

NOTES AND CORRESPONDENCE

Normalized Damage from Major Tornadoes in the United States: 1890–1999

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ABSTRACT

Historical records of damage from major tornadoes in the United States are taken and adjusted for inflation and wealth. Such adjustments provide a more reliable method to compare losses over time in the context of significant societal change. From 1890 to 1999, the costliest tornado on the record, adjusted for inflation, is the 3 May 1999 Oklahoma City tornado, with an adjusted \$963 million in damage (constant 1997 dollars). Including an adjustment for growth in wealth, on the other hand, clearly shows the 27 May 1896 Saint Louis–East Saint Louis tornado to be the costliest on record. An extremely conservative adjustment for the 1896 tornado gives a value of \$2.2 billion. A more realistic adjustment yields a figure of \$2.9 billion. A comparison of the ratio of deaths to wealth-adjusted damage shows a clear break in 1953, at the beginning of the watch/warning/awareness program of the National Weather Service.

1. Introduction

Economic damage from tornadoes will tend to increase with time, in general, for at least three reasons. First, inflation means that prices of goods increase; second, except for periods of recession or depression, people and institutions have tended to acquire more wealth through time (Katz and Herman 1997); and third, population increases. Pielke and Landsea (1998) adjusted historical hurricane damage for inflation and wealth by considering the population in the counties affected by hurricane landfall. For the tornado problem, including population information is problematic. Although a typical county is small compared to the size of a land-falling hurricane, only a small part of most counties is directly affected by even the largest tornadoes. As a result, inclusion of population in adjusting for tornado damage would properly be on a finer scale for the tornado problem. Given the difficulties of obtaining sufficiently accurate and precise tornado track and population information, we have chosen not to use population directly in the analysis that follows. Instead, we will consider simple methods to adjust for inflation and for wealth. The wealth measure does include the effects of population growth at a national level. However, given the variability of population demographics at the scale of tornado damage, this should be considered only a rough approximation of the effects of population changes on the normalized values.

In addition, another fundamental difference between the hurricane and tornado damage problems comes in the completeness of the record. Since land-falling hurricanes are much rarer than tornadoes, the record of hurricane damage is likely to be much more complete than for tornadoes. In addition, the change in time of tornado reports is much larger than that of hurricanes, with the annual number of tornado reports increasing by about an order of magnitude in the last century (Grzulis 1993). As a result, we have focused our attention on a small subset of U.S. tornadoes, those that are the most damaging. Even though we will not be able to address any issues of changes in overall tornado damage, we will be able to address any changes in the most damaging events.

For inflation, the consumer price index (CPI) provides a useful measure. It expresses the cost of goods relative to some fixed point in time (BLS 1997). In general, the CPI has been increasing since the late nineteenth century¹ (Fig. 1). The CPI is roughly 20 times higher than it was a century ago. We can estimate the damage in constant dollars for all events by adjusting the damage by the change in CPI between the year of the tornado and the benchmark year. The year 1997 was chosen as the benchmark year since that is the last year for which we have wealth information, although the choice is arbitrary. We note that Pielke and Landsea (1998) used the implicit gross domestic product (GDP) price deflator as their measure of inflation. In general, the GDP de-

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¹ Data for the CPI back to 1800 are available online at <http://www.lib.umich.edu/libhome/Documents.center/historiccpi.html>.

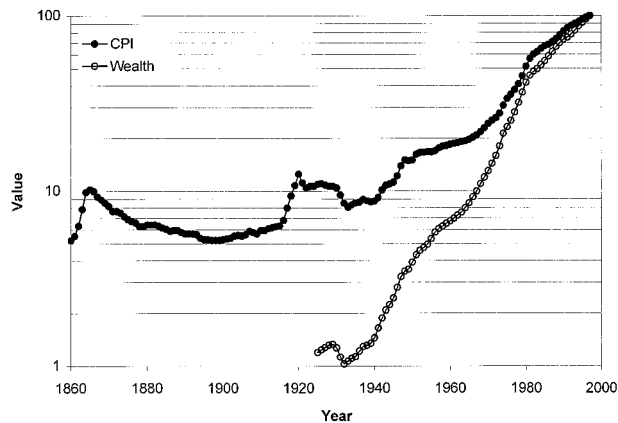


FIG. 1. CPI (solid circles) from 1860 to 1997 and fixed reproducible tangible wealth (wealth) (open circles) from 1925 to 1997 in the United States (1997 index value = 100). Logarithmic scale.

