities for an earthquake, that is, they include fatalities from secondary effects, such as tsunamis and landslides.

The two modern short-term catalogs that we used were compiled by the USGS. The shortest and most recent catalog was compiled by Kristin Marano and colleagues for their investigation of earthquake fatalities caused by secondary effects, that is, nonshaking (Marano et al. 2010). It covers the period from 1968 to 2008 and includes earthquakes with one or more reported fatalities. It is presumably the most complete of all of the catalogs. A second valuable USGS catalog (USGS 2011a), available at http://earthquake.usgs.gov/earthquakes/world/world_deaths.php, includes earthquakes since 1900 that have killed more than 1,000 people. Both catalogs were updated to 2011 with fatalities by year (USGS 2011b; http://earthquake.usgs.gov/earthquakes/eqarchives/year/).

The multicentury catalogs were compiled by Utsu (2002), the NOAA Geophysical Data Center, and the USGS. The Utsu (2002) catalog is his DEQ50 in which earthquakes with 50 or more fatalities that occurred between 1500 and 2000 are listed. It is available digitally in Lee et al. (2002). The NOAA catalog, which is referred to here as the NOAA2010 catalog to distinguish from earlier printed versions (e.g., Dunbar et al. 1992), is the National Geophysical Data Center's Significant Earthquake Database (2011), available online at http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1. It includes earthquakes from 2150 BCE to 2011 CE. The USGS catalog (USGS 2011c) lists the most destructive earthquakes from 800 CE to 2011 CE. This catalog includes only earthquakes with death tolls of more than 50,000 and is maintained at http://earthquake.usgs.gov/earthquakes/world/most_destructive.php. Earthquakes with more than 50,000 fatalities that are included in at least one of the three catalogs are compared in Table 1. For completeness, earthquakes that Utsu (2002) labeled as great are also listed; he did not specify fatalities for these earthquakes, but we assumed "great" implied approximately 50,000 or more fatalities.

Although we were reluctant to modify these catalogs other than to update them to 2011, we reviewed individual earthquakes with exceptionally large reported death tolls in the three multicentury catalogs. Descriptions of older earthquakes often are sparse and subject to alternative interpretation. In particular, counts of fatalities may be poorly documented. An example of a major reinterpretation is the natural disaster in Calcutta, India, in 1737. Many earthquake fatality catalogs include (or have included) this earthquake, which is estimated to have killed 300,000 people. Bilham (1994), however, concluded that it was probably a cyclone or large weather event. Our review prompted us to delete only one earthquake in the longest USGS catalog: the 1789 Palu, Turkey, earthquake, which is reported to have killed 51,000 people. Although it was originally described by Ambraseys (1989), it was omitted from his updated compilation of historical earthquakes in the Mediterranean and Middle East (Ambraseys 2009).

The Utsu (2002) catalog contains many descriptive entries in the fatalities column. Fatality estimates for 257 of the 1,025 fatal earthquakes listed in the catalog are described by descriptive terms. Accordingly, we substituted 50, 300, 3,000, 30,000, and 50,000 fatalities, respectively, for "many" (227 entries); "100s" (9 entries); "1,000s" (13 entries); "10,000s" (3 entries); and "great" (5 entries) in his catalog. With these substitutions, descriptive designations account for approximately 0.393 million of the 5.272 million total fatalities in the catalog. Although observations and conclusions presented here reflect these substitutions, we repeated the analyses without the substitutions to test if our conclusions remained valid, which they did. We will refer to the catalog with these substitutions and the post-2000 earthquakes included as the updated Utsu (2002) catalog. Reference to the Utsu (2002) catalog without the phrase "updated" indicates that the unmodified catalog was used.

World population estimates were obtained from two sources. For pre-1900 population estimates, we relied on Biraben (1980). For post-1900 populations and projections, we relied on compilations by the United Nations Department of Economics and Social Affairs, Population Division, available at http://www.un.org/esa/population/ (UNDESA 2011). Information on the population histories of cities was from Chandler (1987).

Table 1. Comparison of earthquakes with more than 50,000 fatalities in three earthquake fatality catalogs used in this investigation. Earthquake names shown in bold, normal, and italics type, respectively, are USGS, NOAA2010, and Utsu (2002) catalog designations.

Time (calendar year)	Earthquake	Country	Fatalities		
			USGS	NOAA2010	Utsu (2002)
856	**Damghan**	**Iran**	200,000	200,000	–
893	**Ardabil**	**Iran**	150,000	180,000	–
1033	Ramala	Israel	–	70,000	–
1042	Tabriz	Iran	–	50,000	–
1101	Khorasan	Iran	–	60,000	–
1138	**Aleppo**	**Syria**	230,000	230,000	–
1169	Halab	Syria	–	80,000	–
1202	Southwestern	Syria	–	1,100,000	–
1268	**Asia Minor**	**Silicia**	60,000	50,000	–
1290	**Chihli**	**China**	100,000	100,000	–
1505	Kabul	Afghanistan		no estimate	great
1556	**Shaanxi**	**China**	830,000	830,000	830,000
1667	**Shemacha**	**Azerbaijan**	80,000	80,000	80,000
1693	**Sicily**	**Italy**	60,000	93,000	54,000
1695	Shaanxi	China	–	20,000	52,600
1703	Jeddo	Japan	–	–	great
1718	Gansu	China	–	73,000	75,000
1727	**Tabriz**	**Iran**	77,000	77,000	77,000
1739	Ningxia	China		50,000	50,000
1755	**Lisbon**	**Portugal**	70,000	60,000	62,000
1779	Tabriz	Iran		200,000	50,000
1783	**Calabria**	**Italy**	50,000	30,000	35,000
1832	*Hindu Kush*	*Afghanistan*	–	no estimate	great
1844	*Miyaneh*	*Iran*	–	–	great
1861	*Padang*	*Indonesia*	–	no estimate	great
1868	Quayaquil	Ecuador	–	70,000	40,000
1908	**Messina**	**Italy**	72,000	82,000	82,000
1920	**Ningxia**	**China**	200,000	200,000	235,502
1923	**Kanto**	**Japan**	142,800	99,331	142,807
1935	Quetta	Pakistan	–	60,000	60,000
1948	**Ashgabat**	**Turkmenistan**	110,000	19,800	19,800
1970	**Chimbote**	**Peru**	70,000	66,794	66,794
1976	**Tangshan**	**China**	255,000	242,000	242,800
1990	**Manjil-Rudbar**	**Iran**	40,000–50,000	40,000	35,000
2004	**Sumatra-Andaman**	**Indian Ocean**	227,898	175,827	–
2005	**Kashmir**	**Pakistan**	86,000	86,000	–
2008	**Wenchuan**	**China**	87,587	87,652	–
2010	–	**Haiti**	222,570	222,570	–

