Normalized earthquake damage and fatalities in the United States: 1900 - 2005

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ABSTRACT

Damage estimates from 80 United States earthquakes since 1900 are "normalized" to 2005 dollars by adjusting for inflation, increases in wealth and changes in population. A factors accounting for mitigation at 1% and 2% loss reduction per year are also considered. The earthquake damage record is incomplete, perhaps by up to 25% of total events that cause damage, but all of the most damaging events are accounted for. For events with damage estimates, cumulative normalized losses since 1900 total $453 billion, or $235 billion and $143 billion when 1% and 2% mitigation is factored respectively. The 1906 San Francisco earthquake and fire adjusts to $39 - $328 billion depending on assumptions and mitigation factors used, likely the most costly natural disaster in U.S. history in normalized 2005 values. Since 1900, 13 events would have caused $1B or more in losses had they occurred in 2005; five events adjust to more than $10 billion in damages. Annual average losses range from $1.3 billion to $5.7 billion with an average across datasets and calculation methods of $2.5 billion, below catastrophe model estimates and estimates of average annual losses from hurricanes. Fatalities are adjusted for population increase and mitigation, with five events causing over 100 fatalities when mitigation is not considered, four (three) events when 1% (2%) mitigation is considered. Fatalities in the 1906 San Francisco event adjusts from 3,000 to over 24,000, or 8,900 (3,300) if 1% (2%) mitigation is considered. Implications for comparisons of normalized results with catastrophe model output and with normalized damage profiles of other hazards are considered.

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Introduction

Unlike many weather-related hazards, a comprehensive accounting of earthquake damage in the United States through time has yet to be compiled. Accurate understanding of trends in property damage requires accounting for societal factors that, in addition to earthquakes, shape economic losses. This paper contributes to a growing literature that seeks to "normalize" past disaster damage by accounting for societal change, as a complement to other approaches focused on modeling events and their losses.

This paper provides a normalization of earthquake losses in the United States and Puerto Rico. Damage estimates of earthquake events since 1900 are adjusted for changes in inflation, wealth and population in the locales affected by earthquakes. A factor accounting for improvements in building standards is also considered. In addition, fatality data is adjusted for population increase, under several assumptions about the effectiveness of mitigation, providing a non-economic metric by which to compare various disasters.

Normalization Methodologies

Pielke et al. (2008) describe the goals of disaster loss normalization as applied to historical hurricane damage as follows: “to provide longitudinally consistent estimates of the economic damage that past storms would have had under contemporary levels of population and development.” The logic of normalization is straightforward: two identical structures will experience twice the damage of a single structure for a given geophysical event. Over time, normalization becomes more complicated because loss data are influenced by a number of important societal factors, including changes in the number of properties and the value of their contents, as well as efforts to mitigate losses through changing building practices and codes. Catastrophe models are one important tool that has been developed to assess potential losses in the face of changing exposure and vulnerability, in the context of various geophysical events. Normalized losses provide an independent basis of loss estimation for comparison with catastrophe models and have been recommended within the insurance industry as a valuable contribution to loss estimation (e.g. Collins and Lowe 2001).

Normalization methodologies have been applied to weather-related hazards in a wide range of contexts. Pielke et al. (2008) normalize U.S. hurricane losses over 2000-2005, providing an update to two earlier studies (Pielke and Landsea 1998; Collins and Lowe 2001). Pielke et al. (2006) also provide another independent estimate of normalized U.S. hurricane losses based on a dataset compiled by Munich Re insurance. Brooks and Doswell (2001) normalize major tornado losses for 1890 to 1999. Pielke et al. (2003) estimate of twentieth century normalized hurricane losses for Cuba and selected events in Latin America and the Caribbean. Crompton and McAneney (in review) provide normalized loss estimates for weather-related hazards in Australia for 1966 to 2005. Raghavan and Rajesh (2003) provide normalized tropical cyclone losses for the Andhra Pradesh region of India. To date, such methods have not been applied to U.S. earthquake losses.

But do normalization approaches to loss estimation provide valuable information on loss potentials? Several studies have provided rigorous tests of normalized losses suggesting that the methodology is capable of adjusting effectively for societal factors related to losses. For example, using the dataset developed by Pielke and Landsea (1998), Katz (2002) found in the normalized loss data the presence of a climatological signal of the El Niño-Southern Oscillation which has a strong effect on Atlantic hurricane activity. Pielke et al. (2008) found trends in normalized U.S. hurricane losses match trends in the climatology of hurricane landfalls, concluding,

> This finding should add some confidence that, at least to a first degree, the normalization approach has successfully adjusted for changing societal conditions. Given the lack of trends in hurricanes themselves, any trend observed in the normalized losses would necessarily reflect some bias in the adjustment process, such as failing to recognize changes in adaptive capacity or misspecifying wealth. That we do not have a resulting bias suggests that any factors not included in the normalization methods do not have a resulting net large significance.

Thus, one effective approach to evaluating the results of a disaster normalization is to compare the resulting statistical characteristics of the distribution of losses with those of the geophysical phenomena that causes losses. Because the goal of disaster loss normalization is to remove the signal of societal change in the loss data, at a minimum an effectively adjusted dataset should reflect the statistical characteristics of geophysical events better than a non-adjusted dataset.

EARTHQUAKE DATA

Property damage estimates from earthquakes are scattered among hundreds of sources and collated in three databases of varying comprehensiveness. This factor alone means that a normalization of historical earthquake losses is likely to be subject to a greater degree of uncertainty than comparable datasets related to weather disasters which have been collected by single agencies using consistent methodologies (e.g. Downton and Pielke 2005).

The main database used for this research is the Significant Earthquake Database (NGDC-s) published by the National Geophysical Data Center (Dunbar et al. 2006). Each NGDC-s record is listed with at least one source and in some cases many sources. Earthquakes listed in NGDC-s that occurred prior to the 1980's generally draw on Stover and Coffman (1993), Coffman et al. (1982) or other serial reports of the United States Geological Survey (USGS). Like all of the datasets with damage estimates, the information in NGDC-s is sparse before 1970 (Figure 1a). Some NGDC-s records cite EM-DAT (2006) as a primary source, but Stover and Coffman (1993) is the most complete source used.

The SHELDUS database is a product of the Hazards Research Lab of the University of South Carolina (Cutter and Emrich 2005; Hazards Research Lab 2006). In most cases SHELDUS uses the NGDC-s value or the most conservative value if multiple numbers are given by NGDC-s, but in a few cases SHELDUS and NGDC-s disagree or SHELDUS lists a damage estimate that does not match the lowest NGDC-s estimate. In such cases the SHELDUS value is based on other published reports (M. Gall, personal communication, April 2006). SHELDUS contains data only since 1960.

EM-DAT (2006) is a disasters database of the Center for Research on the Epidemiology of Disasters (CRED) at the Université Catholique de Louvain in Brussels, Belgium. Its coverage is much less extensive than NGDC-s, and EM-DAT does not contain any events not also contained by either SHELDUS or NGDC-s, but EM-DAT often lists damage estimates different than NGDC-s. CRED claims that all data in EM-DAT comes from a variety of sources, "including governmental and non-governmental agencies, insurance companies, research institutes and press agencies" and that validation procedures are in place. Citation information for individual events is not readily available, however, making it impossible to evaluate the original source for loss information. Further, when comparing EM-DAT records with NGDC records there is an almost systematic elevation of estimated losses in the EM-DAT report.

The most comprehensive descriptive catalog of United States seismicity is Stover and Coffman (1993), which is not available electronically and ends in 1989. Stover and Coffman (1993) was scanned thoroughly as a check on the NGDC-s, SHELDUS and EMDAT databases. Twenty additional events with estimated property losses were found in Stover and Coffman (1993) that do not appear in any of the databases, and thirteen events were found with estimated damages differing from the database sources.

Other electronic data sources carry more limited earthquake damage information, and were used as a reference for events that carried multiple damage estimates. The California Geological Survey (CAGS) makes available a Significant California Earthquakes list (available at http://www.consrv.ca.gov/CGS/rghm/quakes/eq_chron.htm). Since it is derived directly from Stover and Coffman (1993) and does not report every event given a property damage estimate by Stover and Coffman (1993), the CAGS list is useful only after 1989. Post-1989 citation information is not available. The Munich Re reinsurance company also makes available a disaster list (NATHAN) but it only describes the ten largest U.S. earthquakes and does not carry information independent of the other sources mentioned above. Literature sources were also consulted on various events and are cited where appropriate in Appendix A.

The datasets used report damage values for two Hawaiian tsunamis spawned by Alaskan earthquakes (1-April-1946 Unimak Island and 9-March-1957 Andreanof Islands). Because damages are reported only for the tsunami effects in Hawaii they are not included in the calculations reported in the text or in Tables 2 – 5, but they are listed in Appendix B. Curiously, although extensive infrastructure damage was reported in Alaska in the 1957 event, aside from Hawaiian tsunami damages ($5 million), we located no estimate of Alaskan damage losses.

Among the datasets listed above, there are 64 unique events since 1900. Stover and Coffman (1993) provide damage estimates on an additional 16 events that do not appear in the databases, bringing the total number of events to 80. Since there has never been a systematic methodology for determining total losses from an earthquake (NRC 1999), there is blurry separation between direct and indirect damage throughout the record. Further, many events have multiple estimates of damage. Where different sources provided conflicting damage estimates, three lists are derived from the 80-event list: a "high" list keeping only the highest damage estimate or the solitary estimate when only one is given; a "low" list keeping only the most conservative or solitary estimate; and a subjectively-determined "middle" list from the literature on each earthquake for which multiple damage estimates exist. In cases for which the literature provides no clear consensus, an average of available estimates is used. Appendix A contains a brief discussion of the events for which a "middle" value is derived. All available estimates are provided in Appendix B.

The average difference between the low and high estimates for the database, as a percentage of the low estimate, is 137%. An analysis of flood damages across different sources found differences in estimates varied with the size of the event, with smaller events having larger percentage differences and larger events having smaller percentage differences (Downton and Pielke 2005). The effect is opposite here: of the 80 events, the average percentage difference in the lower half (the 40 events with lowest reported damages) is 50% while for the upper half it is 189%. Thus, estimates for individual events should be interpreted with caution, with an understanding that unique, original damage estimates for the same event could differ by a significant amount.

Normalization of earthquake damages can be improved with a standardized and consistent approach to documenting damage, such as performed by the National Weather Service in context of floods and hurricanes (NRC 1999).

In addition to the four databases that contain property damage estimates, the National Geophysical Data Center publishes the Earthquake Intensity Database (NGDC-i, Dunbar 1985). NGDC-i does not include damage estimates, but does include Modified Mercalli Intensities (MMI), a descriptive assessment of earthquake effects on a twelve-point scale (Wood and Neumann 1931), by convention denoted with Roman numerals. In general, any earthquake that achieves MMI of VIII should be associated with measurable economic losses; the largest quakes will achieve MMI of IX, X and XI. The NGDC-i only contains data to 1985 but is more comprehensive than any of the other databases listed (Figure 1b) so while it does not contain damage estimates, it provides a useful check to ensure that all major earthquakes are included in the damage list, and also a basis for comparing adjusted losses to the geophysical characteristics of past events. NGDC-i contains some records of events MMI VIII, IX and X for which neither NGDC-s, EMDAT nor SHELDUS list property damage estimates. Stover and Coffman (1993) also describe many events with Modified Mercalli Intensities of VIII, IX and X for which estimated damages are not given. To ensure that all of the largest earthquakes are accounted for in this analysis, any event listed at MMI VIII or higher in NGDC-i with no damage estimate was investigated further, and the descriptions in Stover and Coffman (1993) were examined similarly. Most of these major seismic events occurred in sparsely-populated Alaska, Nevada or Utah, with severe damage to only a small number of structures. In some cases significant economic losses probably occurred but were not given. These events are described in Appendix C, listing 27 events that likely caused significant damages. Although the earthquake property damage record is clearly incomplete, likely by at least 25% and especially for events occurring before the 1960's, we are confident that all of the most damaging United States earthquakes of the past century are accounted for.

NORMALIZING PROPERTY DAMAGE DATA

The normalization of past earthquake damage begins with three factors: inflation, wealth and population, and then considers the effects of mitigation (cf. Crompton and McAneney, in review). All damages are normalized to 2005 values. Trends in the variables are displayed in Figure 2.

Inflation

The inflation adjustment uses the Implicit Price Deflator (IPD) for Gross Domestic Product (GDP), available from the U.S. Bureau of Economic Analysis (BEA) for 1929-2005. For years before 1929, the GDP deflator of Johnston and Williamson (2006) is used. The Johnston and Williamson deflator draws on the work of multiple economic historians but is not considered as accurate as the official BEA deflator; Johnston and Williamson suggest that their analysis is accurate to two significant digits. An alternative statistic commonly used for inflation is the Consumer Price Index (CPI), but the IPD is considered a more robust statistic for inflation as it does not rely on a fixed measurement of goods and services. Brooks and Doswell (2001) used CPI rather than IPD because at the time IPD was available only to 1940.

Wealth

The wealth adjustment uses the BEA's Fixed Assets and Consumer Durable Goods (FACDG) statistic, available for the period 1925-2005 (Table 1.1 of http://www.bea.gov/bea/dn/FAweb/AllFATables.asp). In the absence of an available estimate for values before 1925, values to 1900 are extrapolated based on the 1925 - 1928 average change (a reduction of 3% per year; Pielke et al. 2008). Fixed assets are defined as private and government assets such as equipment and structures. Consumer durable goods are non-business goods purchased by households with a life expectancy of at least three years (Parker and Triplett 1995).

Like inflation, the FACDG is a national number with no local information. The wealth numbers are adjusted for inflation and United States population to a per capita basis following (Pielke et al. 2008) in order to separate the independent effects on damage of changes in wealth over time. The *per capita* adjustment is used because while the increasing rate of wealth is population-dependent, wealth and population are not increasing at the same rate. The *per capita* wealth adjustment produces a more conservative estimate than using wealth changes adjusted for inflation alone (Figure 2).

Population

The third adjustment factor used in this analysis is population change between the event year and 2005 in the areas affected by each earthquake, applied at the county level with intra-decadal population estimates interpolated between the totals of the bracketing decades. While the inflation and wealth adjustments for each earthquake are fixed based on the year of the event and are thus straightforward in their application, the population correction introduces some challenges. Large earthquakes are usually regional in their effects, thus population corrections should account for the average change amongst all counties affected by each event. However, an earthquake occurring many decades ago may have caused considerable shaking but little damage in an area that at the time of the event was sparsely populated, but today is densely populated. The effect on the normalization in ignoring these areas would be a significant underestimate of the potential for contemporary damages.

To account for regional population changes, a "Combined Statistical Areas" approach is used to correct certain quakes. The Combined Statistical Area (CSA) is a legal definition set by the Office of Management and Budget for use by the U.S. Census Bureau. The important CSAs used in the normalization adjustments are defined as:

- **San Francisco Bay Area (SF CSA):** Alameda, Contra Costa, Marin, San Francisco, San Mateo, Santa Clara Counties.

- **Los Angeles area (LA CSA):** Kern, Los Angeles, Orange, Riverside, San Bernardino and Ventura Counties.

- **Seattle area:** King, Pierce and Snohomish Counties.

The 1933 Long Beach (California) earthquake (Tables 1 and 2) illustrates the approach of using a CSA rather than only the reported county. The Long Beach event caused extensive damage in Los Angeles County, but the earthquake also affected ten other Southern California counties (Stover and Coffman 1993), most of which were sparsely populated in 1933. While Los Angeles County has grown in population by a factor of 4 since 1933, other area counties have grown by as much as 15 times (San Bernardino County has grown from about 135,000 people in 1933 to almost 2 million people in 2005). The population adjustment factor between 1933 and 2005 using only Los Angeles County is 4.17; the adjustment factor using all counties in the Los Angeles metropolitan CSA is 6.36.

The CSA concept is informed by damage reports collated by Stover and Coffman (1993) and other sources. In general, the CSA adjustment factor is used for any earthquake which NGDC-i lists the maximum MMI as occurring in a county within a defined CSA. The use of a CSA is only an approximation of areas affected. Utilization of the CSA approach likely underestimates the potential for contemporary damages, as it excludes counties beyond the immediate metropolitan areas that are still potentially affected by shaking. Many of these counties have grown considerably in population and are in near-enough proximity to historic epicenters to expect damage in contemporary "repeat" quakes. The CSA usage therefore provides a conservative estimate of population increase for historic events.

The census unit used in the normalization calculations is indicated by a FIPS code (Federal Information Processing Standards), corresponding to an individual county (Appendix B). FIPS codes created for this paper and listed in Appendix B – corresponding to CSAs – are 6901 for the U.S. Census Bureau-defined SF CSA, 6902 for the LA CSA, 53999 for the Seattle CSA. In some cases the defined CSA was not deemed appropriate; customized CSAs appearing in Appendix B for individual events are:

- 2099 for Anchorage Borough (FIPS = 2020), Fairbanks North Star Borough (2090) and Valdez-Cordova Census Area (2261)
- 6903 for San Francisco County (6075) and Santa Clara County (6085)
- 6904 for Orange County (6059) and San Diego County (6073)
- 6905 for Los Angeles County (6037) and San Bernardino County (6071)
- 30999 for Beaverhead County (30001) and Madison County (30057)

Normalization equation

When the three adjustment factors are combined, the normalization calculation is performed as follows:

$$D_{2005} = D_y \times IPD_y \times W_y \times \Delta P_{2005\text{-}y} \times [MF_y]$$

where

D_{2005} : normalized damages in 2005 dollars

D_y : reported damages in event-year dollars

IPD_y : inflation multiplier based on difference between year (y) GDP and 2005 GDP

W_y : wealth multiplier based on difference between FACDG in year (y) and FACDG in 2005

$\Delta P_{2005\text{-}y}$: population change between 2005 and event year

$[MF_y]$: mitigation factor (either no mitigation [1], 1% mitigation [scaled percentage decrease from 2005], or 2% mitigation [scaled percentage decrease from 2005]; mitigation factors are described in the next section)

For example, using the consensus damage estimate (Appendix A), the 1964 Good Friday earthquake near Anchorage, Alaska would be normalized as

$$D_{2005} = \$540{,}000{,}000 \times 5.07 \times 2.44 \times 2.54$$

$$= \$16{,}932{,}000{,}000$$

where \$540M is reported damages in 1964 dollars (consensus value), 5.07 is the inflation adjustment, 2.44 the wealth adjustment, and 2.54 the regional population correction factor accounting for the Anchorage Borough, Fairbanks North Star Borough and Valdez-Cordova census areas. If the same calculation is performed with a 1% mitigation factor it proceeds as

$$D_{2005} = \$540{,}000{,}000 \times 5.07 \times 2.44 \times 2.54 \times 0.66$$

$$= \$11{,}213{,}000{,}000.$$

ACCOUNTING FOR MITIGATION

In the United States, considerable attention has been paid to structural mitigation of buildings in response to the threat of earthquakes. Such mitigation efforts will have the effect of decreasing normalized historical losses. Studies of the value of mitigation suggest a benefit to cost ratio of 2 to 4 (e.g. CBO 2007). Crompton and McAneney (in review) use a dummy variable to reflect an annual decrement in normalized losses resulting from tropical cyclone mitigation policies implemented in Australia. In addition to the no mitigation case, we consider two values for annual effects of mitigation, 1.0% and 2.0% reduction in structural vulnerability per year. A 1.0% reduction in vulnerability per year equates to a halving of vulnerability (and thus losses) over about 70 years, all else being equal, and a 2.0% reduction per year equates to a halving of vulnerability over about 37 years, all else being equal. It seems highly unlikely that earthquake mitigation has resulted in a decrease in vulnerability of more than 2.0% per year (e.g., suggesting that the same quake in the same location 74 years apart would result in 25% of the original losses, all else being equal). However, an evaluation of the effects of mitigation goes well beyond the scope of this paper, and we simply acknowledge that other values for the effectiveness of mitigation are plausible (both inside and outside of the range that we discuss). The values that we present are provided to illustrate the possible effects of mitigation over the long term on loss potentials.