flator provides a slightly lower estimate of the rate of inflation, particularly since 1980. It has the disadvantage of having a shorter period of record, with estimates going back only to 1940. As will become clear, we are interested in a number of events prior to 1940 and, although it would be possible to make an estimate of the GDP deflator prior to then by using its more recent relationship to CPI, we would like to avoid speculating about the GDP–CPI relationship prior to 1940. In general, the change caused by adjusting for GDP, instead of CPI, would be 10%–15% for events prior to 1980.

A measure of national wealth is the “fixed reproducible tangible wealth” (Katz and Herman 1997) (hereafter simply referred to as wealth). Data for this for the period 1925–97 are available from the Bureau of Economic Analysis (BEA 1998). It reached the \$25 trillion mark in 1997. Compared to inflation, wealth has been increasing much more rapidly since 1925 (Fig. 1). Adjusted for inflation, the per capita wealth of the United States has increased by a factor of 4 since 1925, according to this measure. The year 1997 was chosen as the benchmark year for both CPI and wealth since that is the last year for which the wealth data are available, although the choice is again arbitrary.

Our estimates of tornado damage up through 1995 come from Hoffman (1902) and Grazulis (1993, T. P. Grazulis 1998, personal communication). The 1999 Oklahoma City tornado is included with a \$1 billion damage estimate, based on press reports after the fact. We have listed 138 tornadoes dating back to the 1890 Louisville tornado (Table 1).² The tornadoes on the list either killed at least 20 people or had an inflation-adjusted damage total of at least \$50 million in 1997 dol-

lars, or both. The death toll restriction includes the 100 largest death tolls since 1890 and the damage restriction adds in a number of other major events with the hope that no very large events have been left out.

Based on records from the Storm Prediction Center severe weather database, the tornadoes in the list produced slightly over half of the total tornado damage in the period 1950–95. Adjusted for inflation, the total damage from all tornadoes in the period was about \$19.3 billion, or a mean annual amount of \$420 million. The major tornadoes during that period in the list here accounted for \$10.2 billion, or a mean annual amount of \$220 million. These values need to be viewed with some caution, because the quality of damage estimates from individual tornadoes is variable and annual tornado damage is highly skewed. Emphasizing this latter point, the median annual damage is only \$290 million and a quarter of the total damage during that 46-yr period occurred in four years (1953, 1965, 1974, and 1980).

2. Inflation-adjusted damage

Adjusting only for inflation, the most damaging tornado in the record was the Oklahoma City tornado of 3 May 1999, with damage in 1997 dollars of almost \$1 billion (Table 2). The title of “most-damaging tornado in U.S. history” has changed often since 1966, when the Topeka tornado surpassed the 1896 Saint Louis tornado. Since then, tornadoes in 1970, 1975, 1979, and 1999 have taken the place of Topeka as the most expensive when adjusted for inflation. Therefore, the top 30 events are dominated by the latter part of the 1900s, with 15 occurring in 1970 or later. Only two, the Saint Louis tornadoes (1896, including the damage path in East Saint Louis, and 1927) occurred prior to 1930. Since there is no reason to believe that the meteorological aspects of tornadoes have changed, this bias toward recent times is a result of changes in what is being destroyed, just as with hurricanes (Pielke and Landsea 1997).

3. Wealth-adjusted damage

Adjustment for wealth can be made during the 1925–97 period in a similar manner to the inflation adjustment. Outside of this period, we must make some assumptions about the nature of the change of wealth.³ The most conservative method is to assume that the changes in wealth can be modeled by inflation. In other words, we can assume no additional goods are accumulated. This is equivalent to assuming that the gap between the CPI and wealth curves (Fig. 1) stays constant.

A method that is less conservative, but still requires

² The most notable tornado, in terms of property damage, prior to the 1890 tornado (estimated at \$3 million) is the 1840 Natchez tornado (estimated at \$1.3 million). The additional challenges of going even farther into the past had led us to decide to start with the 1890 tornado.