FATALITY TRENDS

Three aspects of earthquake fatalities trends are relevant to the present investigation. These aspects are illustrated in Figures 1 to 3. They include: (1) the significant contributions of earthquakes with large death tolls to global totals, (2) the approximately constant background fatality rate when these earthquakes are removed, and (3) the increase in the number of earthquakes with large death tolls in modern time.

The significant contribution from earthquakes with large death tolls is demonstrated for the 20th century in Figure 1. Cumulative fatalities for two time periods, 1900–2011 and 1968–2011, are plotted. The two time histories are based on the post-1900 USGS and Marano et al. (2010) catalogs. The salient feature of both time histories is that earthquakes with large death tolls are superimposed on a smooth background trend. The impact of earthquakes with large death tolls on the cumulative total is particularly clear in Figure 1. In fact, more than half of the global earthquake fatalities in the 20th century were caused by only seven earthquakes.

Figure 2, based on the updated Utsu (2002) catalog, illustrates the dominant role of earthquakes with large death tolls for a longer time interval, 1500–2011 (see Table 1 for dates of earthquakes with fatalities greater than 50,000). When all earthquakes in the updated catalog are considered, the time history of global fatalities is dominated by steps that reflect the occurrence of earthquakes with large death tolls. Removal of earthquakes with death tolls greater than 100,000, however, produces an approximately linear background residual curve, particularly after 1668. By excluding earthquakes with decreasing numbers of fatalities (i.e., 100,000, 50,000, and 10,000), curvature of the resulting residual curves increases slightly with decreasing thresholds for exclusion (Figure 2a). Of course, the magnitude of the steps in the curves decreases when earthquakes with successively smaller death tolls are removed. This results in smoother curves.

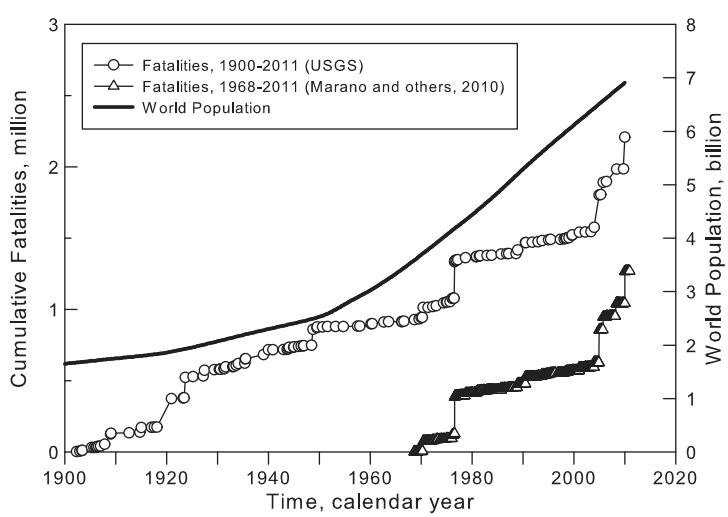

Figure 1. Cumulative global earthquake fatalities from 1900 to 2011 for earthquakes with 1000 or more deaths and from 1968–2011 for earthquakes with one or more deaths.

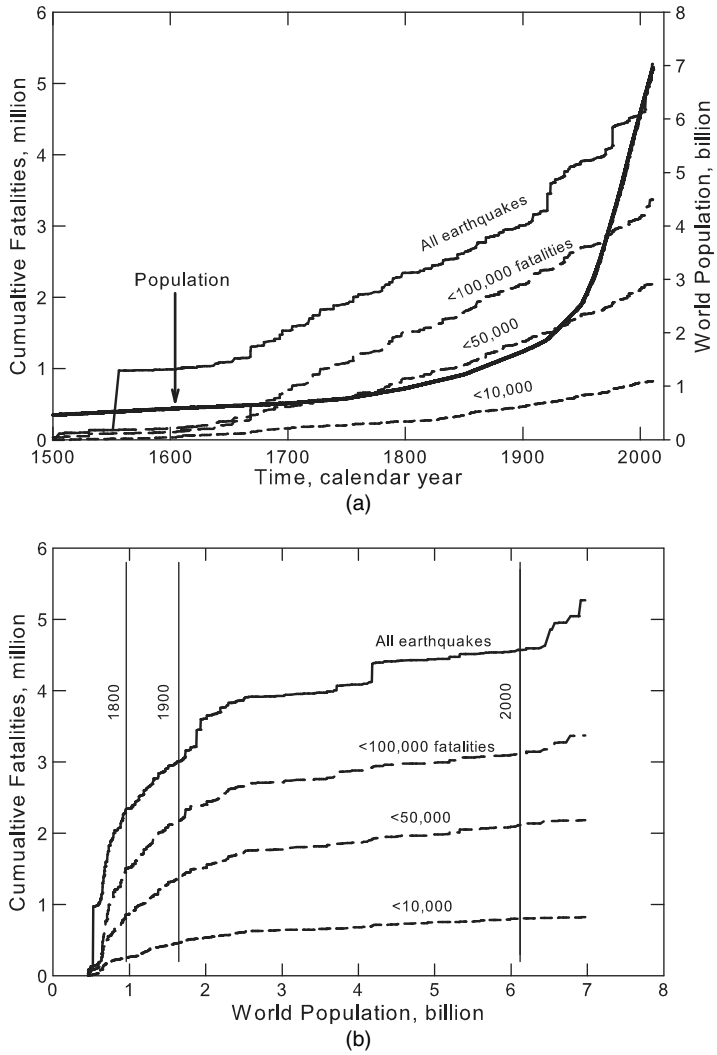

Figure 2. Earthquake fatality data from updated Utsu (2002) catalog. (a) Cumulative global earthquake fatalities, 1500–2011. Different curves show cumulative fatalities for earthquakes for which only indicated death tolls were included. (b) Cumulative global earthquake fatalities versus world population, 1500–2011.