For example, in the case of the 1964 Good Friday earthquake near Anchorage, Alaska, the $16.9 billion normalized loss estimate is reduced to $11.2 billion with 1% mitigation per year and $7.4 billion with 2% mitigation. A consistent time series of disaster losses would also enable a more rigorous evaluation of the effectiveness of mitigation in comparison to growth in population and wealth. The results discussed below are presented with no mitigation, 1% mitigation, and 2% mitigation.

INFLATION-ADJUSTED AND NORMALIZED EARTHQUAKE LOSSES

The ten most damaging earthquakes adjusted only for inflation are listed in Table 1. All 17 events exceeding $500 million in normalized damages by normalizing for inflation, wealth and population, and no mitigation, 1% mitigation, and 2% mitigation are listed in Table 2. Figures 3a-d show annual time series of the inflation-adjusted case and the three mitigation cases with an eight-year running mean overlain on each. Figures 4a-c show the distributions of the no mitigation, 1% and 2% cases.

Normalization significantly readjusts the picture of damaging U.S. earthquakes. Whereas none of their inflation-adjusted damages exceeded $500 million, events from 1918, 1933, 1949 in Puerto Rico, Los Angeles and Olympia (WA) respectively adjust to between $800 million and $16 billion (Tables 1 - 2), indicating that these were extreme events. When only adjusting for inflation, the costliest earthquake in U.S. history is the 1994 Northridge event with losses near $50 billion. With normalization, the 1906 San Francisco earthquake becomes the most costly, with losses of $40-$300 billion, depending upon mitigation, and with maximum losses exceeding $300 billion when a larger affected area is considered (see 1906 SAN FRANCISCO EARTHQUAKE section). With no mitigation, five events exceed $10 billion in damages, thirteen exceed $1 billion and seventeen exceed $500 million. When 1% (2%) mitigation is considered, 14 (12) events exceed $500 million, 11 (9) exceed $1 billion and 4 (2) exceed $10 billion. Figure 5 shows the cumulative distribution function of losses for all three mitigation cases.

Earthquake magnitude and inflation-adjusted damage results are correlated at 0.12. Using the normalized losses improves this correlation to 0.25, suggesting that the normalization adds value to an inflation-only adjustment, as would be expected. Considering mitigation at 1% results in a correlation of 0.25 and 2% results in 0.20. The difference in relationship with magnitude between no mitigation and 1% is not significant, but the degrading of the relationship at 2% is suggestive – but hardly conclusive – that mitigation may have an effect at less than 2%. The overall low relationship should be expected given the uneven distribution of population and wealth in locations exposed to earthquakes, and the unique characteristics of different events. In other words, if population and wealth were uniformly distributed, and earthquake behavior was uniform for every event, we would expect a correlation between intensity and normalized damage of 1.0.

In contrast to earthquakes, normalizing hurricanes to 2005 dollars, Pielke et al. (2008) found the most costly hurricane to be approximately $140 billion from the 1926 Miami event. In 2005 dollars, 90 hurricanes exceed $1 billion in damages and 27 exceed $10 billion (Pielke et al. 2008), more than five times the number of earthquakes with no mitigation, and 6.8 and 13.5 times more with 1% and 2% mitigation respectively.

Normalizing by wealth and inflation but not population, the most expensive tornado in U.S. history was the 1896 St. Louis event at $2.9 billion in 1997 dollars (Brooks and Doswell 2001), or $4.2 billion in 2005 dollars. When the Brooks and Doswell record is adjusted to 2005 dollars, only the 1896 tornado exceeds $2.5 billion, 13 tornados exceed $1 billion in damages, and an additional 11 adjust to between $500 million and $1 billion.

ANNUAL NORMALIZED LOSSES

Interpretation of annual losses from the data record is complicated by the temporal sparseness of events and damage data that is skewed to the recent decades of the 20th century (Figure 1a). Tables 3 and 4 list estimates made using various averaging windows and for different assumptions about mitigation. Sliding the averaging window is sensitive to the two extreme events (1906 and 1994 Northridge). If the 1906 San Francisco event is considered an outlier, annual losses increase when using more recent averaging periods. However, if both the 1906 event and the 1994 event are removed as outliers, no trend in annual losses is apparent. Figure 6 shows average annual losses by decade as a time series.

Estimates of annual losses using individual datasets (Dunbar et al. 2006; EM-DAT 2006; Hazards Research Lab 2006) rather than the consensus damage list produce a range of $434 million to $4.7 billion with a mean across datasets and averaging windows of $2.5 billion ($2.0 billion and $1.7 billion with 1% and 2% mitigation respectively; Table 4).

Using earthquake damage simulations from the HAZUS catastrophe model, FEMA estimated in 2001 expected U.S. annual losses to be $4.4B (in 1994 dollars; FEMA 2001). This loss estimate adjusts to $5.5B accounting solely for inflation and $8.0B in 2005 dollars accounting for inflation as well as proportional growth in national wealth and U.S. population with no adjustment for mitigation. With mitigation considered the FEMA annual estimate drops to about $7.2 billion with 1% annual mitigation, and $6.4 billion with 2% annual mitigation. A comparison with normalized losses developed here suggests that the normalized losses are considerably lower than those estimates provided by FEMA, especially when mitigation is considered in the normalization.

The discrepancy between HAZUS-derived estimates and estimates derived from the normalized record could result for several reasons. One explanation could be a low bias in historical loss estimates. A second could be consideration by HAZUS of large events for which there is no historical precedent, and thus not present in the normalized database. A third factor is macroeconomic factors that drive up the costs of losses (including "demand-surge") in the aftermath of an event (Pielke et al. 2008). In principle, normalized losses of accurate data spanning a range of events encompassing future possibilities should match well with estimates provided by catastrophe models. Because they do not in this case should provide additional motivation to examine the reasons for the differences and improve the baseline information on observed earthquake losses, which goes beyond the scope of the present analysis.

1906 San Francisco earthquake

At $40B – $328B total loss, the April 18, 1906 San Francisco earthquake has the highest normalized loss (Tables 2, 6). In 1906 dollars, damage estimates range from $350M (Haas et al. 1977) to $1B (Steinbrugge 1982). The $350M estimate only counts the cost to rebuild the city of San Francisco, so should be considered an lower bound on total loss. Some groups cite a $400M estimate (Algermissen et al. 1972; Steinbrugge 1982), but currently the most accepted value, considered here as the best estimate, is $524M (Munich Re 2001; Dunbar et al. 2006; EM-DAT 2006; Munich Re 2006). Munich Re (2006) implies that the $524M is conservative.

Different population corrections for the 1906 event can be justified. The event produced greatest damage in San Francisco County, which was the county both closest to the epicenter and the most densely populated during the event. However, many other areas far afield were severely damaged, most notably the city of Santa Rosa in Sonoma County (outside of the SF CSA). The Lawson Report (Lawson 1908) identifies eighteen counties damaged by shaking. Adjusting for San Francisco County alone is considered a lower bound. The SF CSA is used for consistency with how other events are treated in this analysis. The 18-county correction factor, considered most realistic, gives the highest multiplier at 9.28, about 15% greater than the SF CSA correction (Table 6).

Utilizing various 1906-value loss estimates and population factors, the normalization adjustments range from $45B to $626B, with $328B the result of using the $524M estimate and the 18-county population correction factor. The SF CSA population factor adjusts to $284B. When the 1% (2%) mitigation factor is used with the $524M damage estimate and 18-county population factor, the normalized damage adjusts to $121B ($44B); when mitigation is used with the CSA population factor the adjusted values are $105B ($38B).

Using a total damage estimate of $350M - $500M, Odell and Weidenmier (2004) cite the 1906 event as costing 1.3% - 1.8% of nominal 1906 U.S. GNP. As a percentage of 2005 U.S. GNP ($12,521 billion), 1.3% - 1.8% is $163B – $225B, comparable to the normalized adjustment. The discrepancy can be explained by the differences in population increase between the San Francisco area and the United States as a whole: since 1906 U.S. population has increased by about 3.5 times whereas the San Francisco area population has increased 8 – 9 times.

ADJUSTED EARTHQUAKE FATALITIES

Earthquake event fatalities can be adjusted similarly to the damage adjustment, providing a relative comparison in non-economic terms of the magnitude of various calamities, a method pursued for Caribbean hurricanes by Pielke et al. (2003). Fatalities are adjusted only using population change, not economic metrics. As for the damage normalization, the intent is not to estimate how many people would perish in the same earthquake today, but rather to estimate how many people would have perished in the event had it occurred with today's population, all else being equal. As with economic losses, mitigation can also be considered as a factor that serves to reduce losses. The calculation proceeds exactly as for the damage normalization while leaving out the wealth and inflation multipliers:

$$F_{2005} = F_y \times \Delta P_{2005\text{-}y} \times [MF_y]$$

where F_{2005} is adjusted fatalities and F_y is event fatalities. The Alaska Good Friday adjustment with 1% mitigation proceeds as:

$$F_{2005} = 131 \times 2.54 \times 0.66$$

$$= 220.$$

Fatalities that have been recorded for 31 U.S. earthquakes are multiplied by the change in local population from the year of the event to 2005 (Table 7). Some records conflict in fatality numbers for a given event; in those cases the range is presented. All fatality estimates use the numbers given by the datasets employed for this paper, except for the 1906 event. Because the 1906 San Francisco event was a defining moment for the region and country, considerable research has been undertaken on the event. While all database records give a fatalities estimate of 700 (Algermissen et al. 1972) or 2,000 (original source unknown) for this event, more recent research by Hansen and Condon (1989) indicates that fatalities were over 3,000, a number now used by the USGS, Munich Re (2006) and other groups.

When adjusted for population increase and no mitigation, six events caused over 100 fatalities and the 1906 event adjusts to over 24,000 fatalities (Table 7). The second-most deadly event is the 1933 Long Beach (Los Angeles area) earthquake with about 700 fatalities. An M7.9 event occurring near San Francisco today – similar to the 1906 event – is expected to cause an estimated 800 – 3,400 fatalities depending upon the time of day of shaking (Kircher et al. 2006a). With mitigation of 1% and 2% per year the 1906 quake adjusts to 8,900 and 3,250 deaths respectively. The difference between the values presented here with mitigation and Kircher et al.

(2006a), when compared to the normalized economic losses suggest a hypothesis that U.S. (and California) earthquake policy has been more successful in its focus on reducing loss of human life than economic damage. This is certainly the situation with respect to hurricanes, where loss of life has been reduced dramatically, with the notable exception of Katrina, while economic losses have escalated dramatically (and remained unchanged after normalization).

DISCUSSION/CONCLUSION

The most damaging hurricane in U.S. history, the 1924 Miami event, normalizes to $137B in normalized 2005 dollars (Bouwer et al. 2007) and the most expensive tornado, the 1896 St. Louis event, normalizes to $4.2B (2005 dollars, not adjusted for population, Brooks and Doswell 2001). With the possible exception of the 1930's Dust Bowl (Hansen and Libecap 2004), the 1906 San Francisco arguably normalizes to the most expensive single natural disaster event in U.S. history since 1900, although there is some remaining uncertainty. Consistent with the findings of this analysis, the 1906 event represented the single greatest event loss in the 125-year history of the Munich Re Reinsurance Company (Munich Re 2006).

A majority of high-fatality events occurred prior to the era of modern building codes, but after all events are adjusted, recent California quakes of 1971 (San Fernando), 1989 (Loma Prieta) and 1994 (Northridge) are the 6th, 9th and 10th most deadly events. This suggests that while technological sophistication may be a factor in reducing fatalities relative to population levels (10 of the 13 events with more than 30 adjusted fatalities occurred before 1965), loss potential remains a concern for modern earthquakes.

Earthquakes fall between hurricanes and tornados in terms of frequency of extreme damages. In 2005 dollars, 90 hurricanes exceed $1B in damages and 27 exceed $10B, more than five times the number of earthquakes with commensurate damages. Only 13 tornados exceed $1 billion in damages and only one tornado exceeds $3 billion (Brooks and Doswell 2001). However, while hurricanes are far more frequent than large earthquakes with aggregated losses more than double that of earthquakes ($1.05T vs. $432B), at the highest level damages are similar, especially when mitigation is considered in earthquake damage.

The loss data are suggestive of an imbalance between actual damage created by various hazard types and U.S. R&D spending on hazards. While weather-related hazards produce two to three times the damages of earthquakes, federal spending on weather-related hazards are more than an order of magnitude higher than spending on earthquakes (Meade and Abbott 2003). Drawing from Pielke and Carbone (2002), Meade and Abbott account for floods, hurricanes, winter storms, tornadoes, hail, extreme heat, and extreme cold in their weather-related losses calculation; they consider only federal funding in their spending analysis. The results of this paper suggests that the actual damage gap may be even greater than that noted by Meade and Abbott (4.3 times greater weather-related losses than earthquake losses), but still not at a level of equity with funding differences. Looking forward, an important question in natural hazards policy is whether or how to reconcile hazards R&D spending with damages, and more importantly, preventable damages resulting from R&D investments.

An important implication of this analysis is that it provides real-world loss data with which to compare with catastrophe model output. For example, using a HAZUS model analysis with estimated 1906 ground motions over the 19-county northern California/San Francisco area, a modern repeat of the April 1906 shaking is expected to produce $90B – $120B in property loss to buildings (Kircher et al. 2006a). A comparison of HAZUS-derived losses to actual losses of the 1994 Northridge earthquake found that HAZUS produced "modestly conservative" estimates of damage and loss (Kircher et al. 2006b). The ~$40B-$300B results from normalization imply the possibility of larger or smaller losses than suggested by HAZUS. Munich Re (2006) notes that other estimates of economic losses of a repeat of the 1906 event run as high as $400 billion, a figure well in line with the range of normalizations produced in this analysis.

In addition to estimating a range of economic losses from a 1906 repeat, the Kircher et al. (2006a) study also estimates expected fatalities at 800 – 3,400, similar to the adjusted fatalities derived in this paper using a 2% mitigation factor (3,250) and far lower than the fatalities derived from simple population scaling with no mitigation (24,000). The difference in expected fatalities from those resulting from a simple scaling implies strong success in reducing fatality risk exposure, whether through government-directed mitigation programs or natural evolution of building technology.

This analysis should be considered only a first-step toward establishing a rigorous approach to normalized earthquake losses in the United States. Most important for improved estimates is the establishment of a high quality time series of earthquake losses. However, considering the widely varying loss estimates from major recent earthquakes such as the 1994 Northridge and 2001 Nisqually events, it is difficult to have confidence in the accuracy of reported disaster losses through time. Compilation of loss estimates for this analysis bolster the observations of NRC (1999) and Meade and Abbott (2003) that a lack of standardization of disaster loss data collection hampers the ability to assess disaster losses, as well as the effectiveness of disaster mitigation policies. Detailed, systematic research into past event losses and a reconciliation of methods for future loss data collection with past loss estimates, combined with the methods of this paper, would add value to the decision-making process on hazards research and development.

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FIGURE CAPTIONS

Figure 1. Distribution of events in the NGDC-s and NGDC-i databases in 3-year bins starting 1900-1902.

Figure 2. (Pink diamonds) changes in time since 1900 in inflation (Implicit Price Deflator), (red stars) wealth (Fixed Reproducible Tangible Wealth), and (green circles) U.S. and (blue stars) San Francisco Combined Statistical Area population. The population changes are shown as examples; in the normalized record each event has a unique population adjustment.

Figures 3a-d. Time series of annual earthquake losses for (a) inflation-adjusted case; (b) normalized case with no mitigation factor; (c) normalized with 1% annual mitigation factor; (d) normalized with 2% annual mitigation factor. On each plot a 8-year centered running mean is plotted (red line). As there is a five order of magnitude range in the data, not all events appear and some exceed the upper limit on the dependent axis (these events are labeled). Note that each plot is drawn with different y-axis increments and limits.

Figures 4a-c. Distribution of normalized damages for the (a) no mitigation; (b) 1% mitigation; (c) 2% mitigation cases. Independent axis is log-scale and binning is set by half orders of magnitude.

Figure 5. Log-log cumulative distribution function (CDF) of normalized losses for the no mitigation (blue circles), 1% mitigation (black x's), and 2% mitigation (red crosses) cases.

Figure 6. Total losses by decade for the inflation-adjusted (dark blue), normalized with no mitigation (turquoise), normalized with 1% mitigation (yellow) and 2% mitigation (red) cases.

TABLE CAPTIONS

Table 1. List of ten most-damaging earthquakes when adjusting only for inflation. Damage estimates in event-year dollars ("Estimated Property Damage" column) use the consensus list, described in text. Inflation adjustment uses the Implicit Price Deflator to adjust to 2005 dollars. All values are expressed in millions of dollars.

Table 2. List of all earthquake events with normalized losses of $500 million and greater in 2005 dollars. Normalization adjustment accounts for inflation, wealth and population as described in text. Adjustments for 1% and 2% mitigation appear in the rightmost columns. Inflation adjustment also given (5th column) to contrast results of this common adjustment with the normalized adjustment. All values are given in millions of dollars.

Table 3. Calculation of annual losses is complicated by sparseness of events through time and data that is skewed to recent decades. Average annual losses are calculated from the ACC list with no mitigation factor applied, a 1% mitigation and 2% mitigation factor. Numbers in parentheses are annual losses calculated without the 1906 San Francisco and 1994 Northridge events. Second column indicates number of events with recorded damages for decades starting with first year in first column and ending in last year of that decade. For example, in the decade 1940-1949 (fifth row from top), there were eight events with recorded damages.

Table 4. Individual datasets are used to estimate annualized losses with various averaging periods and mitigation levels. Two lists are derived from the NGDC-Significant record: one using only the lowest estimates when multiple loss estimates exist

for the same event, the other using only the highest estimates. SHELDUS data extends back only to 1960.

Table 5. Normalized losses by decade, showing number of events exceeding various damage thresholds. Average damage per year and total damage is shown for each decade, and a ratio given of damage in each decade to total damage.

Table 6. Highlight of the 1906 San Francisco earthquake. From left, columns use population correction factors from San Francisco County, the San Francisco Bay Area Combined Statistical Area, and the 18 counties that sustained damage in the quake (Lawson 1908). See text and Appendix A for discussion of damage estimates used. The inflation and wealth multipliers for the 1906-to-2005 correction are 17.06 and 3.96 respectively. In each column normalized values are stacked vertically using no mitigation correction factor, a 1% factor and a 2% factor.

Table 7. Adjusted earthquake fatalities (table sorted by event date). Third column ("event deaths") represents deaths reported for each event. Fourth column ("% of total population") is event fatalities as a percentage of event-year population. Fifth column ("Proportional deaths") is fatalities reported multiplied by population difference between event year and 2005. Two rightmost columns are same as fifth column with 1% and 2% mitigation factor applied.