³ Thirty-six tornadoes are in record from 1890 to 1924 and two tornadoes are after 1997.

TABLE 1. Tornadoes in dataset. Location is the city or area most affected by the tornado. Dead is number killed and damage is unadjusted damage at time of tornado in millions of dollars.

Date	Location	Dead	Damage
27 Mar 1890	Louisville, KY	76	3
25 Apr 1893	Moore, OK	31	0.02
6 Jul 1893	Pomeroy, IA	71	0.4
15 May 1896	Sherman, TX	73	0.2
25 May 1896	Central MI	47	0.3
27 May 1896	St. Louis, MO–E. St. Louis, IL	255	12
11 Jan 1898	Fort Smith, AR	55	2
27 Apr 1899	Kirksville, MO	34	0.2
12 Jun 1899	New Richmond, WI	117	0.3
20 Nov 1900	Northwest MS	30	0.2
18 May 1902	Goliad, TX	114	0.2
1 Jun 1903	Gainesville, GA	98	1
22 Jan 1904	Moundville, AL	36	0.1
8 May 1905	Marquette, KS	34	0.1
10 May 1905	Snyder, OK	97	0.3
24 Apr 1908	LA–MS (family)	143	0.5
24 Apr 1908	LA–MS (family)	91	0.5
24 Apr 1908	Birmingham, AL	35	0.5
13 May 1908	Gilliam, LA	49	0.1
8 Mar 1909	Brinkley, AR	49	0.6
29 Apr 1909	Rural MS	29	0.1
29 Apr 1909	Rural TN	29	0.1
30 May 1909	Zephyr, TX	34	0.1
23 Mar 1913	Omaha, NE	103	5
23 Mar 1917	New Albany, IN	46	1.5
26 May 1917	Mattoon, IL	101	2
27 May 1917	TN–KY	67	1
21 Aug 1918	Tyler, MN	36	2
22 Jun 1919	Fergus Falls, MN	57	3.5
20 Apr 1920	MS–AL (family)	88	2
20 Apr 1920	Meridian, MS	36	0.2
2 May 1920	Peggs, OK	71	0.2
10 Feb 1921	Gardner, LA	31	0.1
15 Apr 1921	TX–AR	59	2
30 Apr 1924	Rural SC	53	1
28 Jun 1924	Lorain–Sandusky, OH	85	12
18 Mar 1925	Tri-State (MO–IL–IN)	695	16
18 Mar 1925	South–central KY	39	0.2
12 Apr 1927	Rock Springs, TX	74	1.2
9 May 1927	Poplar Bluff, AR	98	2.1
29 Sep 1927	St. Louis, MO	79	22
25 Apr 1929	Statesboro, GA	40	0.9
6 May 1930	Frost, TX	41	1
6 May 1930	Karnes County, TX	36	0.1
21 Mar 1932	Central AL	49	0.3
21 Mar 1932	Sylacuaga, AL	41	1.5
21 Mar 1932	Northeast AL	38	0.8
21 Mar 1932	Northport, AL	37	0.5
21 Mar 1932	Central AL	31	0.2
31 Mar 1933	Jones/Jasper Counties, MS	37	0.3
9 May 1933	Tompkinsville, KY	36	0.2
10 May 1933	Livingston, TN	35	0.1
5 Apr 1936	Tupelo, MS	216	3
6 Apr 1936	Gainesville, GA	203	13
16 Mar 1942	Central MS	63	0.6
27 Apr 1942	Pryor, OK	52	2.5
12 Jun 1942	Oklahoma City, OK	35	0.5
29 Oct 1942	Berryville, AR	29	0.5
23 Jun 1944	Central WV	100	6
23 Jun 1944	Southwestern PA	30	15
12 Apr 1945	Antlers, OK	69	1.5
9 Apr 1947	Woodward, OK	181	8
1 Jun 1947	Pine Bluff, AR	35	0.8
19 Mar 1948	Bunker Hill, IL	33	3.6
3 Jan 1949	Warren, AR	55	1.3
21 Mar 1952	Judsonia, AR	50	3.5
21 Mar 1952	Cotton Plant, AR	40	0.7
21 Mar 1952	Henderson, TN	38	3