The large relative contribution from earthquakes that exceed different death tolls to global earthquake fatalities is indicated by the separation of the curves in Figure 2a. The comparison indicates that earthquakes with more than 10,000, 50,000, and 100,000 fatalities, respectively, were responsible for 82%, 52%, and 25% of global fatalities. These estimates of relative contribution are for the time period 1600–2011 in order to remove the large impact of the 1556 Shaanxi, China, earthquake, which is reported to have killed 830,000 people.

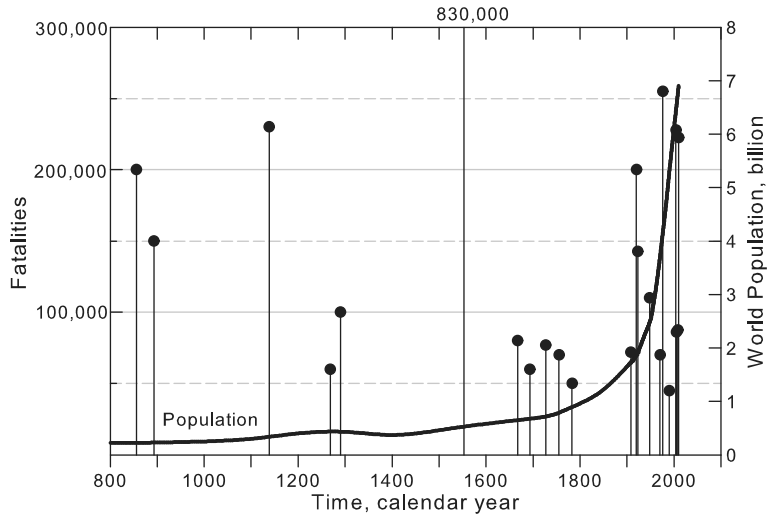

Figure 3. Individual earthquakes from 800 to 2011 with more than 50,000 fatalities from USGS catalog. The 1990 **M**7.4 western Iran earthquake in which reported fatalities ranged from 40,000 to 50,000 is included.

Estimated world population as a function of time is also shown in Figure 2a. By combining the population and fatality data in Figure 2a, we can show cumulative earthquake fatalities versus population after 1600 (Figure 2b). Cumulative global earthquake fatalities obviously are not a linear function of world population. In fact, the ratio of global earthquake fatalities to world population has been steadily decreasing. This conclusion applies to the background fatality trends as well (Figure 2b).

A modern increase in the number of earthquakes with large death tolls is suggested in Figure 3. It shows the time history from 800–2011 of earthquakes in the world's most destructive earthquake (>50,000 fatalities) catalog published by the USGS. This catalog includes only earthquakes with death tolls greater than 50,000. The time history indicates that the number of these earthquakes began to increase in the late 17th century relative to earlier centuries. No earthquakes with more than 50,000 fatalities were reported in the 19th century, but this is a period for which the updated Utsu (2002) catalog documents only 669,151 earthquake fatalities. Both the number of earthquakes with death tolls of more than 50,000 and the total earthquake fatalities, 1,564,241, increased in the 20th century to their highest level. In all, 16 of the 22 earthquakes in the catalog occurred after 1666. The time history in Figure 3 also suggests that the frequency of earthquakes with more than 100,000 fatalities has increased, particularly since 1900.

We assume these trends are real and not an artifact of catalog incompleteness. Although we were reluctant to use pre-1600 portions of catalogs for statistical analysis because of concern about catalog completeness (Hough and Bilham 2006), we assumed that earthquakes

with extremely large death tolls (greater than 50,000 fatalities) were more likely to be reported and their occurrence preserved in the historical record than are earthquakes with smaller death tolls.

PREDICTED CATASTROPHIC EARTHQUAKES AND GLOBAL FATALITIES IN THE 21ST CENTURY

The basic objective of this investigation was to establish the relation between global earthquake fatalities and world population and to use it to predict future global earthquake fatalities. Figures 1 and 2 indicate that global fatalities are not directly proportional to world population, but in fact are dominated by the intermittent but increasing numbers of earthquakes with large death tolls that are superimposed on an approximately constant background rate that appears largely independent of population growth. These observations prompted us to estimate fatalities in the 21st century by separately predicting fatalities from a background rate and fatalities caused by earthquakes with more than 100,000 fatalities, here referred to as *catastrophic earthquakes*, and then combining them. We describe our analysis here.

The background annual rate of fatalities was determined from the updated Utsu DEQ50 catalog by excluding earthquakes with more than 100,000 fatalities (Figure 4a). A linear fit (solid line in Figure 4a) to the cumulative background fatalities after 1825 closely approximates the post-1825 observations. The fatality rate inferred from the linear fit is 8,895±30 fatalities per year (uncertainty quoted is one standard deviation). Orthogonal polynomials of degrees 2, 3, and 4 furnish very good fits to the entire time period, 1600–2011 (Figure 4a). The higher-degree polynomials, however, are more sensitive to short-wavelength trends, which are of less interest here than the lower-degree polynomials that govern the long-term trend. Extrapolation of the polynomial fits to the year 2100 suggests that the linear fit to the post-1825 time period furnishes a minimum estimate of background fatality in the 21st century (Figure 4A).