Table 1. Ten most damaging earthquakes, inflation adjustment only (2005 dollars)

Common event name	Date	Location	Estimated property damage (millions of event-year dollars)[1]	Inflation-adjusted damage (millions of 2005 dollars)
Northridge	January 17, 1994	Los Angeles metro area, California	$38,700	$46,983
San Francisco	April 18, 1906	San Francisco Bay Area, California	$524	$8,942
Loma Prieta	October 18, 1989	San Francisco Bay Area, California	$5,833	$8,206
Good Friday	March 28, 1964	Southern Alaska, Anchorage area	$780	$2,736
Nisqually	February 28, 2001	Seattle/Olympia areas, Washington State	$2,000	$2,190
San Fernando Valley	February 9, 1971	Los Angeles metro area, California	$500	$2,092
Whittier Narrows	October 1, 1987	Los Angeles metro area, California	$350	$542
Long Beach	March 11, 1933	Los Angeles metro area, California	$40	$496
Olympia	April 13, 1949	Olympia/Puget Sound, Washington	$53	$360
Bakersfield	July 21, 1952	Bakersfield / Kern County, California	$50	$342

Table 2. Earthquakes >$500M, millions of normalized 2005 dollars

Common event Name	Date	Location	Est. losses (event year dollars)	Inflation-adjusted losses	Normalized damages (no mitigation)	Normalized damages (1% mitigation)	Normalized damages (2% mitigation)
San Francisco[1]	April 18, 1906	San Francisco Bay Area, California	$524	$8,942	$283,735	$104,905	$38,397
Northridge	January 17, 1994	Los Angeles metro area, California	$47,350	$58,815	$87,381	$78,235	$69,968
Good Friday	March 28, 1964	Southern Alaska, Anchorage area	$540	$2,736	$16,932	$11,213	$7,395
Long Beach	March 11, 1933	Los Angeles metro area, California	$39	$496	$15,599	$7,565	$3,642
Loma Prieta	October 18, 1989	San Francisco Bay Area, California	$5,750	$8,206	$12,315	$10,485	$8,913
San Fernando Valley	February 9, 1971	Los Angeles metro area, California	$540	$2,092	$7,155	$5,084	$3,600
Olympia	April 13, 1949	Olympia, Washington	$53	$360	$5,975	$3,404	$1,928
Mona Passage	October 11, 1918	Puerto Rico	$29	$262	$4,660	$1,944	$804
Kern County	July 21, 1952	Kern County, California	$55	$342	$3,102	$1,821	$1,063
Santa Barbara	June 29, 1925	Santa Barbara, California	$8	$74	$3,066	$1,372	$609
Nisqually	February 28, 2001	Seattle/Olympia areas, Washington State	$2,000	$2,190	$2,476	$2,378	$2,284
Bakersfield	August 22, 1952	Kern County, California	$20	$124	$1,128	$662	$387
Helena	October 31, 1935	Helena, Montana	$6	$70	$1,035	$512	$252
Whittier Narrows	October 1, 1987	Los Angeles metro area, California	$354	$542	$954	$796	$663
Imperial Valley	May 19, 1940	Southern California / Mexico	$6	$69	$753	$392	$202
Terminal Island	November 18, 1949	Los Angeles metro area, California	$9	$62	$728	$415	$235
Hegben Lake	August 18, 1959	Hegben Lake / southeastern Montana	$4	$41	$604	$299	$147

[1] Normalization uses SF CSA for population correction (8.02, see text for explanation)

Table 3: Annual losses based on ACC list with and without 1906/1994 events					
	Averaging Period	**Decade count**	**Average annual losses (no mitigation)**	**Average annual losses (1% mitigation)**	**Average annual losses (2% mitigation)**
ACC record (no 1906/1994) (millions of 2005 dollars)	1900-2005	2	4270 (769)	2215 (487)	1347 (325)
	1910-2005	3	1759 (849)	1353 (538)	1088 (359)
	1920-2005	4	1900 (884)	1484 (574)	1203 (390)
	1930-2005	5	2106 (957)	1660 (630)	1353 (432)
	1940-2005	7	2164 (840)	1784 (598)	1497 (436)
	1950-2005	10	2411 (850)	2024 (627)	1720 (470)
	1960-2005	8	2822 (922)	2397 (696)	2054 (533)
	1970-2005	9	3113 (685)	2736 (563)	2409 (466)
	1980-2005	18	4018 (657)	3580 (571)	3188 (497)
	1990-2005	8	5677 (215)	5094 (205)	4568 (194)
	2000-2005	6	487 (487)	469 (469)	452 (452)

Table 4. Estimates for normalized annual earthquake losses by dataset and averaging period (millions of 2005 dollars)

	Averaging period	No mitigation	1% mitigation	2% mitigation
NGDC-low NGDC-high SHELDUS EMDAT (millions of 2005 dollars)	1900-2005	1,747 4,438 —- 3,921	1,284 2,313 —- 1,843	1,002 1,403 —- 979
	1960-2005	2,933 2,956 1,796 1,877	2,463 2,486 1,466 1,474	2,087 2,110 1,212 1,177
	1970-2005	3,268 3,278 1,805 1,482	2,834 2,846 1,549 1,278	2,464 2,477 1,334 1,107
	1980-2005	3,986 4,240 2,285 1,791	3,528 3,728 1,992 1,587	3,121 3,279 1,739 1,407
	1990-2005	4,849 4,710 2,363 2,136	4,354 4,239 2,125 1,924	3,906 3,812 1,911 1,732
	2000-2005	567 903 434 540	546 869 417 519	525 835 400 500

Table 5: Normalized (no mitigation) damage by decade									
Year range	**Total count**	**count<$100M**	**count>$100M**	**count>$500M**	**count >$1B**	**count >$10B**	**Avg. damage per yr ($M)**	**Total damage ($M)**	**% of total damage**
1900-1909	2	1	1	1	1	1	$28,376	$283,761	62.7%
1910-1919	3	0	3	1	1	0	$543	$5,433	1.2%
1920-1929	4	2	2	1	1	0	$332	$3,324	0.7%
1930-1939	5	2	3	3	2	1	$1,727	$17,274	3.8%
1940-1949	7	3	4	3	1	0	$783	$7,828	1.7%
1950-1959	10	5	5	2	2	0	$518	$5,178	1.1%
1960-1969	8	4	4	1	1	1	$1,776	$17,760	3.9%
1970-1979	9	7	2	1	1	0	$758	$7,582	1.7%
1980-1989	18	15	3	2	1	1	$1,364	$13,642	3.0%
1990-1999	8	5	3	1	1	1	$8,790	$87,905	19.4%
2000-2005	6	4	2	1	1	0	$487	$2,924	0.6%
Total	80	48	32	17	13	5	$45,456	$452,610	100%

Table 6. Estimates for normalization of April 18, 1906 San Francisco earthquake by population correction factor and original damage estimate (millions of 2005 dollars).

		Normalized damage (millions of 2005 dollars)		
		San Francisco County	**SFBA CSA**	**All 18 counties**
	Population multiplier	1.91	8.02	9.28
no mitigation (1% mitigation) (2% mitigation)	Loss estimate (mil 1906 $)			
	$1,000	$128,904 ($47,660) ($17,444)	$541,480 ($200,201) ($73,276)	$626,218 ($231,531) ($84,744)
	$524	$67,546 ($24,974) ($9,141)	$283,735 ($104,905) ($38,397)	**$328,138 ($121,322) ($44,406)**
	$400	$51,562 ($19,064) ($6,978)	$216,592 ($80,080) ($29,311)	$250,487 ($92,613) ($33,897)
	$350	$45,116 ($16,681) ($6,105)	$189,518 ($70,070) ($25,647)	$219,176 ($81,036) ($29,660)

Table 7. Earthquake fatalities adjusted for population increase

event date	location	Event deaths	% of total population	Proportional deaths (no mitigation)	1% mitigation	2% mitigation
4/18/1906	San Francisco, California	3,000	0.4112%	24,062	8,896	3,256
6/22/1915	El Centro, California	6	0.0210%	33	13	5
10/11/1918	Mona Passage, Puerto Rico	116	0.0082%	331	138	57
6/29/1925	Santa Barbara, California	13	0.0245%	98	44	19
3/11/1933	Long Beach, California	100 - 116	0.0035%	636 - 737	308 - 357	149 - 172
10/19/1935	Helena, Montana	2 - 4	0.0099%	6 - 12	3 - 6	1
10/31/1935	Helena, Montana	2	0.0099%	6	3	1
5/19/1940	El Centro/Imperial Valley, California	8 - 9	0.0151%	21 - 23	11 - 12	6
4/13/1949	Olympia, Washington	8	0.0181%	41	24	13
7/21/1952	Kern county/Bakersfield, California	12 - 14	0.0054%	38 - 44	22 - 26	13 - 15
8/22/1952	Kern county/Bakersfield, California	2	0.0008%	6	4	2
12/21/1954	Eureka-Arcata, California	1	0.0012%	2	1	1
10/24/1955	Concord-Walnut Creek, California	1	0.0003%	3	2	1
3/22/1957	Daly City, California	1	0.0003%	2	1	1
8/18/1959	Hebgen Lake, Montana	28	0.1092%	85	54	34
3/28/1964	Anchorage/Fairbanks, Alaska	131	0.0892%	332	220	145
4/29/1965	Seattle, Washington	7	0.0005%	13	9	6
10/2/1969	Santa Rosa, California	1	0.0005%	2	2	1
2/9/1971	San Fernando, California	58 - 65	0.0006%	102 - 114	72 - 81	51 - 57
11/29/1975	Kalapana (Kilauea), Hawaii	2	0.0026%	4	3	2
1/24/1980	Livermore, California	1	0.0000%	1	1	1
11/8/1980	Northwestern California	5	0.0046%	6	5	4
10/28/1983	Borah Peak, Idaho	2 - 3	0.0831%	2 - 3	2	1 - 2
10/1/1987	Whittier (Los Angeles), California	8	0.0001%	10	9	7
10/18/1989	Loma Prieta (SF Bay Area), California	62	0.0012%	71	60	51
6/28/1991	Pasadena area, California	2	0.0000%	2	2	2
6/28/1992	Landers, California	1 - 3	0.0002%	1 - 4	1 - 3	1 - 3
9/21/1993	Klamath Falls, Oregon	2	0.0034%	2	2	2
1/17/1994	Northridge, California	60	0.0004%	69	62	56
2/28/2001	Seattle area, Washington	1	0.0000%	1	1	1
12/22/2003	San Robles, California	2	0.0008%	2	2	2