TABLE 1. (Continued)

Date	Location	Dead	Damage
30 Apr 1953	Warner Robins, GA	19	15
11 May 1953	Waco, TX	114	41
8 Jun 1953	Flint, MI	115	19
9 Jun 1953	Worcester, MA	94	52
5 Dec 1953	Vicksburg, MS	38	25
25 May 1955	Blackwell, OK	20	8
3 Apr 1956	Grand Rapids, MI	18	10
20 May 1957	Ruskin Heights, MO	44	40
20 Jun 1957	Fargo, ND	10	15
10 Feb 1959	St. Louis, MO	21	10
3 Apr 1964	Wichita Falls, TX	7	15
11 Apr 1965	Branch County, MI	44	35
11 Apr 1965	Kokomo, IN	25	20
11 Apr 1965	Toledo, OH	18	25
11 Apr 1965	Grand Rapids, MI	5	15
11 Apr 1965	Dunlap, IN	36	10
6 May 1965	Minneapolis, MN	3	15
6 May 1965	Fridley, MN	1	12
3 Mar 1966	Jackson, MS	57	18
4 Apr 1966	Polk County, FL	11	30
8 Jun 1966	Topeka, KS	16	100
14 Oct 1966	Belmond, IA	6	12
24 Jan 1967	St. Louis County, MO	3	15
21 Apr 1967	Oak Lawn, IL	33	30
21 Apr 1967	Belvidere, IL	24	22
23 Apr 1968	Falmouth, KY-Ripley, OH	6	30
15 May 1968	Charles City, IA	13	30
15 May 1968	Oelwein, IA	5	21
15 May 1968	Jonesboro, AR	35	5
23 Jan 1969	Hazelhurst, MS	32	3
9 Aug 1969	Cincinnati, OH	4	15
11 May 1970	Lubbock, TX	28	135
21 Feb 1971	Rural MS	46	8
31 Mar 1973	Conyers, GA	1	89
31 Mar 1973	Athens, GA	2	24
3 Apr 1974	Xenia, OH	34	100
3 Apr 1974	Guin, AL (1)	30	30
3 Apr 1974	Monticello, IN	19	50
3 Apr 1974	Brandenburg, KY	31	15
3 Apr 1974	Northern AL	28	17
3 Apr 1974	Madison, IN	11	35
3 Apr 1974	Guin, AL (2)	30	15
24 Mar 1975	Atlanta, GA	3	56
6 May 1975	Omaha, NE	3	250
23 Jul 1975	Canton, IL	2	20
4 May 1978	Clearwater, FL	3	43
3 Dec 1978	Bossier City, LA	2	100
10 Apr 1979	Wichita Falls, TX	45	400
10 Apr 1979	Vernon, TX	11	27
3 Oct 1979	Windsor Locks, CT	3	200
13 May 1980	Kalamazoo, MI	5	50
3 Jun 1980	Grand Island, NE	4	140
2 Apr 1982	Paris, TX	10	50
29 May 1982	Marion, IL	10	100
7 Jun 1984	Barneveld, WI	9	40
31 May 1985	Niles, OH-Wheatland, PA	18	100
5 Feb 1986	Harris Co., TX	2	80
22 May 1987	Saragosa, TX	30	1.3
28 Nov 1988	Raleigh, NC	4	77
15 Nov 1989	Huntsville, AL	21	100
28 Aug 1990	Plainfield, IL	29	165
26 Apr 1991	Wichita-Andover, KS	17	60
24 Apr 1993	Tulsa-Catoosa, OK	7	100
6 Aug 1993	Petersburg, VA	4	47
27 Mar 1994	Piedmont, AL	22	50
25 Apr 1994	Lancaster, TX	3	50
7 May 1995	Ardmore, OK	3	100
8 Apr 1998	Birmingham, AL	34	50
3 May 1999	Oklahoma, OK	36	1000

TABLE 2. Thirty most damaging tornadoes in United States (1890–1999) adjusted for inflation. Location is the city or area most affected by the tornado. “Raw” is the raw damage amount in dollars and “adjusted” is the amount adjusted to 1997 dollars. A letter T indicates tie in rank.