Fatality estimates for the 21st century based on the background fatality rate range from 0.890±0.003 million fatalities for a linear extrapolation to 0.98 million and 1.21 million fatalities, respectively, for extrapolations based on second and third degree orthogonal polynomial fits. The fourth degree polynomial yields 1.70 million, but the extrapolation is dominated by the perturbation of the curve during the first decade of the 21st century, and we will not consider it here. The curvature in the polynomial fits, however, is determined largely by the 1600–1825 data, which, as explained below, may not be reliable. Thus, we adopt the linear fit to the post-1825 data for extrapolation of the background fatalities.

We note that both the background fatality rate and the number of fatal earthquakes in the updated Utsu (2002) catalog changed rather abruptly in about 1825 (Figure 4a, 4b). Figure 4a shows that the background annual fatality rate increased from 4,150 to 8,895 fatalities per year, respectively, for the time periods 1600–1825 and 1825–2011. Figure 4B shows that the increase of fatality rate coincides with an increase in the reported number of fatal earthquakes (>50 fatalities) in the updated Utsu (2002) catalog. The number of fatal earthquakes per year increased from 1.3 from 1600–1825 to 3.8 from 1825–2011. Both increases presumably reflect improved reporting because the annual number of events with less than 10,000 fatalities before 1825 in the updated Utsu (2002) catalog is less than half of the annual number after 1825 (Figure 4C). This suggests a bias in reporting, in which smaller (<10,000 fatalities)

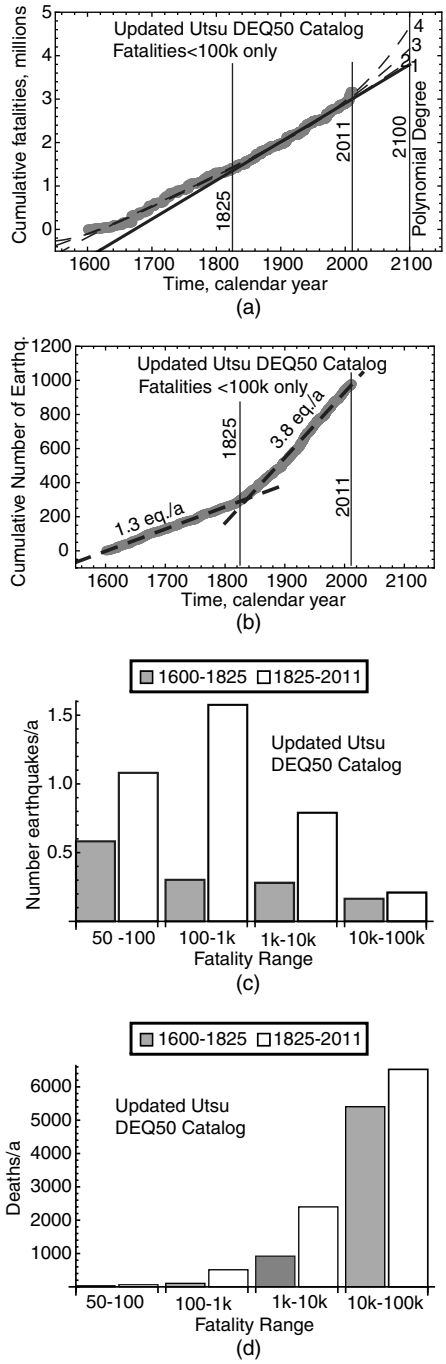

Figure 4. Earthquakes with <100,000 fatalities from the updated Utsu DEQ50 Catalog. (a) Cumulative fatalities (solid gray dots) plotted as a function of time. Linear fit to the 1825–2011 data (solid line) and orthogonal polynomial fits to the 1600–2011 data (dashed lines with degrees 2, 3, and 4 polynomials labeled in figure). (b) Cumulative number of earthquakes (solid gray dots) plotted as a function of time. Dashed lines are linear fits to the 1600–1825 and 1825–2011 data. (c) Histogram of the average number of earthquakes/a for the 1600–1825 and 1825–2011 intervals as a function of fatality/event categories. (d) Histogram of the average number of deaths per year for the 1600–1825 and 1825–2011 intervals as a function of fatality/event categories.

events have been underreported in the past. (We note that the cumulative fatality plot (Figure 4a) is less sensitive to this bias because most of the fatalities in the updated Utsu (2002) catalog are associated with earthquakes with more than 10,000 fatalities (Figures 2b and 4d), which presumably are more reliably reported.)

The increase in the frequency of catastrophic earthquakes with that of world population prompted us to model their occurrence as a nonstationary Poisson process (see the online Appendix). In a nonstationary Poisson process, the probability that an event will occur in the time interval $(t,\ t+dt)$ is $\lambda(t)dt$. If $\lambda(t)$ is a constant, the Poisson process is stationary. Here we assume that the annual probability of the occurrence of a catastrophic earthquake is proportional to population $\lambda(t) = \alpha N(t)$ where α is a constant and $N(t)$ is the world population at time t. Then the cumulative number of events expected in the time interval (S, t) is $\alpha\int_s^t N(\tau)dt$. Given a sequence of n events at times $t_1, t_2, \ldots t_n$ within the time interval $(S,\ T)$, the maximum likelihood estimate of α is $\dfrac{n}{\int_S^T N(\tau)dt}$ (see the online Appendix).