Figure 1: Histogram of data availability

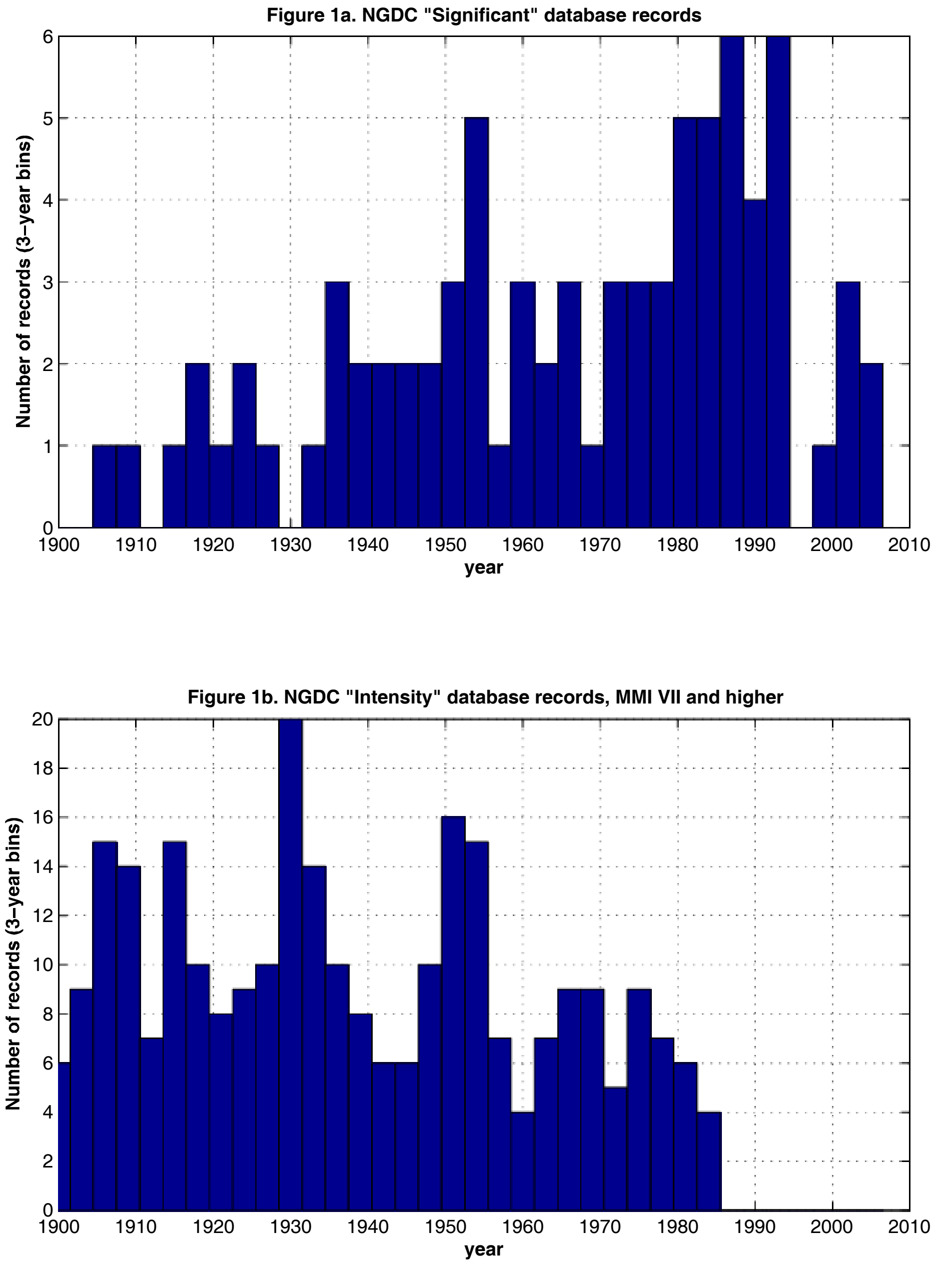


FIG-1

Figure 2: wealth/pop/IPD trends + SF CSA population trend

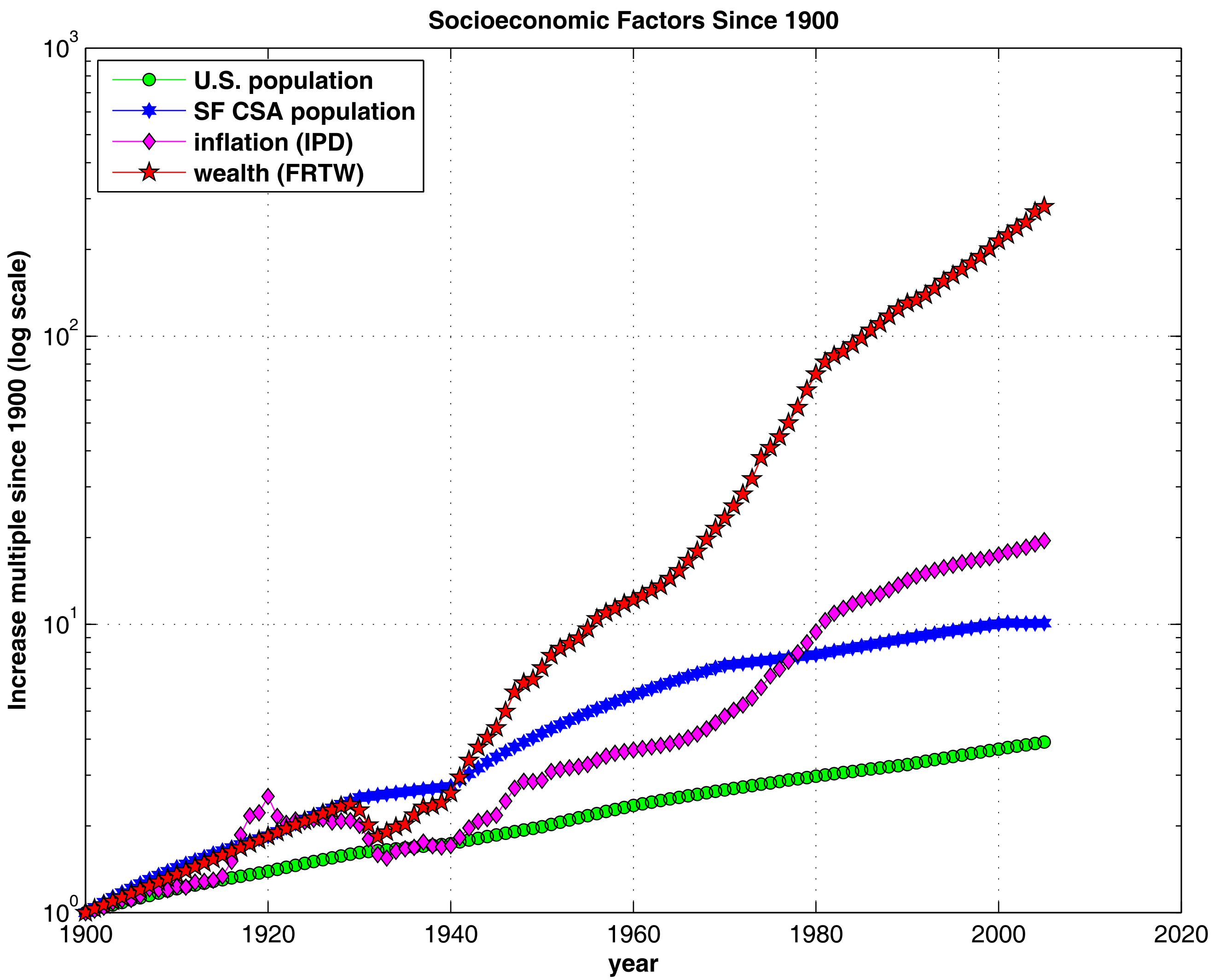


FIG-2

Figure 3a: Annual damages for inflation-adjusted series

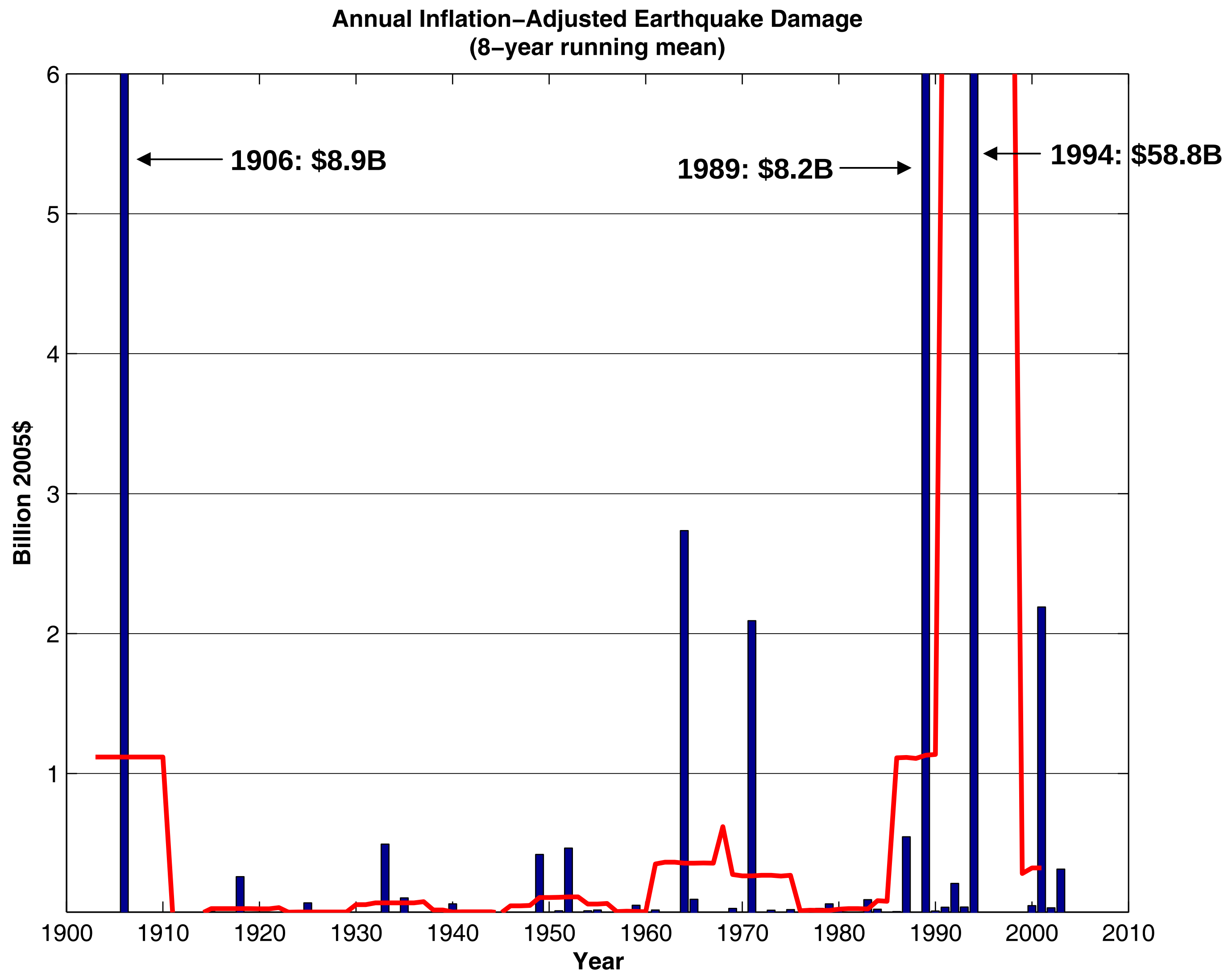


FIG-3

Figure 3b: Annual damages for normalized case with no mitigation

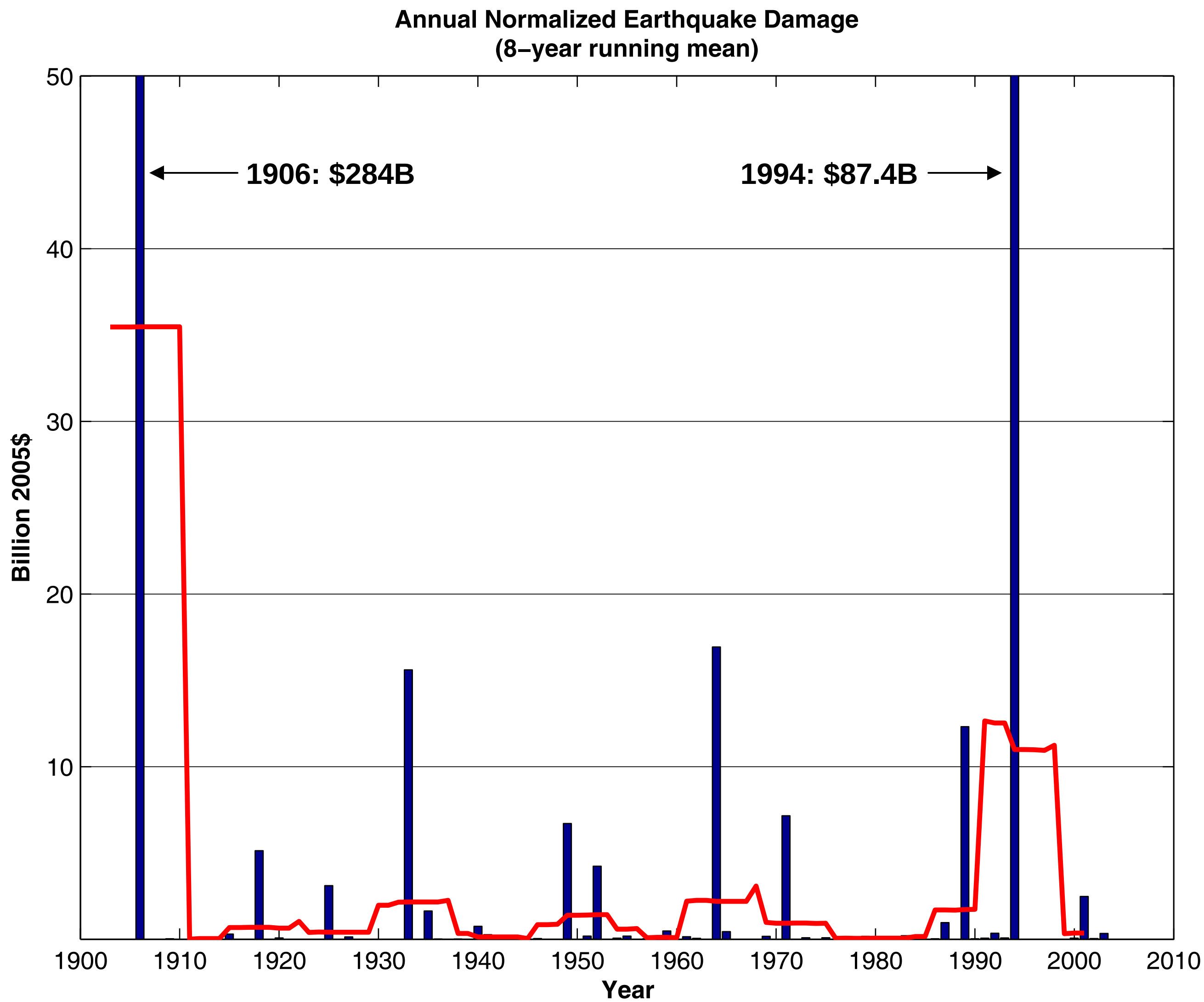


FIG-4

Figure 3c: Annual damages for normalized 1% mitigation case

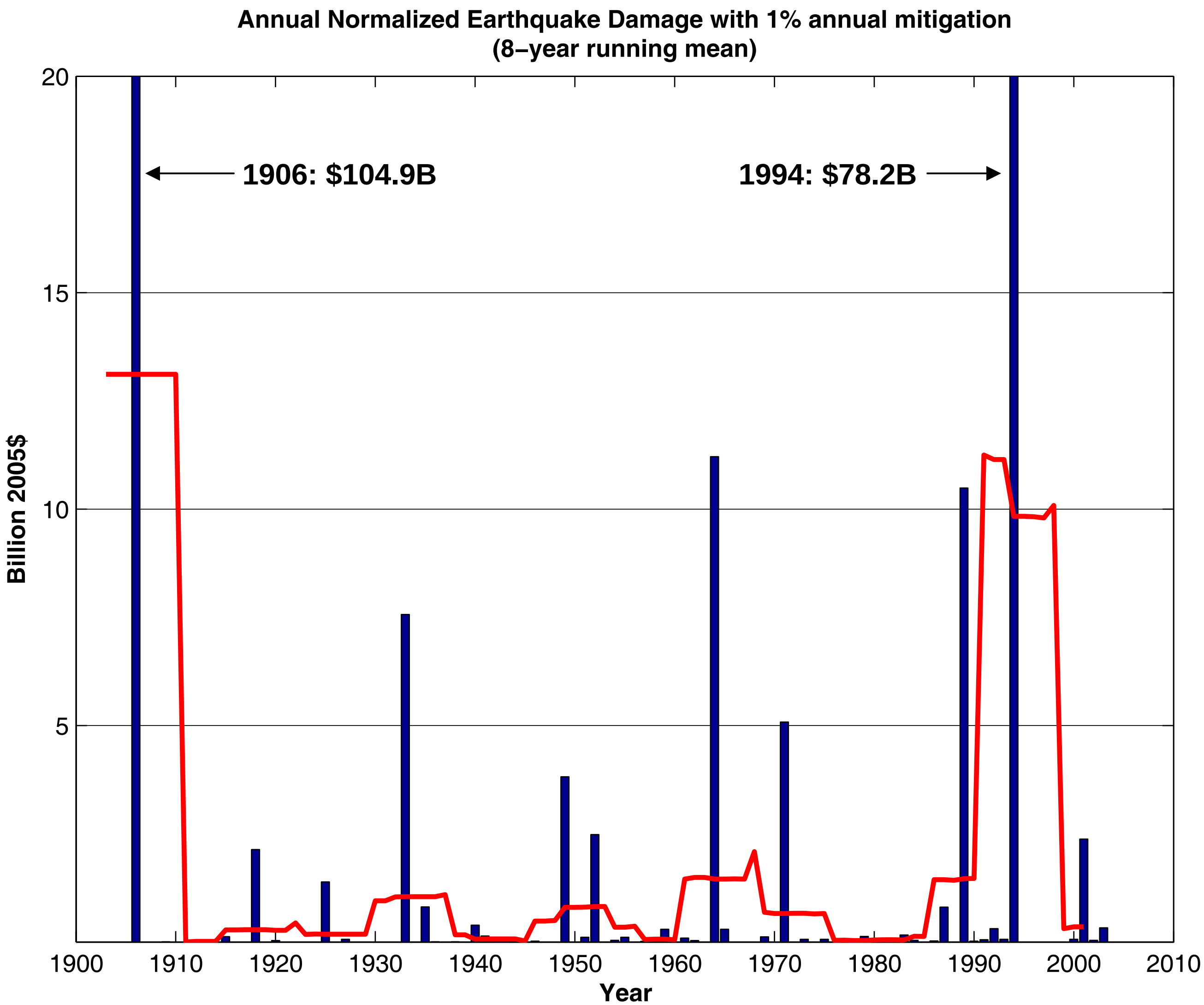


FIG-5

Figure 3d: Annual damages for normalized 2% mitigation case

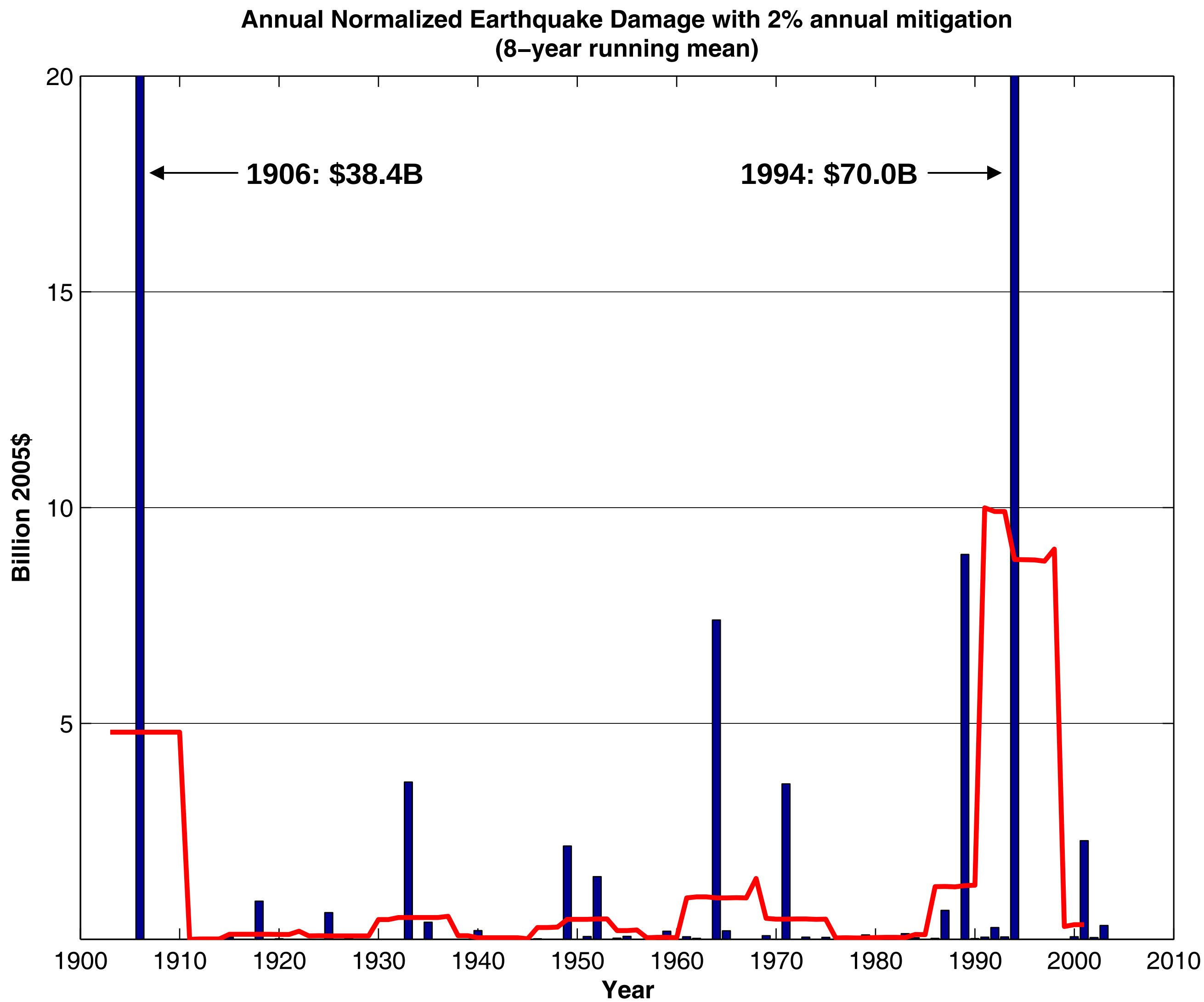
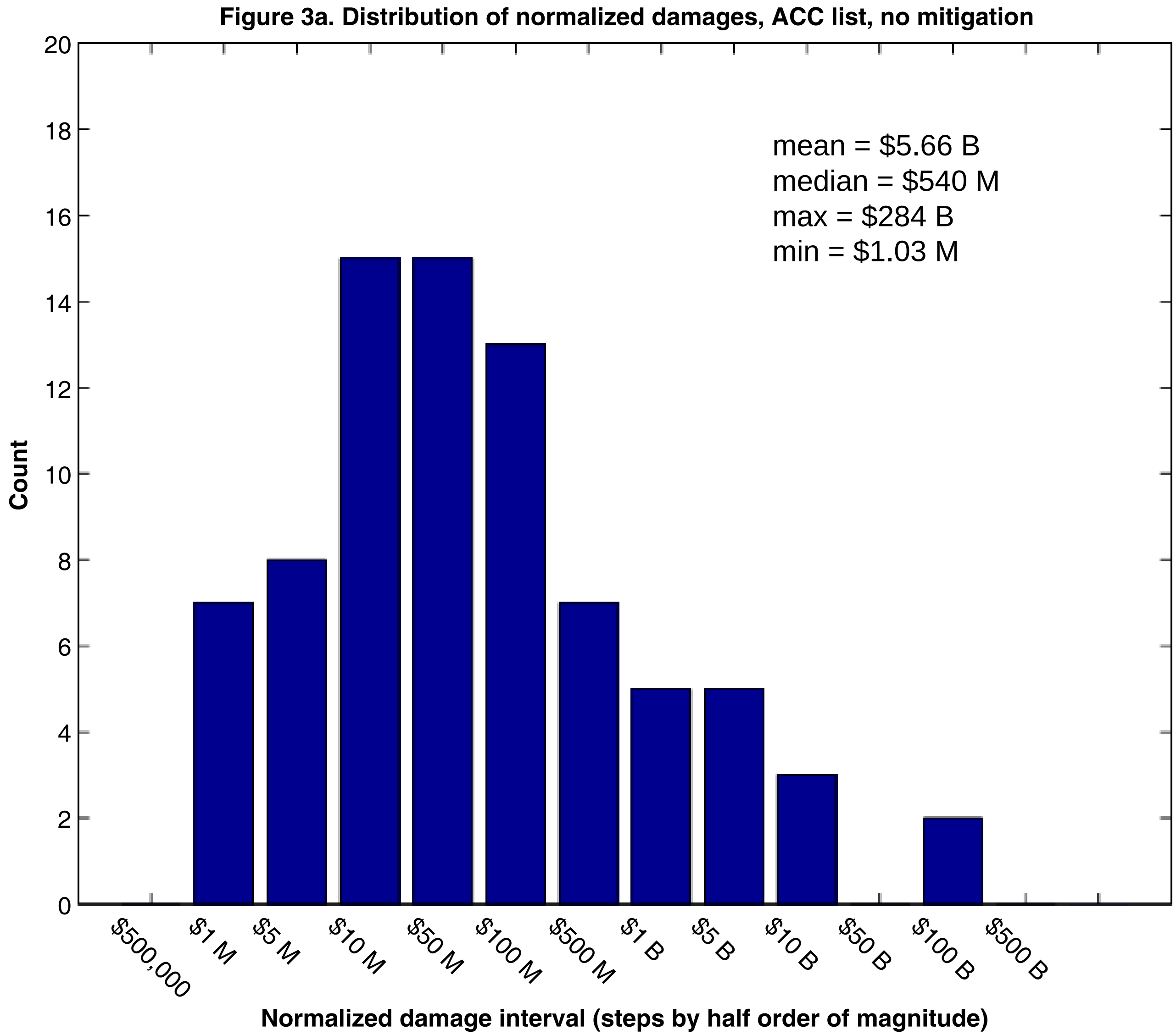


FIG-6

Figure 4a: histogram of ACC with no mitigation



($2005 USD)