Rank	Date	Location	Raw	Adjusted
1	3 May 1999	Oklahoma City, OK	1000	963
2	10 Apr 1979	Wichita Falls, TX	400	884
3	6 May 1975	Omaha, NE	250	745
4	11 May 1970	Lubbock, TX	135	558
5	8 Jun 1966	Topeka, KS	100	494
6	3 Oct 1979	Windsor Locks, CT	200	442
7	27, May 1896	St. Louis, MO–E. St. Louis, IL	12	380
8	3 Apr 1974	Xenia, OH	100	325
9	31 Mar 1973	Conyers, GA	89	321
10	9 Jun 1953	Worcester, MA	52	311
11	3 Jun 1980	Grand Island, NE	140	273
T12	11 May 1953	Waco, TX	41	246
T12	3 Dec 1978	Bossier City, LA	100	246
14	20 May 1957	Ruskin Heights, MO	40	228
T15	29 Sep 1927	St. Louis, MO	22	203
T15	28 Aug 1990	Plainfield, IL	165	203
17	11 Apr 1965	Branch County, MI	35	178
18	24 Mar 1975	Atlanta, GA	56	167
19	29 May 1982	Marion, IL	100	166
20	3 Apr 1974	Monticello, IN	50	163
T21	18 Mar 1925	Tri-State (MO–IL–IN)	16	151
T21	6 Apr 1936	Gainesville, GA	13	151
23	5 Dec 1953	Vicksburg, MS	25	150
24	31 May 1985	Niles, OH–Wheatland, PA	100	149
25	4 Apr 1966	Polk County, FL	30	148
26	21 Apr 1967	Oak Lawn, IL	30	144
T27	23 Apr 1968	Falmouth, KY–Ripley, OH	30	138
T27	15 May 1968	Charles City, IA	30	138
29	23 Jun 1944	southwestern PA	15	137
30	15 Nov 1989	Huntsville, AL	100	129

few assumptions, for the pre-1925 period is to assume that the rate of increase in wealth followed the gross national product (GNP)⁴ (Fig. 2). After 1997, with only the Oklahoma City tornado to consider, we have extrapolated from 1997’s wealth values by assuming that the increase in wealth in 1998 and 1999 was the same as the average increase from 1990 to 1997, a period when the annual rate of increase was relatively consistent at a rate of 4.9%.

The 3 May 1999 Oklahoma City tornado, the most damaging when values are adjusted for inflation, is the 11th most damaging tornado in the record for wealth adjustment (Table 3), with an estimated damage of \$909 million. (Recall that changes that result only from inflation gives a value for this event of \$963 million, still in 11th place within the rankings adjusted for wealth.) Just above this, there is a tight grouping of wealth-

adjusted damage values around \$1.1 billion for the 4th–10th highest damage tornadoes, with a range of \$60 million. The Lorain–Sandusky, Ohio, tornado of 1924 has a wealth-adjusted damage of \$1.0–\$1.1 billion, depending on the assumptions made, placing it 10th on the list. Standing out above that tight group of tornadoes is the third-rated tornado, the 1925 Tri-State tornado, with an adjusted damage of \$1.4 billion, about 20% higher than the “pack.”

There are five tornadoes earlier than Lorain–Sandusky in the top 30 for which we have had to estimate the

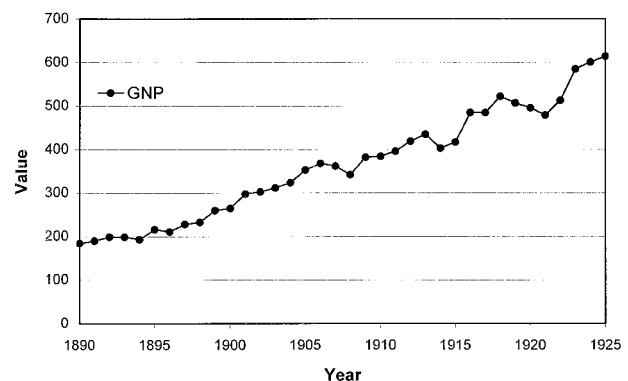


FIG. 2. GNP in billions of dollars from 1890 to 1925.