Figure 5 shows the nonstationary Poisson process fits to the cumulative number of earthquakes with more than 100,000 fatalities in the updated Utsu (2002) DEQ50, NOAA2010, and USGS catalogs (Table 1). The 100,000 death toll was selected as the threshold, rather than 50,000, because of the ambiguity in the Utsu (2002) catalog with the descriptor "great." It is uncertain whether death tolls in "great" earthquakes exceed 50,000. Post-1500 was selected because it coincides with the beginning of the time period covered by the Utsu (2002) DEQ50 catalog. We then determined α for the catastrophic earthquakes (fatalities greater than 100,000) in each of the three catalogs (updated Utsu 2002, NOAA2010, and USGS) and compared the cumulative number of earthquakes observed with the expected number predicted by the nonstationary Poisson distribution (Figure 5). Solid curves in these plots represent the cumulative number of earthquakes expected from the maximum likelihood fits to the data for a nonstationary Poisson process in which the probability of an event in the time interval $(t,\ t+dt)$ is $\alpha N(t)$. We evaluated the nonstationary fit for each catalog by comparing the observed number of catastrophic earthquakes in each of the subintervals 1600–1836.36, 1836.36–1964.55, and 1964.55–2011, intervals chosen so that the expected number of events in each interval is the same. We used Pearson's chi-square test to calculate the percentage P of independent trials from the nonstationary Poisson distribution that would be expected to give a better agreement with theory (online Appendix). Any value of P in the interval (5% to 95%) is deemed acceptable. The values of α and P are given in the legends of each of the plots in Figure 5. The values of α in the three plots do not differ significantly, and the values of P are all within the acceptable range. However, some caution is advised in accepting the significance of the fits in Figure 5 because of the small number of catastrophic earthquakes in the 1500–2011 interval.

The dashed curves in Figure 5 represent the maximum likelihood fit to a stationary Poisson process in which the probability of an event in the time interval $(t,\ t+dt)$ is constant. The nonstationary process furnished the better fit to the data in each of the three plots in Figure 5.

If world population were to remain constant at 6.12 billion and $\alpha = 0.0098 \pm 0.0037$ per billion person years based on the USGS catalog, the nonstationary Poisson process implies

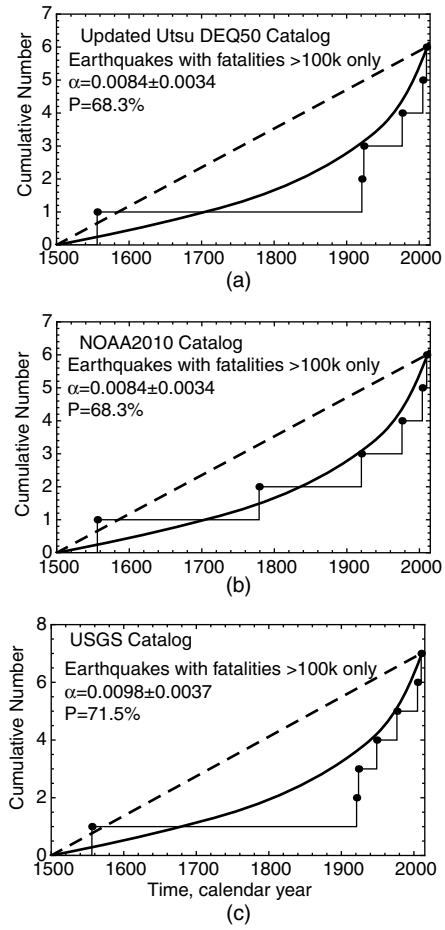

Figure 5. Cumulative number of catastrophic earthquakes (>100,000 fatalities) plotted as a function of time (a) updated Utsu (2002) DEQ50 Catalog, (b) NOAA2010 catalog, and (c) USGS catalog (see Table 1). The values of α (in units of per billion people year) and P are quoted in the legend for each plot. The solid and dashed curves, respectively, show the expected values for the nonstationary Poisson process and the stationary Poisson process representations.

that the world would experience approximately 6.0±2.3 catastrophic earthquakes in the 21st century (uncertainty quoted is one standard deviation). If we use the United Nations (UNDESA 2011) medium-fertility projections of world population for the 21st century, which will grow from 6.12 to 10.1 billion, 8.7±3.3 catastrophic earthquakes are expected in the century. This forecast is approximately a doubling of the four catastrophic earthquakes observed in the 20th century when world population grew from 1.61 billion to 6.12 billion.

Total global earthquake fatalities for the 21st century can be estimated by combining fatalities caused by catastrophic earthquakes with those caused by the annual background rate. Estimates of global fatalities are compiled in Tables 2 and 3 for earthquakes with

Table 2. Predicted minimum global earthquake fatalities in 21st century, based on United Nations (UNDESA 2011) medium-fertility population projections

Catalog	Catastrophic earthquakes: Number	Catastrophic earthquakes: Fatalities (millions)	Background fatalities (millions)	Total fatalities (millions)
Earthquakes with fatalities > 100,000 (Fatalities per earthquake = 100,000)				
Utsu (2002) updated	7.5±3.0	0.75±0.30	0.89±0.003	1.64±0.30
NOAA2010	7.5±3.0	0.75±0.30	0.89±0.003	1.64±0.30
USGS	8.7±3.3	0.87±0.33	0.89±0.003	1.76±0.33
Earthquakes with fatalities > 50,000 (Fatalities per earthquake = 50,000)				
Utsu (2002) updated	31.1±6.2	1.56±0.31	0.68±0.002	2.24±0.31
NOAA2010	27.1±5.1	1.36±0.26	0.68±0.002	2.04±0.26
USGS	20.5±4.3	1.03±0.22	0.68±0.002	1.71±0.22

Table 3. Predicted global earthquake fatalities in 21st century based on United Nations (UNDESA 2011) medium-fertility population projections and 1900–2010 average death tolls of catastrophic earthquakes