FIG-7

Figure 4b: histogram of ACC with 1% mitigation

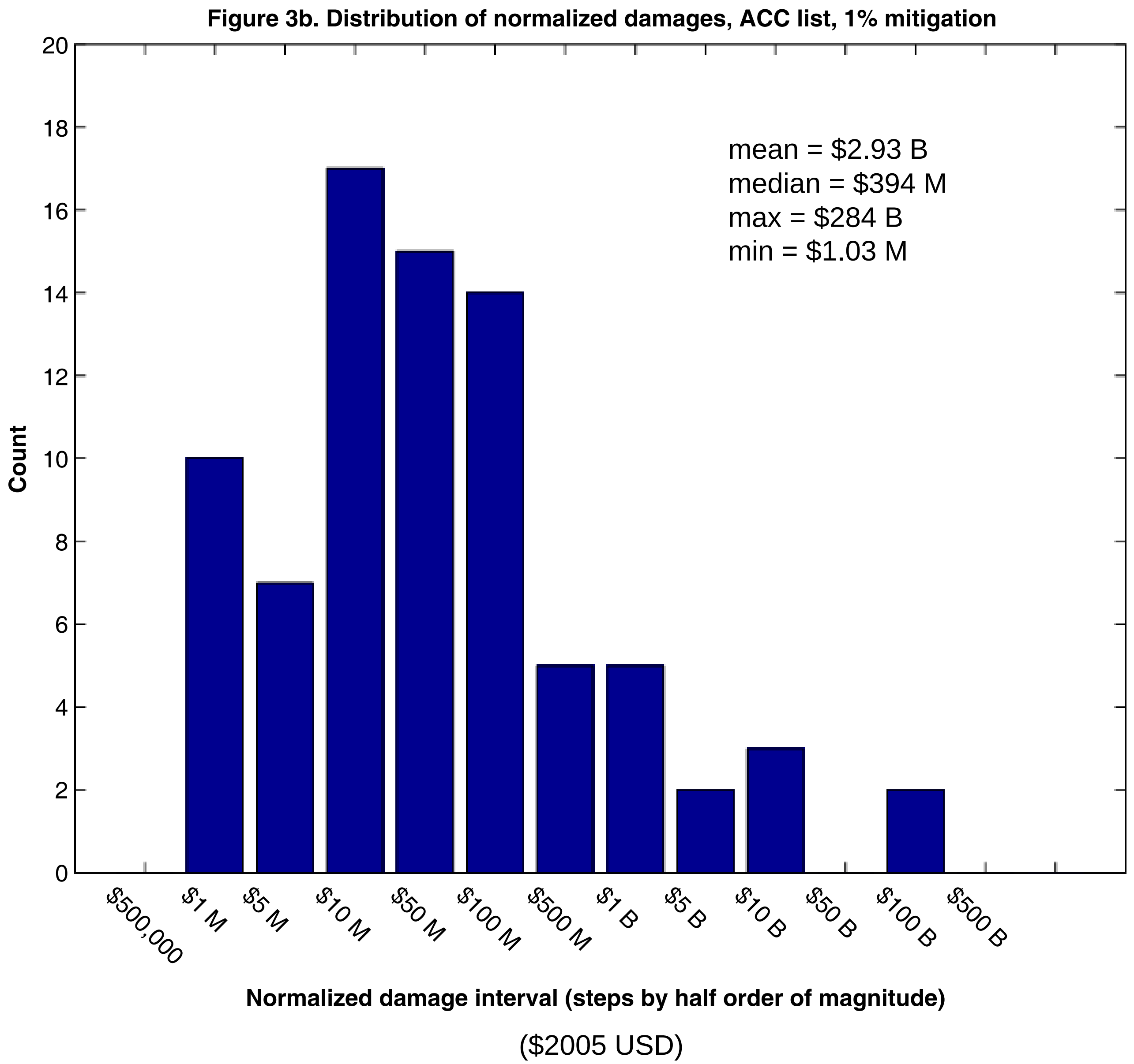


FIG-8

Figure 4c: histogram of ACC with 2% mitigation

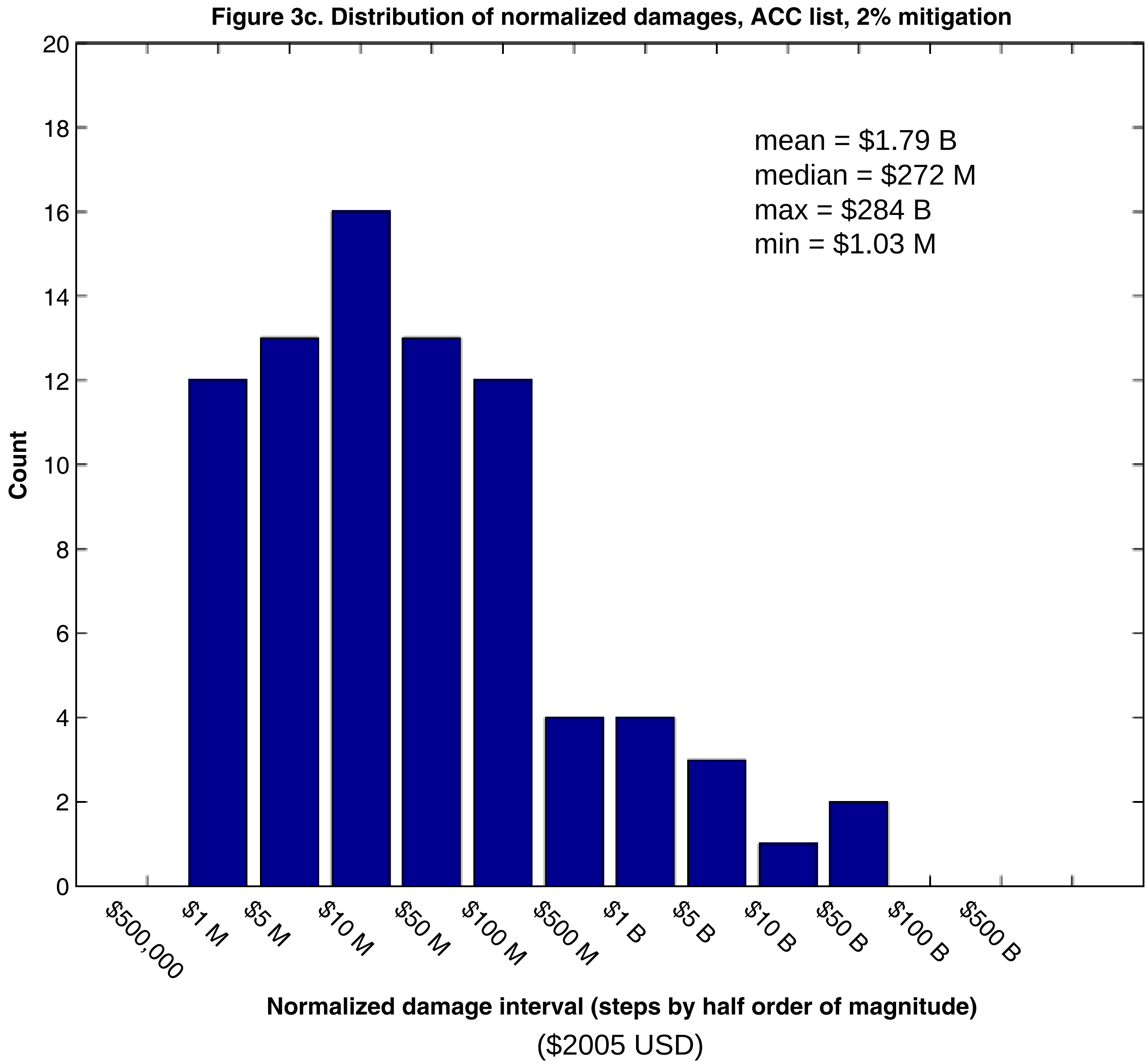


FIG-9

Figure 5: log-log CDF of normalized cases

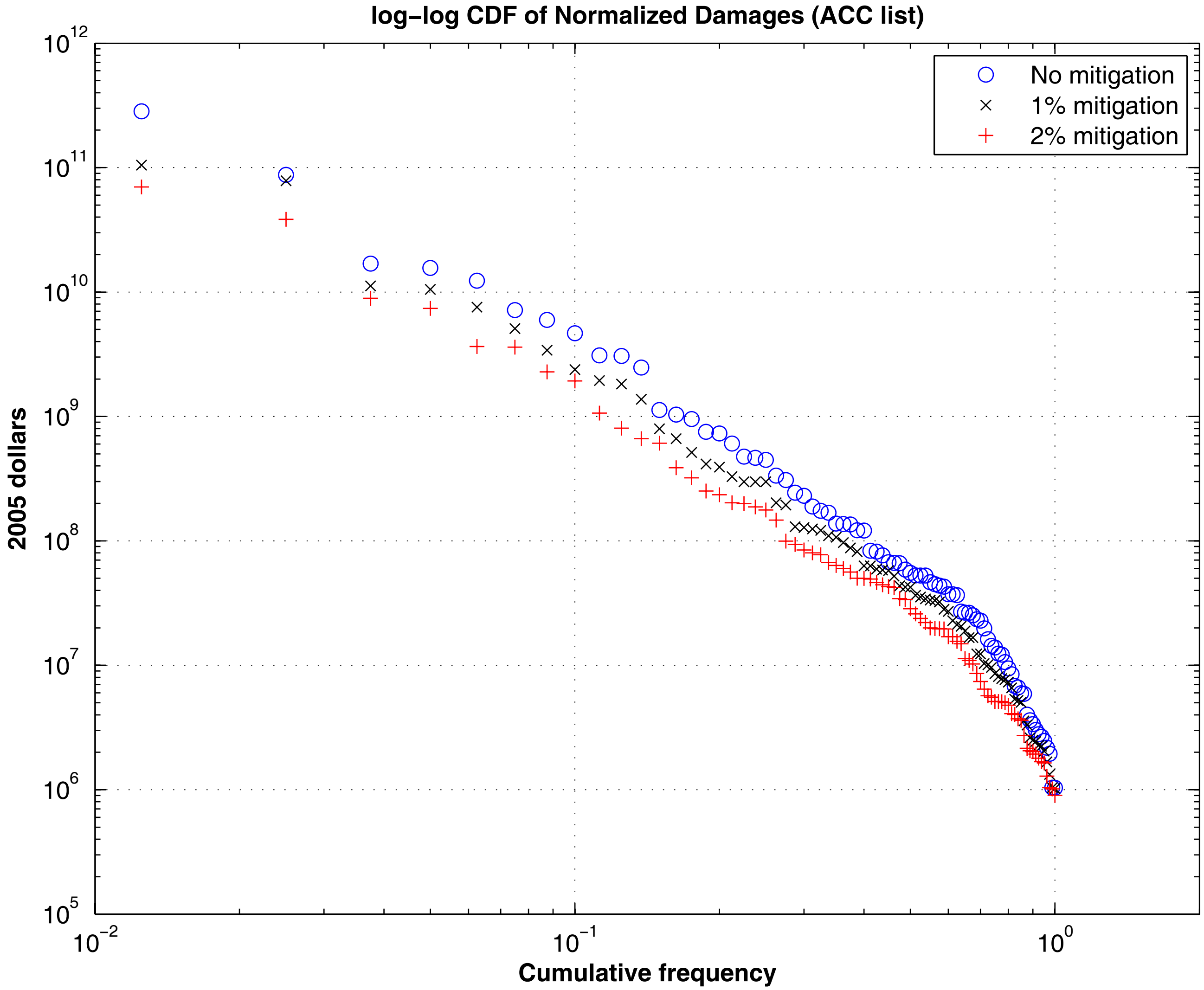


FIG-10

Figure 6: Average annual losses by decade with and without mitigation

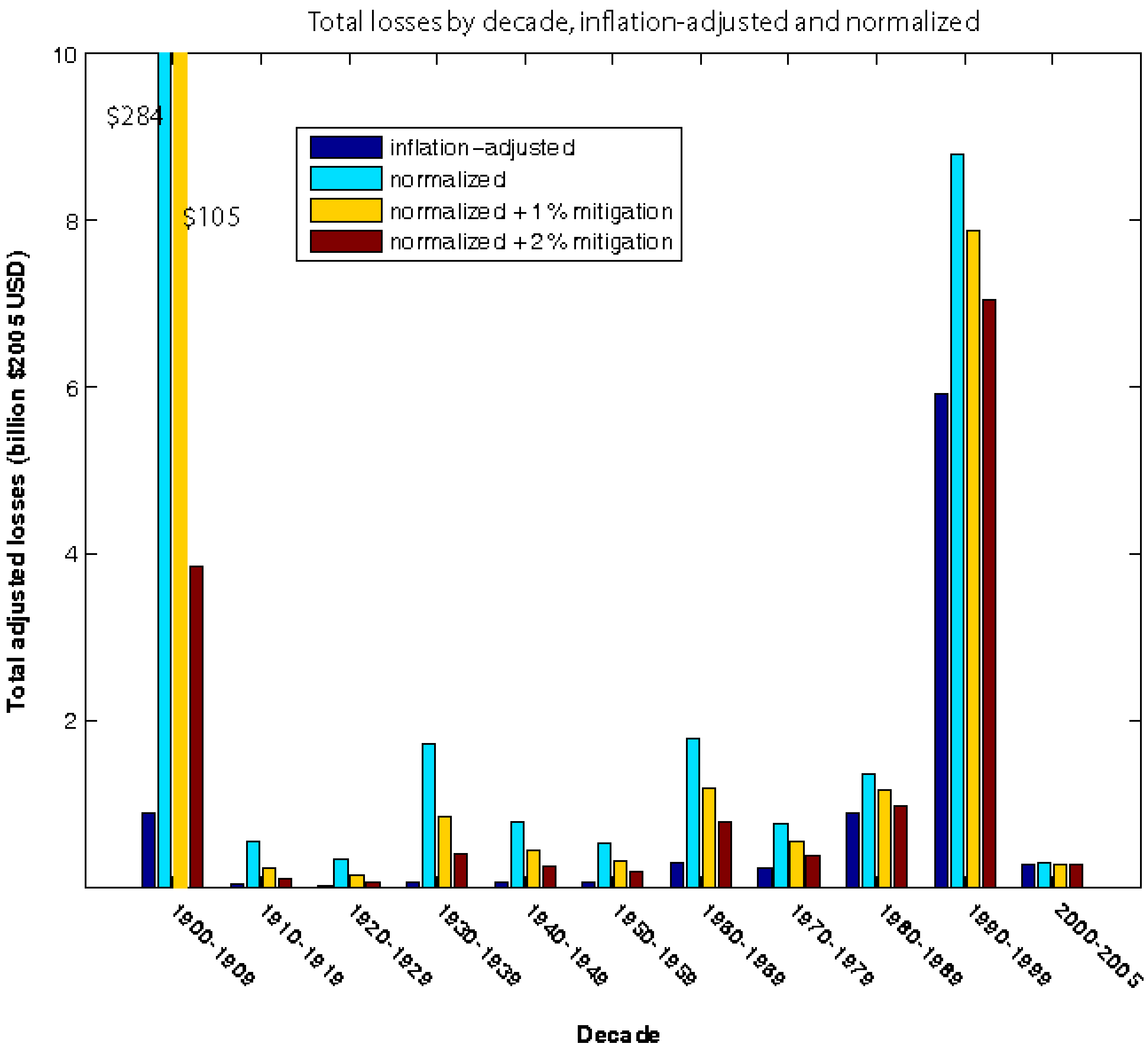


FIG-11

APPENDIX A: LOSS ESTIMATES

In many of the 80 earthquake events cited in this paper, multiple sources for an event give conflicting damage estimates. The following is a brief discussion of those events with a discussion of the number used in this paper for the "middle" or "ACC" list. All available estimates are listed in Appendix B.

As a general rule, the most conservative estimate was used by Pielke and Landsea (1998) for hurricanes. However, in the case of earthquake losses, sometimes the most conservative estimate is clearly an outlier when all sources are taken into consideration. In all cases where discrepancies exist, an attempt is first made to find a consensus number. If a consensus does not clearly emerge, a judgment is made on whether one number or range of numbers is more credible than another. Finally, if no consensus or credible numbers emerge, an average of the high and low numbers is used.

- **San Francisco (CA), April 18, 1906.** Sources range between $24M (Coffman et al. 1982) and $80M to $400M (Algermissen et al. 1972; Dunbar et al. 2006) to $1B (Steinbrugge 1982), but the majority of sources list this event as costing $524M, which is the figure used here. It should be noted that $524M includes the fire and dynamiting of buildings for firefighting, but only counts building loss in the city of San Francisco (Munich Re 2006). Coffman et al. (1982) estimated that actual shaking produced only $24M in damages, but it is impossible to differentiate between buildings that were only destroyed because of fire and would have otherwise been in acceptable condition in the absence of the fire. Munich Re (2006) states that the $524M estimate is conservative.

- **Santa Barbara (CA), June 29, 1925.** NGDC-s gives estimates of $8M and $6M but only $8M is supported in the literature cited. EM-DAT uses the $8M estimate.

- **Helena (MT), October 1935.** There were over 1000 felt earthquakes in a swarm between October 12, 1935 and February 1936, but the October 19 and 31 events caused the most damage. Loss estimates vary widely, from a minimum of $3M Stover and Coffman (1993) (hereafter referred to as "SC1527" using the USGS file report number) to a maximum of $19M (EM-DAT) for the October 19 event. There is some confusion in the literature as to whether losses cited were for the aggregate of the 19-Oct and 31-Oct events, or whether losses for each were cited separately. Stover and Coffman (1993) cite $3M for the 19-Oct event but newspaper sources indicate that the number was probably higher. The $19M figure is plausible given the damage descriptions but is not supported in a scan of newspaper articles. Newspaper articles on the events were collected by the University of Utah Seismograph Stations (http://www.seis.utah.edu/lqthreat/nehrp_htm/1935hele/1935he1.shtml). For the ACC list, the $3.5M estimate in NGDC-s is used for the 19-Oct event and $6M is used for the 31-Oct event. It is possible that $6M estimate for the 31-Oct event is an estimate of total damage from both events, but it is the only number available. The $3.5M number is probably conservative while the $6M figure is likely an overestimate of single-event damages from the 31-Oct event.

- **El Centro (CA), May 19, 1940.** Two estimates are cited in various sources: $6M and $33M. The $6M figure appears to refer to damage in Imperial Valley, El Centro and Holtsville while the $33M figure encompasses damage that also occurred around Mexicali in Mexico. Some sources cite damage to irrigation systems that led to crop failures but no additional loss estimates are given. The $6M figure is used for the ACC list and is probably conservative.

- **Massena (NY), September 5, 1944.** The database sources used cite estimate of $1.5M and $2.0M but at least one source cites damages of $18M. The event occurred on the New York – Ontario border and also affected Cornwall, Ontario. It is not clear if damages have been differentiated between Massena and Cornwall in any of the estimates. (Hodgson 1945) estimates Massena damage at $1M and Cornwall damage at $1M while noting that damage seemed more severe in Cornwall. An average of the $1.5M and $2.0M estimates are used for the ACC list.

- **Olympia/Puget Sound (WA), April 13, 1949.** The range of estimates is $25M to $80M and an average of those is used for the ACC list. List many other events, the difference in estimates is between SC1527 on the low side and EM-DAT on the high side. (Noson et al. 1988) give a figure of $150M in 1984 dollars, which adjusts to approximately $36M in 1949 dollars. One USGS page claims the event caused over $250M in damages.

- **Bakersfield/Kern County (CA), July 21, 1952.** Damage estimates range from $50M to $60M and an average of the two figures is used here. This is one of the few events for which EM-DAT is on the low side of the estimates.

- **Bakersfield/Kern County (CA), August 22, 1952.** This event was the second largest of the July-August swarm. Stover and Coffman (1993) list $10M in damages while EM-DAT gives a $30M estimate. The average of the high and low estimates ($20M) is used here.

- **Hebgen Lake (MT), August 18, 1959.** The largest earthquake in Montana history. All sources except for EM-DAT estimate losses at $11M and no accounts can be founding supporting EM-DAT's estimate of $26M, so $11M is used.

- **Cache Valley (UT), August 30, 1962.** SC1527 cite $1M in losses while NGDC-s cites $2M based on UNESCO source. An average of the two is used.

- **Good Friday (AK), March 28, 1964.** EM-DAT gives an estimate of $1.02B while NGDC-s gives an estimate of $540M. The lower estimate is much better supported, so it used here.

- **Seattle-Tacoma (WA), April 29, 1965.** Two values are given in the databases: $12.5M (SC1527) and $28M (EM-DAT). (Noson et al. 1988) give damages of $50M in 1984 dollars, adjusting to $16.7M in 1965 dollars. An average of the $12.5M and $28M figures is used.

- **Santa Rosa/Sonoma County (CA), October 2, 1969.** Estimates range from $7M to $10M. An average of three estimates is used ($8.45M).

- **San Fernando (CA), February 9, 1971.** All damage estimates for this event are within a few percent, from $500M to $570M. The CAGS estimate is $505M, EM-DAT is $535M and NGDC-s lists sources between $500M to $553M. The 1999 Economic Report of the President (Office of the President 1999) gives a value of $1.7B in 1992 dollars, which adjusts to $570M in 1971 dollars. An average of all estimates ($539.5 million) is used.

- **Kilauea, Hawaii (HI), April 26, 1973.** Estimates differ slightly ($5.6M vs. $5.75M); an average is used.

- **Oroville Reservoir (CA), August 1, 1975.** SC1527 cite $2.5M in damages but other sources cite $6M. No other information could be found on the event. An average of the two values is used.

- **Goleta (CA), August 13, 1978.** Estimates range from a low of $1.5M to a high of $15M. (Miller 1979) cites an estimate of "more than $7 million." The City of Santa Barbara General

Plan, dated August 1979, cites total damages of \$11.62M. Other sources give ranges from \$12M - \$15M. As the University of California – Santa Barbara campus alone reported damages over \$3M, the \$1.5M estimate is clearly incorrect. The \$15M estimate seems most plausible considering all sources, so it is used.