⁴ GNP is used here instead of GDP because of the longer historical record. GDP, which is now the accepted measure of the size of the U.S. economy in keeping with standard international usage, is the market value of all goods and services produced in a country during a year regardless of who owns the production and GNP is the market value of all goods and services produced by residents of a country, regardless of what country they are produced in. Typically, differences in the two measures are less than 1% (Office of the President 2000).

TABLE 3. Thirty most damaging tornadoes in United States (1890–1999) adjusted for wealth. Italicized events occurred outside the range of the wealth data. First value under “adjusted” assumes that all wealth changes before 1925 can be modeled using changes in the gross national product and after 1997 can be modeled using the rate of increase from 1990 to 1997. The parenthetical value models wealth changes by assuming that all wealth changes before 1925 and after 1997 can be modeled just with inflation.

Rank	Date	Location	Raw	Adjusted
1	<i>27 May 1896</i>	<i>St. Louis, MO–E. St. Louis, IL</i>	12	2916 (2167)
2	29 Sep 1927	St. Louis, MO	22	1797
3	18 Mar 1925	Tri-State (MO–IL–IN)	16	1392
4	10 Apr 1979	Wichita Falls, TX	400	1141
5	9 Jun 1953	Worcester, MA	52	1140
6	6 May 1975	Omaha, NE	250	1127
7	8 Jun 1966	Topeka, KS	100	1126
8	6 Apr 1936	Gainesville, GA	13	1111
9	11 May 1970	Lubbock, TX	135	1081
10	<i>28 Jun 1924</i>	<i>Lorain–Sandusky, OH</i>	12	1023 (1071)
11	<i>3 May 1999</i>	<i>Oklahoma City, OK</i>	1000	909 (963)
12	11 May 1953	Waco, TX	41	899
13	<i>27 Mar 1890</i>	<i>Louisville, KY</i>	3	836 (586)
14	23 Jun 1944	Southwestern PA	15	697
15	20 May 1957	Ruskin Heights, MO	40	685
16	<i>23 Mar 1913</i>	<i>Omaha, NE</i>	5	589 (769)
17	3 Oct 1979	Windsor Locks, CT	200	570
18	5 Dec 1953	Vicksburg, MS	25	548
19	31 Mar 1973	Conyers, GA	89	515
20	3 Apr 1974	Xenia, OH	100	491
21	<i>11 Jan 1898</i>	<i>Fort Smith, AR</i>	2	440 (349)
22	11 Apr 1965	Branch County, MI	35	410
23	8 Jun 1953	Flint, MI	19	400
24	<i>22 Jun 1919</i>	<i>Fergus Falls, MN</i>	4	354 (296)
25	3 Jun 1980	Grand Island, NE	140	337
26	4 Apr 1966	Polk County, FL	30	324
27	30 Apr 1953	Warner Robins, GA	15	316
28	3 Dec 1978	Bossier City, LA	100	314
29	21 Apr 1967	Oak Lawn, IL	30	301
30	11 Apr 1965	Toledo, OH	25	293

adjustment. Obviously, the earlier we look, the larger the range of values. The GNP adjustment yields a value of \$589 million for the 1913 Omaha tornado and \$836 million for the 1890 Louisville tornado. The GNP and inflation adjustments place the tornadoes between 13th and 16th on the list. Lower on the lists are the 1898 Fort Smith, Arkansas, and 1919 Fergus Falls, Minnesota, tornadoes. There is little doubt as to where the other tornado, the 1896 Saint Louis–East Saint Louis tornado, falls on the list. The GNP adjustment gives a value of \$2.9 billion. Even the most conservative adjustment, inflation only, estimates the damage as \$2.2 billion, still 20% more than the second most damaging tornado, the 1927 Saint Louis tornado, which is adjusted to \$1.8 billion.