Catalog	Catastrophic earthquakes: Number	Catastrophic earthquakes: Fatalities (millions)	Background fatalities (millions)	Total fatalities (millions)
Earthquakes with fatalities > 100,000 (Average fatalities per earthquake = 193,000)				
Utsu (2002) updated	7.5±3.0	1.45±0.58	0.89±0.003	2.34±0.58
NOAA2010	7.5±3.0	1.45±0.58	0.89±0.003	2.34±0.58
USGS	8.7±3.3	1.68±0.64	0.89±0.003	2.57±0.64
Earthquakes with fatalities > 50,000 (Average fatalities per earthquake = 138,500)				
Utsu (2002) updated	31.1±6.2	4.31±0.86	0.68±0.002	4.99±0.86
NOAA2010	27.1±5.1	3.75±0.71	0.68±0.002	4.44±0.71
USGS	20.5±4.3	2.84±0.60	0.68±0.002	3.52±0.60

death tolls greater than 100,000 and 50,000 (entries for the latter will be discussed later). The tables show fatality estimates using the number of catastrophic earthquakes predicted with each of the three long-term catalogs. Table 2 compiles minimum fatality estimates; Table 3 compiles "average" fatality estimates. The number of catastrophic earthquakes predicted with each catalog (see column 2) is based on the United Nations medium-fertility projection of world population in the 21st century, which is predicted to grow from 6.12 billion to 10.1 billion. Because fatality estimates based on each catalog agree at one standard deviation, only estimates based on the USGS catalog are discussed here.

The USGS catalog indicates that a minimum of 1.76±0.33 million fatalities will occur in the 21st century (Table 2). The minimum estimate was derived by assuming a death toll of

Table 4. Predicted global earthquake fatalities in 21st century based on United Nations (UNDESA 2011) high-fertility population projections and 1900–2010 average death toll of catastrophic earthquakes

	Catastrophic earthquakes			
Catalog	Number	Fatalities (millions)	Background fatalities (millions)	Total fatalities (millions)
Earthquakes with fatalities > 100,000 (Average fatalities per earthquake = 193,000)				
Utsu (2002) updated	9.0±3.6	1.74±0.69	0.89±0.003	2.63±0.69
NOAA2010	9.0±3.6	1.74±0.69	0.89±0.003	2.63±0.69
USGS	10.5±3.9	2.03±0.75	0.89±0.003	2.92±0.75
Earthquakes with fatalities > 50,000 (Average fatalities per earthquake = 138,500)				
Utsu (2002) updated	37.5±7.5	5.19±1.04	0.68±0.002	5.88±1.04
NOAA2010	32.7±6.1	4.53±0.84	0.68±0.002	5.21±0.84
USGS	24.7±5.2	3.42±0.72	0.68±0.002	4.10±0.72

only 100,000 for each of the predicted 8.7 catastrophic earthquakes. If the average post-1900 death toll for catastrophic earthquakes (193,000) is assumed, estimated global fatalities increase to 2.57±0.64 million (Table 3). These estimates compare to 1.564 million fatalities in the 20th century reported in the updated Utsu (2002) catalog.

Table 4 shows predicted global earthquake fatalities if world population reaches the upper range projected by the United Nations, 15.8 billion, which is based on a high-fertility rate. Global fatalities increase slightly to 2.92±0.75 million from 2.56±0.64 million. The relatively small increase is the result of only a modest increase in the number of predicted catastrophic earthquakes from 8.7±3.3 to 10.5±3.9.

DISCUSSION

This section addresses the reliability of the catalogs and the sensitivity of our analysis to alternative assumptions. We conclude with discussion and speculation about the causes of the observed trends.

As discussed previously, the completeness of earthquake catalogs, particularly for older events, is not known. In our analysis, we used the catalogs in two very different ways: (1) to determine and then extrapolate background fatality rates and (2) to count the number of catastrophic earthquakes. The latter use requires a less complete catalog than does the former use. For the latter use, it is required that the reporting of only catastrophic earthquakes is approximately complete. For the former use, it is required that most of the earthquake fatalities have been reported.

We believe that the inferred change of the background fatality rate in Figure 4a in about 1825 is a consequence of the incompleteness of the updated Utsu (2002) catalog. As shown in Figure 4c the annual number of earthquakes with fatalities less than 10,000 in the 1600–1825 interval is less than half that in the 1825–2011 interval. The simple explanation for this discrepancy is that the reporting of events with fewer than 10,000 fatalities was less complete in

the earlier interval than in the later interval. The discrepancy between the two intervals is broadly consistent with changes in the NOAA catalog inferred by Nichols and Beavers (2008). They considered fatalities per earthquake in both the full and 20th century portion of the NOAA catalog as of 2000 and reported that the death toll per earthquake had decreased from 8,026 to 4,477 fatalities. They hypothesized that the decrease was either caused by under-reporting of smaller events in the older portion of the catalog or an increase in the number of fatal earthquakes. Based on our analysis, we prefer their former interpretation.

Although we cannot explain the apparent linearity in the cumulative plots of background earthquake fatalities versus time (Figure 4a), we think it is real and not a result of deficiencies in the underlying catalogs. There are biases (e.g., under-reporting of fatalities in the earliest earthquakes) that should affect those plots, but one would not expect such extraneous effects to produce a linear plot. Linear dependence is a very special case out of all the possible relationships, and it is unlikely that an extraneous effect would transform a nonlinear relation into that special case. Note that Bilham (2009, Figure 12) has plotted curves similar to Figure 2a in which background earthquakes are taken as those with death tolls less than either 5,000 or 30,000, rather than the death tolls used here. In those cases, he concluded that the cumulative fatalities associated with the background earthquakes was better explained by a power law fit $(a + bt^{10})$ than a linear fit. We suspect that the modest increase in the background rate with time is due to the improved reporting with time of earthquakes with smaller death tolls.

We used linear extrapolation of the background rate for predictions despite the increase of the fatality rate in the last ten years, 2001–2011. We do not believe a ten-year record is very reliable for defining new trends. Nevertheless, as noted, a linear fit provides a minimum estimate. On this basis, we used the constant rate to predict the background fatalities.