- **Imperial Valley (CA), October 15, 1979.** Two estimates differ by an order of magnitude (\$3M vs. \$30M) but the higher number appears to be better supported and is used by the California Geological Survey.

- **Livermore (CA), January 24, 1980.** Estimates of \$3.5M and \$11.5M are available but the higher number appears better supported. The lower number is improbable as at least \$10M in damage was reported at the Lawrence Livermore National Laboratory.

- **Borah Peak (ID), October 28, 1983.** Estimates range from \$12.5M to \$15M to \$25M. An average of the highest and lowest estimates (\$18.75M) is used.

- **Kapapala, Hawaii (HI), November 16, 1983.** Estimates vary slightly from \$6.25M to \$6.5M; the average is used.

- **Morgan Hill/Santa Clara (CA), April 24, 1984.** Estimates range from \$7.5M to \$30M with \$8M and \$10M also given. An average of the highest and lowest estimates is used (\$18.75M).

- **Palm Springs (CA), July 8, 1986.** Two estimates are available, \$4.5M and \$6M. An average of the two is used.

- **San Diego/Newport Beach (CA), July 13, 1986.** An average of two available estimates (\$720K and \$1M) is used.

- **Chalfant Valley/Bishop (CA), July 13, 1986.** Estimates of $1M (NGDC) and $2.7M (SC1527) are cited and an average is used.

- **Whittier/Los Angeles (CA), October 1, 1987.** Estimates range from $213M (EM-DAT) to $358M (NGDC based on SC1527). Two other records in NGDC cite $350M, so the lower estimate is discarded and an average of the two higher estimates is used ($354M).

- **Loma Prieta (CA), October 18, 1989.** NGDC-s lists an estimate of $12B, but lists its source as EM-DAT. However, EM-DAT currently estimates $5.6B in damages and SHELDUS estimates $5.9B. The California Geological Survey and Munich Re list estimates of $6B in damages, which may simply be a rounding of either of the $5.6B or $5.9B estimates. Table 2.2 of the 1999 Economic Report of the President cites an estimate of $14.4B (adjusted to 1989 dollars, Office of the President 1999, pg. 82). Since this seems to be an outlier from a group of similar reports, an average of the three lower estimates, or $5.8 billion, is used.

- **Ferndale/Petrolia/Humboldt County (CA), April 25, 1992.** Estimates range from $66M (NGDC and SHELDUS) to $75M (EM-DAT) to $100M (NGDC), although the highest estimate references EM-DAT as its source. CAGS estimates damages at $48.3M. A California State University – Humboldt (CSUH) web page cites $60M. Most news reports in the two months following the event give a number of $51M but some cite $61M. $66M is used as the best consensus figure.

- **Landers (CA), June 28, 1992.** Most sources cite a figure of $100M although one source gives an estimate of $92M. The former is used here as the consensus estimate.

- **Northridge (CA), January 17, 1994.** NGDC-s lists this event as costing $40B, using the figure published by the California Geological Survey (CAGS). EM-DAT estimates the event at

$16.5B and SHELDUS uses $20B following the official U.S. Geologic Survey report (United States Geological Survey 1996). Many news and internet sources cite numbers in the $12B-$15B range. Table 2.2 of the 1999 Economic Report of the President estimates total damages at $74.8B in 1992 dollars ($78.2B in 1994, Office of the President 1999, pg. 82). Finding no clearly definitive source, the average of the low (EM-DAT) and high (President's Economic Report) are used for an estimate of $47.35B.

- **Eureka/Arcata (CA), December 26, 1994.** A low of $2.1M (EM-DAT) and high of $5M (NGDC) are cited. CSUH cites $5M but there is a lack of strong support for either number, so an average is used.

- **Nisqually/Seattle metro area (WA), February 28, 2001.** Although NGDC-s lists damages of $2B and $4B, most damage estimates for this earthquake, including the work of Beyers and Chang (2002) and Meszaros and Fiegener (2002), settle on $2B as a conservative estimate.

- **Mentasta Lake/Denali Fault (AK), November 3, 2002.** Estimates range from $20M to $56M. News reports show a similar range so an average of the two is used.

- **Paso Robles/San Simeon (CA), December 22, 2003.** EM-DAT cites $200M while NGDC and most other sources cite $300M. Report number 04-02 of the California Seismic Safety Commission (dated May 5, 2004) reports, "FEMA, state and local officials estimate there were over $239 million in direct losses." McEntire and Cope (2004) note, "Total financial losses along with the cost of debris removal and emergency protective measures amounted to $226,557,500 for the entire county (County of San Luis Obispo 2004). These figures do not include state road systems and other damages or indirect losses/expenses." Since the $200M estimate is contradicted by strong evidence and the specific figures cited are minimum estimates, the $300M estimate is used.

APPENDIX B: ALL EARTHQUAKES WITH KNOWN RECORDED DAMAGES

See text for explanation of sources. "ACC" refers to the average, credible or consensus "middle" value chosen (see text and Appendix A). FIPS refers to the county code following the U.S. Census Bureau standard. When a CSA is used for the population factor (see text for further explanation) a FIPS code of 6901 denotes the SF CSA, 6902 denotes the LA CSA and 53999 denotes the Seattle CSA.

Event information								Adjustment multipliers					Damage adjustments				Fatalities		
Source	Date	Year	City / place name	State	FIPS	Deaths	Event-year property damage	Inflation multiplier (IPD)	Wealth multiplier (FRTW)	Population multiplier (DP)	1% mitigation	2% mitigation	Inflation-only adjustment	Normalized Damages	Normalized damages with 1% mitigation	Normalized damages with 2% mitigation	Proportional fatalities	Prop. fatalities 1% mitigation	Prop. fatalities 2% mitigation
ACC	4/18/1906	1906	San Francisco	CA	6901	3000	524,000,000	17.06	3.96	8.02	0.37	0.14	8,941,736,986	283,735,348,599	104,905,367,626	38,396,791,758	24062	8896	3256
EM-DAT	4/18/1906	1906	San Francisco	CA	6901	2000	524,000,000	17.06	3.96	8.02	0.37	0.14	8,941,736,986	283,735,348,599	104,905,367,626	38,396,791,758	16041	5931	2171
NGDC-s	4/18/1906	1906	San Francisco	CA	6901	700	24,000,000	17.06	3.96	8.02	0.37	0.14	409,545,205	12,995,512,150	4,804,825,998	1,758,631,684	5614	2076	760
NGDC-s	4/18/1906	1906	San Francisco	CA	6901	700	400,000,000	17.06	3.96	8.02	0.37	0.14	6,825,753,425	216,591,869,159	80,080,433,302	29,310,528,060	5614	2076	760
NGDC-s	4/18/1906	1906	San Francisco	CA	6901	2000	524,000,000	17.06	3.96	8.02	0.37	0.14	8,941,736,986	283,735,348,599	104,905,367,626	38,396,791,758	16041	5931	2171
SC1527	10/29/1909	1909	Scotia/Fortuna/Rohnerville	CA	6023		100,000	16.27	4.00	3.87	0.38	0.14	1,627,184	25,172,700	9,591,985	3,619,371			
EM-DAT	6/22/1915	1915	El Centro	CA	6025	6	1,000,000	14.60	4.06	5.46	0.40	0.16	14,598,047	323,859,643	131,076,352	52,565,844	33	13	5
NGDC-s	6/23/1915	1915	El Centro	CA	6025	6	900,000	14.60	4.06	5.46	0.40	0.16	13,138,242	291,473,678	117,968,717	47,309,260	33	13	5
NGDC-s	4/21/1918	1918	San Jacinto/Riverside County	CA	6065		200,000	9.02	6.25	41.26	0.42	0.17	1,803,910	465,069,251	193,990,095	80,202,187			
EM-DAT	10/11/1918	1918	Mona Passage	PR	72000	116	29,000,000	9.02	6.25	2.85	0.42	0.17	261,566,935	4,660,408,782	1,943,953,812	803,697,463	331	138	57
NGDC-s	10/11/1918	1918	Mona Passage	PR	72000	116	29,000,000	9.02	6.25	2.85	0.42	0.17	261,566,935	4,660,408,782	1,943,953,812	803,697,463	331	138	57
SC1527	6/22/1920	1920	Inglewood/Los Angeles	CA	6902		100,000	7.73	7.05	15.26	0.43	0.18	772,660	83,071,283	35,354,317	14,916,514			
SC1527	6/28/1925	1925	Clarkston Valley	MT	30031		150,000	9.28	5.47	4.89	0.45	0.20	1,392,132	37,264,822	16,676,873	7,402,614			
EM-DAT	6/29/1925	1925	Santa Barbara	CA	6083	13	8,000,000	9.28	5.47	7.54	0.45	0.20	74,247,020	3,065,652,695	1,371,950,746	608,988,383	98	44	19
NGDC-s	6/29/1925	1925	Santa Barbara	CA	6083	13	6,000,000	9.28	5.47	7.54	0.45	0.20	55,685,265	2,299,239,521	1,028,963,060	456,741,287	98	44	19
NGDC-s	6/29/1925	1925	Santa Barbara	CA	6083	13	8,000,000	9.28	5.47	7.54	0.45	0.20	74,247,020	3,065,652,695	1,371,950,746	608,988,383	98	44	19
NGDC-s	1/1/1927	1927	Imperial Valley	CA	6025		1,000,000	9.47	5.20	2.80	0.46	0.21	9,469,003	137,780,393	62,911,870	28,498,455			
ACC	3/11/1933	1933	Long Beach	CA	6902	116	39,250,000	12.63	4.95	6.36	0.48	0.23	495,767,829	15,598,670,404	7,565,220,534	3,642,210,411	737	358	172
EM-DAT	3/11/1933	1933	Long Beach	CA	6902	116	38,500,000	12.63	4.95	6.36	0.48	0.23	486,294,558	15,300,606,638	7,420,662,179	3,572,614,034	737	358	172
NGDC-s	3/11/1933	1933	Long Beach	CA	6902	100	40,000,000	12.63	4.95	6.36	0.48	0.23	505,241,100	15,896,734,169	7,709,778,888	3,711,806,789	636	308	148
NGDC-s	10/19/1935	1935	Helena	MT	30049	4	3,500,000	11.73	5.08	2.90	0.49	0.24	41,054,143	604,011,985	298,888,481	146,848,953	12	6	3
NGDC-s	10/19/1935	1935	Helena	MT	30049	2	19,000,000	11.73	5.08	2.90	0.49	0.24	222,865,348	3,278,922,204	1,622,537,468	797,180,031	6	3	1
NGDC-s	10/31/1935	1935	Helena	MT	30049	2	6,000,000	11.73	5.08	2.90	0.49	0.24	70,378,531	1,035,449,117	512,380,253	251,741,062	6	3	1
SC1527	7/16/1936	1936	Milton-Freewater	OR	41059		100,000	11.60	4.80	2.91	0.50	0.25	1,159,990	16,215,592	8,105,154	4,022,833			
SC1527	1/23/1938	1938	Maui	HI	15009		150,000	11.45	4.58	2.52	0.51	0.26	1,717,768	19,819,855	10,107,844	5,119,736			
EM-DAT	5/19/1940	1940	El Centro/Imperial Valley	CA	6025	9	33,000,000	11.43	4.21	2.61	0.52	0.27	377,215,436	4,139,551,757	2,153,976,525	1,113,392,360	23	12	6
NGDC-s	5/19/1940	1940	El Centro/Imperial Valley	CA	6025	9	6,000,000	11.43	4.21	2.61	0.52	0.27	68,584,625	752,645,774	391,632,095	202,434,975	23	12	6
NGDC-s	5/19/1940	1940	El Centro/Imperial Valley	CA	6025	8	6,000,000	11.43	4.21	2.61	0.52	0.27	68,584,625	752,645,774	391,632,095	202,434,975	21	11	6
NGDC-s	5/19/1940	1940	El Centro/Imperial Valley	CA	6025	9	33,000,000	11.43	4.21	2.61	0.52	0.27	377,215,436	4,139,551,757	2,153,976,525	1,113,392,360	23	12	6
SC1527	7/1/1941	1941	Santa Barbara	CA	6083		100,000	10.71	4.01	5.47	0.53	0.27	1,071,314	23,473,787	12,337,740	6,442,464			
SC1527	11/14/1941	1941	Gardena-Torrance	CA	6902		1,100,000	10.71	4.01	5.16	0.53	0.27	11,784,453	243,625,735	128,048,831	66,863,947			
ACC	9/5/1944	1944	Massena	NY	36089		1,750,000	9.22	3.54	1.18	0.54	0.29	16,126,726	67,441,686	36,532,155	19,666,136			
NGDC-s	9/5/1944	1944	Massena	NY	36089		1,500,000	9.22	3.54	1.18	0.54	0.29	13,822,908	57,807,159	31,313,276	16,856,688			
NGDC-s	9/5/1944	1944	Massena	NY	36089		2,000,000	9.22	3.54	1.18	0.54	0.29	18,430,544	77,076,213	41,751,034	22,475,584			
SC1527	2/15/1946	1946	Puget Sound area	WA	53067		250,000	8.02	3.39	5.47	0.55	0.30	2,004,022	37,192,416	20,555,634	11,292,572			
EM-DAT	4/1/1946	1946	Unimak Island quake/Hilo Hawaii tsunami	HI	15001	165	25,000,000	8.02	3.39	2.38	0.55	0.30	200,402,188	1,617,719,853	894,087,033	491,181,251	393	217	119
NGDC-s	4/1/1946	1946	Unimak Island quake/Hilo Hawaii tsunami	HI	15001		25,000,000	8.02	3.39	2.38	0.55	0.30	200,402,188	1,617,719,853	894,087,033	491,181,251			
ACC	4/13/1949	1949	Puget Sound/Olympia	WA	53067	8	52,500,000	6.86	3.20	5.19	0.57	0.32	359,951,841	5,975,383,570	3,403,585,667	1,927,640,434	41	24	13
EM-DAT	4/13/1949	1949	Puget Sound/Olympia	WA	53067	8	80,000,000	6.86	3.20	5.19	0.57	0.32	548,498,043	9,105,346,393	5,186,416,254	2,937,356,852	41	24	13
NGDC-s	4/13/1949	1949	Puget Sound/Olympia	WA	53067	8	25,000,000	6.86	3.20	5.19	0.57	0.32	171,405,638	2,845,420,748	1,620,755,079	917,924,016	41	24	13
NGDC-s	4/13/1949	1949	Puget Sound/Olympia	WA	53067	8	80,000,000	6.86	3.20	5.19	0.57	0.32	548,498,043	9,105,346,393	5,186,416,254	2,937,356,852	41	24	13
NGDC-s	11/18/1949	1949	Terminal Island	CA	6902		9,000,000	6.86	3.20	3.69	0.57	0.32	61,706,030	728,392,848	414,893,442	234,977,301			
NGDC-s	8/15/1951	1951	Terminal Island	CA	6902		3,000,000	6.33	2.95	3.37	0.58	0.34	18,982,899	189,125,878	109,913,608	63,527,102			
ACC	7/21/1952	1952	Kern County/Bakersfield	CA	6029	14	55,000,000	6.22	2.89	3.14	0.59	0.34	342,149,318	3,101,503,444	1,820,696,601	1,063,051,438	44	26	15
EM-DAT	7/21/1952	1952	Kern County/Bakersfield	CA	6029	14	50,000,000	6.22	2.89	3.14	0.59	0.34	311,044,834	2,819,548,585	1,655,178,728	966,410,399	44	26	15
NGDC-s	7/21/1952	1952	Kern County/Bakersfield	CA	6029	12	50,000,000	6.22	2.89	3.14	0.59	0.34	311,044,834	2,819,548,585	1,655,178,728	966,410,399	38	22	13
NGDC-s	7/21/1952	1952	Kern County/Bakersfield	CA	6029	13	60,000,000	6.22	2.89	3.14	0.59	0.34	373,253,801	3,383,458,303	1,986,214,474	1,159,692,478	41	24	14
ACC	8/22/1952	1952	Kern County/Bakersfield	CA	6029	2	20,000,000	6.22	2.89	3.14	0.59	0.34	124,417,934	1,127,819,434	662,071,491	386,564,159	6	4	2
EM-DAT	8/22/1952	1952	Kern County/Bakersfield	CA	6029	2	30,000,000	6.22	2.89	3.14	0.59	0.34	186,626,900	1,691,729,151	993,107,237	579,846,239	6	4	2
NGDC-s	8/22/1952	1952	Kern County/Bakersfield	CA	6029	2	10,000,000	6.22	2.89	3.14	0.59	0.34	62,208,967	563,909,717	331,035,746	193,282,080	6	4	2
NGDC-s	8/22/1952	1952	Kern County/Bakersfield	CA	6029	2	30,000,000	6.22	2.89	3.14	0.59	0.34	186,626,900	1,691,729,151	993,107,237	579,846,239	6	4	2
SC1527	2/21/1954	1954	Wilkes-Barre	PA	42079		1,000,000	6.09	2.81	0.84	0.60	0.36	6,087,474	14,319,740	8,576,894	5,110,519			
SC1527	12/21/1954	1954	Eureka-Arcata	CA	6023	1	2,100,000	6.09	2.81	1.54	0.60	0.36	12,783,694	55,286,764	33,114,339	19,731,088	2	1	1
NGDC-s	1/25/1955	1955	Terminal Island	CA	6902		3,000,000	5.98	2.71	2.78	0.61	0.36	17,944,779	135,325,398	81,872,687	49,281,407			
SC1527	9/5/1955	1955	San Jose	CA	6085		100,000	5.98	2.71	3.64	0.61	0.36	598,159	5,901,009	3,570,146	2,148,969			
SC1527	10/24/1955	1955	Concord-Walnut Creek	CA	6013	1	1,000,000	5.98	2.71	2.88	0.61	0.36	5,981,593	46,574,915	28,178,106	16,961,172	3	2	1
NGDC-s	3/9/1957	1957	Andreanof Islands quake/Hawaii tsunami	AK	2016		3,000,000	5.60	2.63	0.93	0.62	0.38	16,785,058	41,025,225	25,324,467	15,556,167			
SC1527	3/9/1957	1957	Andreanof Islands quake/Hawaii tsunami	HI	15003		5,000,000	5.60	2.63	1.98	0.62	0.38	27,975,097	146,171,526	90,230,242	55,426,112			
SC1527	3/22/1957	1957	Daly City	CA	6081	1	1,000,000	5.60	2.63	1.83	0.62	0.38	5,595,019	26,997,253	16,665,138	10,236,965	2	1	1
EM-DAT	8/18/1959	1959	Hebgen Lake	MT	30031	28	26,000,000	5.40	2.62	3.05	0.63	0.39	140,472,170	1,122,319,913	706,863,603	443,114,693	85	54	34
NGDC-s	8/18/1959	1959	Hebgen Lake	MT	30031	28	11,000,000	5.40	2.62	3.05	0.63	0.39	59,430,533	474,827,656	299,057,678	187,471,601	85	54	34
NGDC-s	8/18/1959	1959	Hebgen Lake	MT	30031	28	26,000,000	5.40	2.62	3.05	0.63	0.39	140,472,170	1,122,319,913	706,863,603	443,114,693	85	54	34
NGDC-s	4/4/1961	1961	Terminal Island	CA	6902		4,500,000	5.27	2.59	2.22	0.64	0.41	23,710,335	136,623,087	87,795,581	56,165,732			
SHLDS	4/4/1961	1961	Terminal Island	CA	6902		4,500,000	5.27	2.59	2.22	0.64	0.41	23,710,335	136,623,087	87,795,581	56,165,732			
SC1527	4/29/1961	1961	Holister	CA	6069		250,000	5.27	2.59	3.57	0.64	0.41	1,317,241	12,178,648	7,826,140	5,006,640			
ACC	8/30/1962	1962	Cache County	UT	49005		1,500,000	5.20	2.55	2.64	0.65	0.42	7,796,815	52,620,495	34,156,101	22,073,753			
NGDC-s	8/30/1962	1962	Cache County	UT	49005		2,000,000	5.20	2.55	2.64	0.65	0.42	10,395,753	70,160,659	45,541,468	29,431,671			
SC1527	8/30/1962	1962	Cache County	UT	49005		1,000,000	5.20	2.55	2.64	0.65	0.42	5,197,877	35,080,330	22,770,734	14,715,835			
SHLDS	8/30/1962	1962	Cache County	UT	49005		2,000,000	5.20	2.55	2.64	0.65	0.42	10,395,753	70,160,659	45,541,468	29,431,671			

EM-DAT	3/28/1964	1964	Prince William Sound/Anchorage	AK	2099	131	1,020,000,000	5.07	2.44	2.54	0.66	0.44	5,167,198,048	31,981,914,028	21,181,047,297	13,969,264,962	332	220	145
NGDC-s	3/28/1964	1964	Prince William Sound/Anchorage	AK	2099	131	540,000,000	5.07	2.44	2.54	0.66	0.44	2,735,575,437	16,931,601,544	11,213,495,628	7,395,493,215	332	220	145
SC1527	3/28/1964	1964	Prince William Sound, Anchorage (Alaska)	AK	2099	125	311,000,000	5.07	2.44	5.47	0.66	0.44	1,575,488,817	21,026,877,327	13,925,723,232	9,184,253,964	684	453	299
SHLDS	3/28/1964	1964	Prince William Sound, Anchorage (Alaska)	AK	2099	131	540,000,000	5.07	2.44	2.54	0.66	0.44	2,735,575,437	16,931,601,544	11,213,495,628	7,395,493,215	332	220	145
ACC	4/29/1965	1965	Seattle	WA	53999	7	20,250,000	4.98	2.36	1.88	0.67	0.45	100,744,986	447,245,997	299,194,941	199,337,722	13	9	6
EM-DAT	4/29/1965	1965	Seattle	WA	53999	7	28,000,000	4.98	2.36	1.88	0.67	0.45	139,301,708	618,414,218	413,701,647	275,627,467	13	9	6
NGDC-s	4/29/1965	1965	Seattle	WA	53999	7	12,500,000	4.98	2.36	1.88	0.67	0.45	62,188,263	276,077,776	184,688,235	123,047,976	13	9	6
NGDC-s	4/29/1965	1965	Seattle	WA	53999	7	28,000,000	4.98	2.36	1.88	0.67	0.45	139,301,708	618,414,218	413,701,647	275,627,467	13	9	6
SHLDS	4/29/1965	1965	Seattle	WA	53999	7	12,500,000	4.98	2.36	1.88	0.67	0.45	62,188,263	276,077,776	184,688,235	123,047,976	13	9	6
SC1527	1/23/1966	1966	Dulce/Rio Arriba County	NM	35039		200,000	4.84	2.27	1.65	0.68	0.45	967,492	3,615,756	2,443,272	1,644,433			
SC1527	5/21/1967	1967	Anza/Riverside	CA	6065		40,000	4.69	2.20	4.71	0.68	0.46	187,692	1,944,115	1,326,965	902,221			
NGDC-s	10/2/1969	1969	Santa Rosa	CA	6097		7,000,000	4.29	2.06	2.34	0.70	0.48	30,012,276	144,601,883	100,702,662	69,873,528			
NGDC-s	10/2/1969	1969	Santa Rosa	CA	6097		10,000,000	4.29	2.06	2.34	0.70	0.48	42,874,680	206,574,118	143,860,946	99,819,326			
SC1527	10/2/1969	1969	Santa Rosa	CA	6097	1	8,350,000	4.29	2.06	2.34	0.70	0.48	35,800,358	172,489,388	120,123,890	83,349,137	2	2	1
SHLDS	10/2/1969	1969	Santa Rosa	CA	6097		10,000,000	4.29	2.06	2.34	0.70	0.48	42,874,680	206,574,118	143,860,946	99,819,326			
ACC	2/9/1971	1971	San Fernando	CA	6902	65	539,500,000	3.88	1.95	1.76	0.71	0.50	2,092,109,007	7,154,916,482	5,083,948,997	3,599,905,847	114	81	57
EM-DAT	2/9/1971	1971	San Fernando	CA	6902	65	535,000,000	3.88	1.95	1.76	0.71	0.50	2,074,658,607	7,095,236,919	5,041,543,491	3,569,878,829	114	81	57
NGDC-s	2/9/1971	1971	San Fernando	CA	6902	58	500,000,000	3.88	1.95	1.76	0.71	0.50	1,938,933,278	6,631,062,542	4,711,722,889	3,336,335,354	102	72	51
NGDC-s	2/9/1971	1971	San Fernando	CA	6902	65	553,000,000	3.88	1.95	1.76	0.71	0.50	2,144,460,205	7,333,955,171	5,211,165,515	3,689,986,902	114	81	57
SHLDS	2/9/1971	1971	San Fernando	CA	6037	65	500,000,000	3.88	1.95	1.40	0.71	0.50	1,938,933,278	5,296,973,108	3,763,781,336	2,665,105,108	91	65	46
NGDC-s	2/21/1973	1973	Oxnard	CA	6902		1,000,000	3.52	1.76	1.71	0.72	0.52	3,520,142	10,592,786	7,679,561	5,549,382			
SHLDS	2/21/1973	1973	Oxnard	CA	6902		1,000,000	3.52	1.76	1.71	0.72	0.52	3,520,142	10,592,786	7,679,561	5,549,382			
ACC	4/26/1973	1973	Kilauea/Hawaii	HI	15001		5,675,000	3.52	1.76	2.32	0.72	0.52	19,976,805	81,850,069	59,339,690	42,879,871			
NGDC-s	4/26/1973	1973	Kilauea/Hawaii	HI	15001		5,600,000	3.52	1.76	2.32	0.72	0.52	19,712,795	80,768,350	58,555,465	42,313,177			
SC1527	4/26/1973	1973	Kilauea/Hawaii	HI	15001		5,750,000	3.52	1.76	2.32	0.72	0.52	20,240,816	82,931,788	60,123,915	43,446,565			
SHLDS	4/26/1973	1973	Kilauea/Hawaii	HI	15001		5,600,000	3.52	1.76	2.32	0.72	0.52	19,712,795	80,768,350	58,555,465	42,313,177			
NGDC-s	3/28/1975	1975	Pocatello Valley	ID	16071		1,000,000	2.95	1.68	1.38	0.74	0.55	2,950,187	6,804,602	5,033,366	3,711,803			
SHLDS	3/28/1975	1975	Pocatello Valley	ID	16071		1,000,000	2.95	1.68	1.38	0.74	0.55	2,950,187	6,804,602	5,033,366	3,711,803			
ACC	8/1/1975	1975	Oroville Reservoir	CA	6007		4,250,000	2.95	1.68	1.74	0.74	0.55	12,538,294	36,650,328	27,110,261	19,992,179			
NGDC-s	8/1/1975	1975	Oroville Reservoir	CA	6007		6,000,000	2.95	1.68	1.74	0.74	0.55	17,701,121	51,741,639	38,273,310	28,224,253			
SC1527	8/1/1975	1975	Oroville Reservoir	CA	6007		2,500,000	2.95	1.68	1.74	0.74	0.55	7,375,467	21,559,016	15,947,212	11,760,105			
SHLDS	8/1/1975	1975	Oroville Reservoir	CA	6007		6,000,000	2.95	1.68	1.74	0.74	0.55	17,701,121	51,741,639	38,273,310	28,224,253			
NGDC-s	11/29/1975	1975	Hilo/Hawaii	HI	15001	2	4,000,000	2.95	1.68	2.15	0.74	0.55	11,800,747	42,585,625	31,500,603	23,229,791	4	3	2
SHLDS	11/29/1975	1975	Hilo/Hawaii	HI	15001	2	4,100,000	2.95	1.68	2.15	0.74	0.55	12,095,766	43,650,265	32,288,118	23,810,535	4	3	2
NGDC-s	8/13/1978	1978	Goleta/Santa Barbara	CA	6083		15,000,000	2.45	1.51	1.37	0.76	0.58	36,752,737	76,412,348	58,252,397	44,286,116			
SC1527	8/13/1978	1978	Goleta/Santa Barbara	CA	6083		1,200,000	2.45	1.51	1.37	0.76	0.58	2,940,219	6,112,988	4,660,192	3,542,889			
SHLDS	8/13/1978	1978	Goleta/Santa Barbara	CA	6083		15,000,000	2.45	1.51	1.37	0.76	0.58	36,752,737	76,412,348	58,252,397	44,286,116			
SC1527	8/6/1979	1979	Gilroy	CA	6085		500,000	2.26	1.44	1.34	0.77	0.59	1,131,357	2,175,824	1,675,478	1,286,772			
SHLDS	8/6/1979	1979	Gilroy	CA	6085		500,000	2.26	1.44	1.34	0.77	0.59	1,131,357	2,175,824	1,675,478	1,286,772			
NGDC-s	10/15/1979	1979	Imperial Valley	CA	6025		3,000,000	2.26	1.44	1.72	0.77	0.59	6,788,145	16,857,005	12,980,621	9,969,156			
NGDC-s	10/15/1979	1979	Imperial Valley	CA	6025		30,000,000	2.26	1.44	1.72	0.77	0.59	67,881,448	168,570,053	129,806,214	99,691,560			
SHLDS	10/15/1979	1979	Imperial Valley	CA	6025		3,000,000	2.26	1.44	1.72	0.77	0.59	6,788,145	16,857,005	12,980,621	9,969,156			
NGDC-s	1/24/1980	1980	Livermore	CA	6901	1	3,500,000	2.07	1.40	1.29	0.78	0.60	7,260,802	13,056,369	10,155,522	7,879,058	1	1	1
NGDC-s	1/24/1980	1980	Livermore	CA	6901	1	11,500,000	2.07	1.40	1.29	0.78	0.60	23,856,919	42,899,497	33,368,145	25,888,333	1	1	1
SHLDS	1/24/1980	1980	Livermore	CA	6901	1	11,500,000	2.07	1.40	1.29	0.78	0.60	23,856,919	42,899,497	33,368,145	25,888,333	1	1	1
NGDC-s	5/18/1980	1980	Mt. St. Helens eruption	WA	53059	31	2,000,000,000	2.07	1.40	1.35	0.78	0.60	4,149,029,477	7,804,588,125	6,070,575,345	4,709,793,664	42	32	25
SHLDS	5/18/1980	1980	Mt. St. Helens eruption	WA	53059	32	2,000,000,000	2.07	1.40	1.35	0.78	0.60	4,149,029,477	7,804,588,125	6,070,575,345	4,709,793,664	43	34	26
NGDC-s	5/25/1980	1980	Mammoth Lakes	CA	6051		2,000,000	2.07	1.40	1.46	0.78	0.60	4,149,029	8,452,543	6,574,568	5,100,811			
SC1527	5/25/1980	1980	Mammoth Lakes	CA	6051		1,500,000	2.07	1.40	1.46	0.78	0.60	3,111,772	6,339,407	4,930,926	3,825,609			
SHLDS	5/25/1980	1980	Mammoth Lakes	CA	6051		2,000,000	2.07	1.40	1.46	0.78	0.60	4,149,029	8,452,543	6,574,568	5,100,811			
NGDC-s	7/27/1980	1980	Maysville	KY	21011		1,000,000	2.07	1.40	1.16	0.78	0.60	2,074,515	3,360,595	2,613,942	2,028,000			
SHLDS	7/27/1980	1980	Maysville	KY	21011		1,000,000	2.07	1.40	1.16	0.78	0.60	2,074,515	3,360,595	2,613,942	2,028,000			
NGDC-s	11/8/1980	1980	Humboldt County	CA	6023	5	2,750,000	2.07	1.40	1.18	0.78	0.60	5,704,916	9,427,596	7,332,985	5,689,222	6	5	4
SC1527	11/8/1980	1980	Humboldt County	CA	6023		2,000,000	2.07	1.40	1.18	0.78	0.60	4,149,029	6,856,433	5,333,080	4,137,616			
SHLDS	11/8/1980	1980	Humboldt County	CA	6023	5	2,750,000	2.07	1.40	1.18	0.78	0.60	5,704,916	9,427,596	7,332,985	5,689,222	6	5	4
NGDC-s	4/26/1981	1981	Westmorland/Calipatria	CA	6025		1,500,000	1.90	1.40	1.66	0.79	0.62	2,844,593	6,629,340	5,208,527	4,082,217			
SC1527	4/26/1981	1981	Westmorland/Calipatria	CA	6025		1,000,000	1.90	1.40	1.66	0.79	0.62	1,896,395	4,419,560	3,472,351	2,721,478			
SC1527	4/26/1981	1981	Westmorland/Calipatria	CA	6025		3,000,000	1.90	1.40	1.66	0.79	0.62	5,689,186	13,258,679	10,417,054	8,164,434			
SHLDS	4/26/1981	1981	Westmorland/Calipatria	CA	6025		1,500,000	1.90	1.40	1.66	0.79	0.62	2,844,593	6,629,340	5,208,527	4,082,217			
EM-DAT	5/2/1983	1983	Coalinga area	CA	6019		31,000,000	1.72	1.45	1.57	0.80	0.64	53,299,538	120,899,296	96,916,574	77,517,086			
NGDC-s	5/2/1983	1983	Coalinga area	CA	6019		31,000,000	1.72	1.45	1.57	0.80	0.64	53,299,538	120,899,296	96,916,574	77,517,086			
SC1527	5/2/1983	1983	Coalinga area	CA	6019		10,000,000	1.72	1.45	1.57	0.80	0.64	17,193,399	38,999,773	31,263,411	25,005,512			
SHLDS	5/2/1983	1983	Coalinga area	CA	6019		31,000,000	1.72	1.45	1.57	0.80	0.64	53,299,538	120,899,296	96,916,574	77,517,086			
NGDC-s	7/12/1983	1983	Prince William Sound/Valdez-Cordova	AK	2261		1,000,000	1.72	1.45	1.12	0.80	0.64	1,719,340	2,792,639	2,238,665	1,790,559			
SHLDS	7/12/1983	1983	Prince William Sound/Valdez-Cordova	AK	2261		1,000,000	1.72	1.45	1.12	0.80	0.64	1,719,340	2,792,639	2,238,665	1,790,559			
ACC	10/28/1983	1983	Borah Peak	ID	16037	3	18,750,000	1.72	1.45	1.13	0.80	0.64	32,237,624	52,758,222	42,292,605	33,827,026	3	3	2
EM-DAT	10/28/1983	1983	Borah Peak	ID	16037	2	15,000,000	1.72	1.45	1.13	0.80	0.64	25,790,099	42,206,578	33,834,084	27,061,621	2	2	1
NGDC-s	10/28/1983	1983	Borah Peak	ID	16037	2	12,500,000	1.72	1.45	1.13	0.80	0.64	21,491,749	35,172,148	28,195,070	22,551,351	2	2	1
NGDC-s	10/28/1983	1983	Borah Peak	ID	16037	2	12,500,000	1.72	1.45	1.13	0.80	0.64	21,491,749	35,172,148	28,195,070	22,551,351	2	2	1
NGDC-s	10/28/1983	1983	Borah Peak	ID	16037	2	15,000,000	1.72	1.45	1.13	0.80	0.64	25,790,099	42,206,578	33,834,084	27,061,621	2	2	1
NGDC-s	10/28/1983	1983	Borah Peak	ID	16037	3	25,000,000	1.72	1.45	1.13	0.80	0.64	42,983,499	70,344,296	56,390,140	45,102,701	3	3	2
SHLDS	10/28/1983	1983	Borah Peak	ID	16037	2	12,500,000	1.72	1.45	1.13	0.80	0.64	21,491,749	35,172,148	28,195,070	22,551,351	2	2	1
ACC	11/16/1983	1983	Kapapala/Hawaii	HI	15001		6,375,000	1.72	1.45	1.66	0.80	0.64	10,960,792	26,423,399	21,181,805	16,941,909			
EM-DAT	11/16/1983	1983	Kapapala/Hawaii	HI	15001		6,250,000	1.72	1.45	1.66	0.80	0.64	10,745,875	25,905,293	20,766,476	16,609,715			
NGDC-s	11/16/1983	1983	Kapapala/Hawaii	HI	15001		6,500,000	1.72	1.45	1.66	0.80	0.64	11,175,710	26,941,505	21,597,135	17,274,104			
SHLDS	11/16/1983	1983	Kapapala/Hawaii	HI	15001		6,500,000	1.72	1.45	1.66	0.80	0.64	11,175,710	26,941,505	21,597,135	17,274,104			
ACC	4/24/1984	1984	Morgan Hill	CA	6903		18,750,000	1.66	1.44	1.18	0.81	0.65	31,071,151	52,568,609	42,566,267	34,393,318			
NGDC-s	4/24/1984	1984	Morgan Hill	CA	6903		7,500,000	1.66	1.44	1.18	0.81	0.65	12,428,461	21,027,443	17,026,507	13,757,327			
NGDC-s	4/24/1984	1984	Morgan Hill	CA	6903		10,000,000	1.66	1.44	1.18	0.81	0.65	16,571,281	28,036,591	22,702,009	18,343,103			
NGDC-s	4/24/1984	1984	Morgan Hill	CA	6903		30,000,000	1.66	1.44	1.18	0.81	0.65	49,713,842	84,109,774	68,106,028	55,029,309			
SC1527	4/24/1984	1984	Morgan Hill	CA	6903		8,000,000	1.66	1.44	1.18	0.81	0.65	13,257,025	22,429,273	18,161,607	14,674,482			
SHLDS	4/24/1984	1984	Morgan Hill	CA	6903		7,500,000	1.66	1.44	1.18	0.81	0.65	12,428,461	21,027,443	17,026,507	13,757,327			
SC1527	1/26/1986	1986	Paicines/San Benito	CA	6069		800,000	1.57	1.37	1.75	0.83	0.68	1,258,813	3,021,937	2,496,629	2,058,642			
SHLDS	1/26/1986	1986	Paicines/San Benito	CA	6069		800,000	1.57	1.37	1.75	0.83	0.68	1,258,813	3,021,937	2,496,629	2,058,642			
ACC	7/8/1986	1986	Palm Springs	CA	6065		5,250,000	1.57	1.37	2.01	0.83	0.68	8,260,958	22,838,295	18,868,282	15,558,191			
NGDC-s	7/8/1986	1986	Palm Springs	CA	6065		4,500,000	1.57	1.37	2.01	0.83	0.68	7,080,821	19,575,681	16,172,813	13,335,593			
SC1527	7/8/1986	1986	Palm Springs	CA	6065		6,000,000	1.57	1.37	2.01	0.83	0.68	9,441,095	26,100,908	21,563,751	17,780,790			
SHLDS	7/8/1986	1986	Palm Springs	CA	6065		4,500,000	1.57	1.37	2.01	0.83	0.68	7,080,821	19,575,681	16,172,813	13,335,593			
ACC	7/13/1986	1986	San Diego/Newport Beach	CA	6904		860,000	1.57	1.37	1.33	0.83	0.68	1,353,224	2,467,371	2,038,465	1,680,854			
EM-DAT	7/13/1986	1986	San Diego/Newport Beach	CA	6904		720,000	1.57	1.37	1.33	0.83	0.68	1,132,931	2,065,706	1,706,622	1,407,226			
NGDC-s	7/13/1986	1986	San Diego/Newport Beach	CA	6904		720,000	1.57	1.37	1.33	0.83	0.68	1,132,931	2,065,706	1,706,622	1,407,226			
NGDC-s	7/13/1986	1986	San Diego/Newport Beach	CA	6904		1,000,000	1.57	1.37	1.33	0.83	0.68	1,573,516	2,869,036	2,370,308	1,954,481			
SHLDS	7/13/1986	1986	San Diego/Newport Beach	CA	6904		720,000	1.57	1.37	1.33	0.83	0.68	1,132,931	2,065,706	1,706,622	1,407,226			
ACC	7/21/1986	1986	Chalfant Valley/Bishop	CA	6027		1,850,000	1.57	1.37	1.00	0.83	0.68	2,911,004	4,006,741	3,310,244	2,729,523			
NGDC-s	7/21/1986	1986	Chalfant Valley/Bishop	CA	6027		1,000,000	1.57	1.37	1.00	0.83	0.68	1,573,516	2,165,806	1,789,321	1,475,418			
SC1527	7/21/1986	1986	Chalfant Valley/Bishop	CA	6027		2,700,000	1.57	1.37	1.00	0.83	0.68	4,248,493	5,847,676	4,831,166	3,983,628			
SHLDS	7/21/1986	1986	Chalfant Valley/Bishop	CA	6027		1,000,000	1.57	1.37	1.00	0.83	0.68	1,573,516	2,165,806	1,789,321	1,475,418			
ACC	10/1/1987	1987	Whittier/Los Angeles	CA	6902	8	354,000,000	1.53	1.35	1.30	0.83	0.70	542,215,449	953,715,053	795,888,336	662,961,029	10	9	7
EM-DAT	10/1/1987	1987	Whittier/Los Angeles	CA	6037	8	213,000,000	1.53	1.35	1.18	0.83	0.70	326,248,279	518,414,889	432,624,359	360,368,505	9	8	7
NGDC-s	10/1/1987	1987	Whittier/Los Angeles	CA	6902	8	350,000,000	1.53	1.35	1.30	0.83	0.70	536,088,721	942,938,612	786,895,248	655,469,944	10	9	7