Testing the reliability of reports of catastrophic earthquakes in the earthquake fatality catalogs is challenging because much of the uncertainty derives from pre-1900 earthquakes for which documentation may be sparse and interpretations subjective. Without discovery of new historical information for the oldest earthquakes, we are limited to the available information. The existing ambiguity is illustrated by a comparison of the USGS, Utsu (2002), and NOAA2010 earthquake catalogs (Table 1). The criterion for listing an earthquake in Table 1 was that fatalities exceeded 50,000 in at least one of the catalogs. The NOAA catalog includes ten catastrophic earthquakes from 800–1500 while the USGS catalog lists only five, which is a significant difference. It is also informative to note that death tolls of individual earthquakes even in the modern era can vary significantly between catalogs. The 1933 Quetta, Pakistan, earthquake is assigned 60,000 fatalities in the Utsu (2002) and NOAA catalogs, and only 30,000 fatalities in the USGS post-1900 catalog of earthquakes with 1,000 or more fatalities. By contrast, the 1948 Ashgabat, Turkmenistan, earthquake is listed as catastrophic in the USGS catalog (110,000 fatalities), but not in either of the other catalogs (19,800 fatalities).

Because we could not rigorously evaluate the reliability of the reporting of catastrophic earthquakes in the three multicentury catalogs, we tested the assumption of a nonstationary Poisson process with each of the catalogs (Figure 5). This is not a completely satisfying test because the catalogs do not represent entirely independent observations and presumably inform each other to some degree. Nevertheless, the similarity of the fits is reassuring

and indicates the nonstationary Poisson process predicts the occurrence of catastrophic earthquakes far better than a stationary Poisson process (dashed lines in Figure 5).

We also tested how well the nonstationary Poisson process fit earthquakes in the three catalogs using earthquakes with 50,000 or more fatalities because the definition of the catastrophic earthquake as an event with more than 100,000 fatalities is arbitrary. The fits were made for longer time periods than in Figure 5 in order to take advantage of the full catalogs. The time period considered for the USGS catalog was 800–2011, for NOAA2010 catalog 800–2011, and for the updated Utsu catalog 1500–2011. Results are shown in Figure 6.

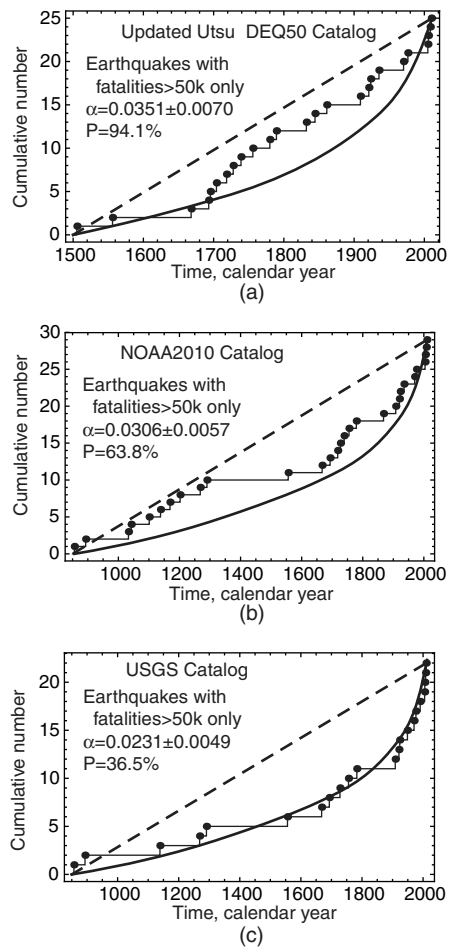

Figure 6. Cumulative number of earthquakes with >50,000 fatalities plotted as a function of time. (a) Updated Utsu (2002) DEQ50 catalog, (b) NOAA2010 catalog, and (c) USGS catalog (see Table 1). The values of α (in units of per billion people year) and P are quoted in the legend for each plot. The solid and dashed curves, respectively, show the expected values for the nonstationary Poisson process and the stationary Poisson process representations.

In evaluating the significance of the fits, the overall time interval was divided into four subintervals such that the expected number of events in each time interval was the same. The values of α and P for each fit are shown in the legend for each plot in Figure 6. Values of α found for the three catalogs do not differ significantly. Values of P found for the three catalogs are all within the acceptable range, although that for the updated Utsu (2002) catalog is marginal. There are a sufficient number of events in each of the plots in Figure 6 that we are confident in the Pearson's chi-square evaluation of the significance of the fits.

For $\alpha = 0.0231 \pm 0.0049$ per billion person years determined from the USGS catalog (Figure 6c) and the medium-fertility population projections by the United Nations, one predicts 20.5±4.3 earthquakes with more than 50,000 fatalities in the 21st century. Values of α determined from the updated Utsu (2002) and NOAA2010 catalogs do not differ significantly from the α determined from the USGS catalog, but the fits to the cumulative number of earthquakes were less satisfactory. On the basis of the fit to the USGS catalog of earthquakes with 50,000 or more fatalities, we estimate that a minimum of 1.71±0.22 million fatalities will occur in the 21st century based on the medium-fertility United Nations population projection (Table 2). If a post-1900 average death toll (138,500 fatalities) for earthquakes with death tolls greater than 50,000 is assumed, estimated global fatalities increase to 3.52± 0.60 million (Table 3). This estimate is not significantly different from estimated global fatalities of 2.57±0.64 based on the 100,000 fatality criterion that we used to define a catastrophic earthquake (Table 3).

We are inclined to place more confidence in the completeness of the USGS catalog with regard to the reporting of earthquakes with 50,000 or more fatalities because it just focuses on these earthquakes. In particular, Bruce Presgrave (2011, written communication) indicated that the catalog, although originally based on the NOAA catalog, is periodically reviewed and updated in light of new information.