NGDC-s	10/1/1987	1987	Whittier/Los Angeles	CA	6902	8	358,000,000	1.53	1.35	1.30	0.83	0.70	548,342,177	964,491,495	804,881,425	670,452,114	10	9	7
SHLDS	10/1/1987	1987	Whittier/Los Angeles	CA	6037	8	350,000,000	1.53	1.35	1.18	0.83	0.70	536,088,721	851,855,451	710,885,097	592,154,821	9	8	7
EM-DAT	11/24/1987	1987	Superstition Hills/Imperial County	CA	6025		4,000,000	1.53	1.35	1.50	0.83	0.70	6,126,728	12,384,795	10,335,282	8,609,108			
NGDC-s	11/24/1987	1987	Superstition Hills/Imperial County	CA	6025		4,000,000	1.53	1.35	1.50	0.83	0.70	6,126,728	12,384,795	10,335,282	8,609,108			
SHLDS	11/24/1987	1987	Superstition Hills/Imperial County	CA	6025		4,000,000	1.53	1.35	1.50	0.83	0.70	6,126,728	12,384,795	10,335,282	8,609,108			
SC1527	6/26/1989	1989	Kalapana/Puna District	HI	15001		1,000,000	1.43	1.31	1.42	0.85	0.72	1,427,173	2,668,320	2,271,961	1,931,324			
SHLDS	6/26/1989	1989	Kalapana/Puna District	HI	15001	6	1,000,000	1.43	1.31	1.42	0.85	0.72	1,427,173	2,668,320	2,271,961	1,931,324	9	7	6
EM-DAT	10/18/1989	1989	Loma Prieta/San Francisco	CA	6901	62	5,600,000,000	1.43	1.31	1.14	0.85	0.72	7,992,168,644	11,993,348,683	10,211,829,938	8,680,758,439	71	60	51
NGDC-s	10/18/1989	1989	Loma Prieta/San Francisco	CA	6901	62	12,000,000,000	1.43	1.31	1.14	0.85	0.72	17,126,075,666	25,700,032,892	21,882,492,724	18,601,625,227	71	60	51
SHLDS	10/18/1989	1989	Loma Prieta/San Francisco	CA	6901	62	5,900,000,000	1.43	1.31	1.14	0.85	0.72	8,420,320,536	12,635,849,505	10,758,892,256	9,145,799,070	71	60	51
EM-DAT	2/28/1990	1990	Covina/Claremont	CA	6905		12,700,000	1.37	1.31	1.16	0.86	0.74	17,451,098	26,521,805	22,810,300	19,588,186			
NGDC-s	2/28/1990	1990	Covina/Claremont	CA	6905		12,700,000	1.37	1.31	1.16	0.86	0.74	17,451,098	26,521,805	22,810,300	19,588,186			
SHLDS	2/28/1990	1990	Covina/Claremont	CA	6905		12,700,000	1.37	1.31	1.16	0.86	0.74	17,451,098	26,521,805	22,810,300	19,588,186			
EM-DAT	6/28/1991	1991	Glendale/Arcadia/Los Angeles	CA	6037	2	33,500,000	1.33	1.34	1.11	0.87	0.75	44,476,641	66,495,041	57,767,289	50,113,452	2	2	2
NGDC-s	6/28/1991	1991	Glendale/Arcadia/Los Angeles	CA	6037	2	33,500,000	1.33	1.34	1.11	0.87	0.75	44,476,641	66,495,041	57,767,289	50,113,452	2	2	2
SHLDS	6/28/1991	1991	Glendale/Arcadia/Los Angeles	CA	6037	2	33,500,000	1.33	1.34	1.11	0.87	0.75	44,476,641	66,495,041	57,767,289	50,113,452	2	2	2
ACC	4/25/1992	1992	Ferndale/Fortuna/Petrolia	CA	6023		66,000,000	1.30	1.34	1.06	0.88	0.77	85,656,746	121,902,196	106,971,740	93,745,518			
EM-DAT	4/25/1992	1992	Ferndale/Fortuna/Petrolia	CA	6023		75,000,000	1.30	1.34	1.06	0.88	0.77	97,337,211	138,525,223	121,558,795	106,528,998			
NGDC-s	4/25/1992	1992	.	CA	6023		66,000,000	1.30	1.34	1.06	0.88	0.77	85,656,746	121,902,196	106,971,740	93,745,518			
NGDC-s	4/25/1992	1992	Ferndale/Fortuna/Petrolia	CA	6023		100,000,000	1.30	1.34	1.06	0.88	0.77	129,782,948	184,700,297	162,078,394	142,038,664			
SHLDS	4/25/1992	1992	Ferndale/Fortuna/Petrolia	CA	6023		66,000,000	1.30	1.34	1.06	0.88	0.77	85,656,746	121,902,196	106,971,740	93,745,518			
ACC	6/28/1992	1992	Landers/Yucca Valley	CA	6071	3	100,000,000	1.30	1.34	1.33	0.88	0.77	129,782,948	230,358,463	202,144,394	177,150,816	4	3	3
EM-DAT	6/28/1992	1992	Landers/Yucca Valley	CA	6071	1	100,000,000	1.30	1.34	1.33	0.88	0.77	129,782,948	230,358,463	202,144,394	177,150,816	1	1	1
NGDC-s	6/28/1992	1992	Landers/Yucca Valley	CA	6071	3	92,000,000	1.30	1.34	1.33	0.88	0.77	119,400,313	211,929,786	185,972,843	162,978,751	4	3	3
NGDC-s	6/28/1992	1992	Landers/Yucca Valley	CA	6071	3	100,000,000	1.30	1.34	1.33	0.88	0.77	129,782,948	230,358,463	202,144,394	177,150,816	4	3	3
SHLDS	6/28/1992	1992	Landers/Yucca Valley	CA	6071	3	100,000,000	1.30	1.34	1.33	0.88	0.77	129,782,948	230,358,463	202,144,394	177,150,816	4	3	3
NGDC-s	3/25/1993	1993	Clackamas	OR	41005		28,400,000	1.27	1.32	1.24	0.89	0.78	36,025,947	58,810,258	52,128,523	46,149,393			
SHLDS	3/25/1993	1993	Clackamas	OR	41005		28,400,000	1.27	1.32	1.24	0.89	0.78	36,025,947	58,810,258	52,128,523	46,149,393			
EM-DAT	9/21/1993	1993	Klamath Falls	OR	41035	2	7,500,000	1.27	1.32	1.11	0.89	0.78	9,513,894	13,913,876	12,333,049	10,918,451	2	2	2
NGDC-s	9/21/1993	1993	Klamath Falls	OR	41035	2	7,500,000	1.27	1.32	1.11	0.89	0.78	9,513,894	13,913,876	12,333,049	10,918,451	2	2	2
SHLDS	9/21/1993	1993	Klamath Falls	OR	41035	2	7,500,000	1.27	1.32	1.11	0.89	0.78	9,513,894	13,913,876	12,333,049	10,918,451	2	2	2
ACC	1/17/1994	1994	Northridge/Los Angeles	CA	6902	60	47,350,000,000	1.24	1.28	1.16	0.90	0.80	58,814,639,537	87,380,606,298	78,235,199,499	69,968,390,910	69	62	56
EM-DAT	1/17/1994	1994	Northridge/Los Angeles	CA	6902	60	16,500,000,000	1.24	1.28	1.16	0.90	0.80	20,495,069,744	30,449,419,301	27,262,529,920	24,381,804,647	69	62	56
NGDC-s	1/17/1994	1994	Northridge/Los Angeles	CA	6902	60	40,000,000,000	1.24	1.28	1.16	0.90	0.80	49,685,017,561	73,816,774,064	66,090,981,625	59,107,405,204	69	62	56
SHLDS	1/17/1994	1994	Northridge/Los Angeles	CA	6902	60	20,000,000,000	1.24	1.28	1.16	0.90	0.80	24,842,508,780	36,908,387,032	33,045,490,813	29,553,702,602	69	62	56
ACC	12/26/1994	1994	Eureka/Arcata/Humboldt County	CA	6023		3,550,000	1.24	1.28	1.05	0.90	0.80	4,409,545	5,955,819	5,332,473	4,769,011			
EM-DAT	12/26/1994	1994	Eureka/Arcata/Humboldt County	CA	6023		2,100,000	1.24	1.28	1.05	0.90	0.80	2,608,463	3,523,161	3,154,421	2,821,105			
NGDC-s	12/26/1994	1994	Eureka/Arcata/Humboldt County	CA	6023		2,100,000	1.24	1.28	1.05	0.90	0.80	2,608,463	3,523,161	3,154,421	2,821,105			
NGDC-s	12/26/1994	1994	Eureka/Arcata/Humboldt County	CA	6023		5,000,000	1.24	1.28	1.05	0.90	0.80	6,210,627	8,388,478	7,510,525	6,716,917			
SHLDS	12/26/1994	1994	Eureka/Arcata/Humboldt County	CA	6023		2,100,000	1.24	1.28	1.05	0.90	0.80	2,608,463	3,523,161	3,154,421	2,821,105			
EM-DAT	9/3/2000	2000	Yountville/Napa	CA	6055		50,000,000	1.12	1.11	1.07	0.95	0.90	56,056,500	66,250,163	63,003,246	59,884,900			
NGDC-s	9/3/2000	2000	Yountville/Napa	CA	6055		50,000,000	1.12	1.11	1.07	0.95	0.90	56,056,500	66,250,163	63,003,246	59,884,900			
SHLDS	9/3/2000	2000	Yountville/Napa	CA	6055		50,000,000	1.12	1.11	1.07	0.95	0.90	56,056,500	66,250,163	63,003,246	59,884,900			
ACC	2/28/2001	2001	Seattle/Tacoma/Olympia	WA	53999	1	2,000,000,000	1.09	1.09	1.03	0.96	0.92	2,189,728,415	2,475,801,901	2,378,245,427	2,283,600,844	1	1	1
EM-DAT	2/28/2001	2001	Seattle/Tacoma/Olympia	WA	53999	1	2,000,000,000	1.09	1.09	1.03	0.96	0.92	2,189,728,415	2,475,801,901	2,378,245,427	2,283,600,844	1	1	1
NGDC-s	2/28/2001	2001	Seattle/Tacoma/Olympia	WA	53999	1	2,000,000,000	1.09	1.09	1.03	0.96	0.92	2,189,728,415	2,475,801,901	2,378,245,427	2,283,600,844	1	1	1
NGDC-s	2/28/2001	2001	Seattle/Tacoma/Olympia	WA	53999		4,000,000,000	1.09	1.09	1.03	0.96	0.92	4,379,456,831	4,951,603,801	4,756,490,854	4,567,201,687			
SHLDS	2/28/2001	2001	Seattle/Tacoma/Olympia	WA	53999	1	2,000,000,000	1.09	1.09	1.03	0.96	0.92	2,189,728,415	2,475,801,901	2,378,245,427	2,283,600,844	1	1	1
ACC	11/3/2002	2002	Denali Fault/Mentasa Lake	AK	2099		38,000,000	1.08	1.07	1.03	0.97	0.94	40,890,841	44,786,329	43,456,130	42,152,534			
NGDC-s	11/3/2002	2002	Denali Fault/Mentasa Lake	AK	2099		20,000,000	1.08	1.07	1.03	0.97	0.94	21,521,495	23,571,752	22,871,647	22,185,544			
NGDC-s	11/3/2002	2002	Denali Fault/Mentasa Lake	AK	2099		56,000,000	1.08	1.07	1.03	0.97	0.94	60,260,186	66,000,906	64,040,613	62,119,524			
SHLDS	11/3/2002	2002	Denali Fault/Mentasa Lake	AK	2099		20,000,000	1.08	1.07	1.03	0.97	0.94	21,521,495	23,571,752	22,871,647	22,185,544			
ACC	12/22/2003	2003	Paso Robles/San Simeon	CA	6079	2	300,000,000	1.05	1.05	1.01	0.98	0.96	316,390,574	334,948,813	328,283,332	321,684,840	2	2	2
EM-DAT	12/22/2003	2003	Paso Robles/San Simeon	CA	6079	2	200,000,000	1.05	1.05	1.01	0.98	0.96	210,927,050	223,299,209	218,855,555	214,456,560	2	2	2
NGDC-s	12/22/2003	2003	Paso Robles/San Simeon	CA	6079	2	300,000,000	1.05	1.05	1.01	0.98	0.96	316,390,574	334,948,813	328,283,332	321,684,840	2	2	2
SHLDS	12/22/2003	2003	Paso Robles/San Simeon	CA	6079	2	300,000,000	1.05	1.05	1.01	0.98	0.96	316,390,574	334,948,813	328,283,332	321,684,840	2	2	2
SHLDS	7/26/2004	2004	Twin Bridges	MT	30999		1,000,000	1.03	1.00	1.01	0.99	0.98	1,027,626	1,039,028	1,028,638	1,018,248			
SHLDS	9/28/2004	2004	San Miguel	CA	6079		1,000,000	1.03	1.00	1.00	0.99	0.98	1,027,626	1,034,758	1,024,411	1,014,063			

APPENDIX C: SIGNIFICANT EARTHQUAKES WITH NO DAMAGE ESTIMATE

The following is a list of events from Stover and Coffman (1993) with damage descriptions that imply that considerable economic losses, but for which no estimates are available. Events for which damage reports are confined to chimney collapses, broken windows and/or falling plaster are not included in the list. In general, events with a Modified Mercalli Intensity (MMI) of VIII probably caused damages in the hundreds of thousands to millions of dollars. Extreme events with MMI of IX or X are included even where they did not produce extensive damage due to occurrence in sparsely populated areas. The table is sorted by state and then by date.

MMI = Modified Mercalli Intensity (I – XII)
M_S = Surface-wave magnitude
m_b = Body-wave magnitude
M_L = Local (Richter) magnitude (Western U.S.)
M_{La} = Local (California) magnitude
M_N = Local and regional magnitude (Eastern U.S.)
Unk = Unknown computational method

Date	Place	State	MMI	Magnitude	Comment
16-Oct-1947	Fairbanks area	AK	VIII	7.2M_S	Extensive infrastructure damage reported.
3-Oct-1954	Kenai Peninsula	AK	VIII	6.5Unk	Damage to buildings and infrastructure.
9-Mar-1957	Andreanof Islands	AK	VIII	8.1M_S	Hawaiian tsunami losses given in Appendix B. Extensive damage also reported in Alaska, including two bridges destroyed, but no loss estimates.
2-Feb-1975	Aleutian Islands	AK	IX	7.4M_S	Severe damage on Shemya Island, home of an Air Force base.
28-Jul-1902	Los Alamos/Santa Barbara County	CA	VIII	5.4M_{La}	Extensive damage from this and a 31-Jul aftershock.
3-Aug-1903	San Jose	CA	VII	5.3M_S	Many buildings damaged severely.
19-Apr-1906	Brawley/Imperial Valley	CA	VIII	6+M_S	Every building in Brawley damaged, minor damage in four other towns.
10-Mar-1922	Cholame Valley/San Luis Obispo County	CA	IX	6.5M_S	Many houses severely damaged along the San Andreas fault.

22-Jan-1923	Humboldt County	CA	VIII	$7.2M_S$	Houses damaged severely in three towns.
29-Jun-1926	Santa Barbara	CA	VII	$5.5M_{La}$	Minor damages reported but one person killed by falling brick.
22-Oct-1926	Coastal Monterey County	CA	VII	$6.1M_S$	Considerable damage in the Monterey Bay region.
6-Jun-1932	West of Eureka, Humboldt County	CA	VIII	$6.4M_S$	"Severe" property damage reported with one fatality and numerous injuries.
14-Dec-1950	Herlong/Lassen County	CA	VII	$5.6M_L$	Considerable structural damage in Herlong.
8-Aug-1989	Redwood Estates/Santa Clara County	CA	VII	$5.4M_L$	One fatality and moderate damage to many structures.
10-Apr-1967	Denver-Boulder area	CO	VI	$4.3M_n$	Minor damage reported, but spread widely throughout metro region.
9-Aug-1967	Denver-Boulder area	CO	VII	$5.3m_b$	Foundation damage on many buildings.
26-Sep-1929	Kona	HI	VII	$5.6M_S$	Houses and infrastructure damaged.
6-Oct-1929	Holualoa	HI	VII	$6.5M_S$	Extensive structural damage to residences and roads.
21-Aug-1951	Napoopoo	HI	VIII	$6.9M_S$	Severe damage to residences, churches, schools and infrastructure.
3-Oct-1915	Pleasant Valley	NV	X	$7.7M_S$	Severe damage throughout a sparsely populated region.
21-Dec-1932	Cedar Mountain	NV		$4.6M_X$	Very strong earthquake in a then-sparsely populated area.
6-Jul-1954	Fallon-Stillwater	NV	IX	$6.8M_L$	Severe damage in Fallon, otherwise area sparsely populated at the time.
16-Dec-1954	Dixie Valley-Fairview Peak	NV	X	$7.2M_L$	Major earthquake in a sparsely populated area.
12-Jul-1906	Socorro area	NM	VII		Extensive, severe damage to business district. Aftershocks of 16-Jul and 15-Nov added to the damage.
12-Aug-1929	Attica/Wyoming County	NY	VIII	$5.2M_N$	Extensive building damage and some infrastructure damage.
16-Aug-1931	Valentine/Jeff Davis County	TX	VIII	$5.8M_N$	All buildings in Valentine except wood-frame houses severely damaged.
12-Mar-1934	Kosmo/Box Elder County	UT	VIII	$6.6M_S$	Sparsely populated area; killed two.