Although we will argue that it is an oversimplification, it is tempting to conclude that the increase in the frequency of catastrophic earthquakes was caused by the growth in size and number of cities, which began late in the 17th century with the onset of the industrial revolution and improved municipal hygiene. Such growth, as has been pointed out by Bilham (2009), increases the likelihood of catastrophic earthquakes by concentrating population. This places more people at risk if an earthquake occurs nearby, and increases the potential for massive loss of life. Without such population concentrations, catastrophic earthquakes are less likely. The increase in the size and number of cities is documented in Figure 7, which shows the history of the number of cities of different population sizes. It is based on the compilation by Chandler (1987). *City* as used by Chandler (1987) includes suburbs lying outside the municipal area. The history illustrates how large (>1,000,000 people) cities are a modern phenomenon. The first city in the modern era to reach a million inhabitants was Beijing, China, which grew to this size in about 1815 (Chandler 1987). By 1900, only 16 cities had populations greater than one million. Today, 476 cities have populations of a million or more (Brinkhoff 2010). Even cities with more than 500,000 inhabitants are historically recent. In 1800, only six cities had populations in excess of half a million.

To test the hypothesis that the growth of cities is the primary factor controlling the increase of catastrophic earthquakes, we used the urban population of the world instead of the world population for $N(t)$ in the nonstationary Poisson process. This population as a function of time

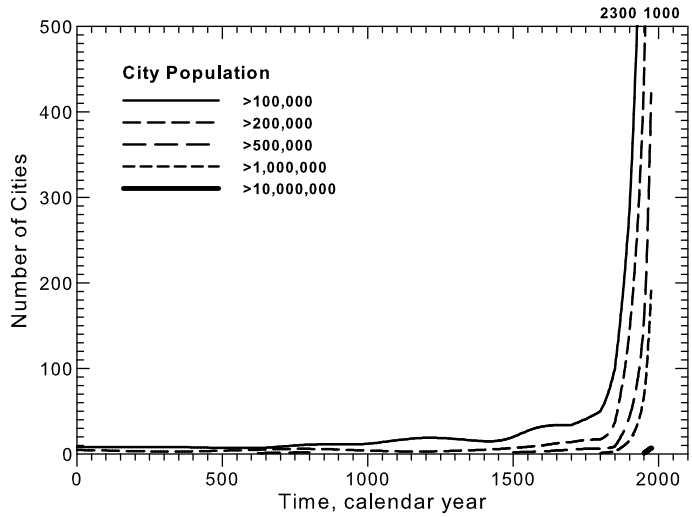

Figure 7. History of total number of cities with different populations (data from Chandler 1987). There were 476 cities in the world in 2010 with populations of more than one million.

was estimated from the number of cities exceeding a given population as shown in Figure 7. However, the number $\alpha\int_s^t N(\tau)dt$ predicted at any time t by a nonstationary Poisson process with $N(t)$ equal to the urban population increased too abruptly in the 20th century to fit the observed cumulative number of catastrophic earthquakes for any of the three catalogs in Table 1. This suggests that part of the world population living outside of cities is also significantly contributing to the increase of catastrophic earthquakes. Thus, some catastrophic earthquakes result from the devastation of multiple, but closely spaced, villages (e.g., the 2005 Kashmir, Pakistan, earthquake), or in the case of tsunamis, multiple coastal inundations. Such a conclusion could have been anticipated from Table 1 because not all of the catastrophic earthquakes listed there are associated with a specific city. This is not meant to imply that the growth of cities is inconsequential. Clearly, the million-fatality earthquake striking a megacity proposed by Bilham (2009) is more likely as the number of large cities and their size grows.

Finally, we note that for our predictions to be fulfilled, the percentage of the world population living in earthquake-resistant buildings must not proportionally increase during the 21st century. Wyss and Trendafiloski (2011) concluded that seismic design and construction practices have improved in the last 100 years and that these improvements have protected populations from building collapse in some countries. The challenge that remains is whether these improved practices will be adopted in other seismically hazardous areas. As we previously noted, we estimate that approximately 62% of the world population lives in countries with a significant seismic hazard. Based on the UNDESA (2011) 2100 medium-fertility population projections for these countries, we estimate this percentage will decline only modestly to 47% in 2100. Thus, without a significant increase in seismic-resistant buildings at a global scale, the number of catastrophic earthquakes and earthquake fatalities will continue to increase, and our predictions are likely to be fulfilled.

CONCLUSIONS

Global earthquake fatalities appear to be controlled by two processes: (1) a steady background fatality rate, which has remained largely constant and independent of population growth since 1825; and (2) large catastrophic (>100,000 fatalities) earthquakes, which have been increasing in number over time. The annual background fatality rate is 8,895±30 deaths per year, which indicates that 0.8895 million fatalities will occur in the 21st century even if no catastrophic earthquakes occur. Modeling of the three long-term earthquake fatality catalogs indicates catastrophic earthquakes obey a nonstationary Poisson process in which their rate is proportional to world population. Accordingly, we predict that there will be 8.7±3.3 catastrophic earthquakes in the 21st century assuming medium-fertility population projections by the United Nations. This estimate compares to the four observed in the 20th century. This prediction implies that a minimum of 0.87±0.33 million people will die in catastrophic earthquakes. The combination of these two estimates indicates minimum global earthquake fatalities in the 21st century will be 1.76±0.33 million. Based on the average post-1900 death toll of catastrophic earthquakes (193,000), global earthquake fatalities in 21st century will be 2.57± 0.64 million.

Earthquakes with more than 50,000 fatalities also appear to obey a nonstationary process. This indicates that 20.5±4.3 earthquakes with death tolls of more than 50,000 will occur in the 21st century if world population follows medium-fertility projections by the United Nations. Minimum global fatality estimates are 1.71±0.22 million, which compares favorably at one standard deviation to the minimum estimate of 1.76±0.33 million fatalities based on catastrophic earthquakes (>100,000 fatalities). If an average post-1900 death toll (138,500) for earthquakes with more than 50,000 fatalities is assumed, global earthquake fatalities in the 21st century will be 3.52±0.60 million, which does not differ significantly from the estimate of 2.57±0.64 million fatalities based on catastrophic earthquakes (>100,000 fatalities). Thus, estimates of global earthquake fatalities in the 21st century are statistically independent of the death toll criterion—50,000 and 100,000 fatalities—used to define a catastrophic earthquake.

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