The wealth adjustment produces a list that is more evenly distributed through time than the inflation adjustment did. Seven of the top 30 events occurred from 1970 to 1999, and eight occurred before 1930. The three highest estimates are all associated with tornadoes prior to 1930. One of these, the Tri-State tornado, is the biggest killer tornado in U.S. history and was a very long-track event with a reported path length of over 200 mi. The other two both involve long-track, violent tornadoes going through the downtown and industrial area of a large city, Saint Louis. Thus, the resulting wealth-ad-

justed rankings seem plausible, with the benefit of not implying a secular change in damage production since 1970.

4. Relationship of damage and death tolls

Since there is little that can be done to reduce property damage from tornadoes after a warning has been issued, we might expect that some value of normalized tornado damage would be relatively constant over time, but that warnings and public awareness might have an effect on death tolls. As a result, it is plausible that the ratio of deaths to adjusted damage would be lower with good warnings and public awareness. Doswell et al. (1999) showed a long-term decline in the number of deaths per inflation-adjusted damage (Fig. 3). The slope of the decline is a feature of interest. An equivalent analysis using wealth adjustment still shows a break in 1953, but the slope in the two periods is almost zero (Fig. 4). Given the noise in the data, there is not likely to be much meaning that can be associated with the slope after wealth adjustment. The difference in the values in the two eras (pre- and post-1953) is statistically significant at a 99.99% confidence level, using a Mann–Whitney test (Wilks 1995). This date corresponds to the be-

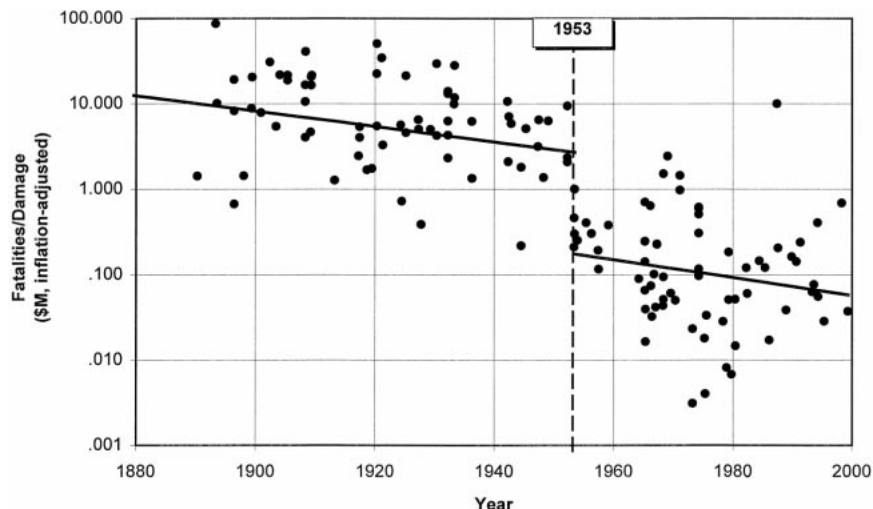


FIG. 3. Fatalities per million dollars damage (adjusted for inflation to 1997) for each of the major tornadoes since 1880, on log scale. Solid lines represent least squares fit to data before and after 1953, indicated by dashed line. [Adapted from Doswell et al. (1999).]

ginning of the watch/warning/awareness program of the National Weather Service (Doswell et al. 1999).

The interpretation of the small slope in Fig. 4, even if it has real meaning, is unclear. It implies that the long-term decline seen in Fig. 3 is due mostly to the accumulation of goods. From that perspective, the slope in Fig. 3 corresponds to an approximation to a wealth adjustment; that is, inflation-adjustment with the slope removed equals wealth. We caution against interpreting the slope as having any relevance to questions involving changes in warning performance or public response. The scatter around the lines and the background change in wealth means that a zero slope does not imply a lack of improvement in the quality or value of watches and warnings.

5. Discussion

Comparing the amount of dollar damage between tornadoes of different eras without adjusting for the fact that values of property increase through time leads to a kind of “temporal myopia” that emphasizes only the most recent events. We have applied two different methods to adjust for era to begin to address the problem. The first involves adjusting for inflation. This still retains considerable bias toward the modern era, but starts to address the myopia.

A method that more completely adjusts for differences in era is to adjust for wealth. One result of this is that roughly the same number of high-damage tornadoes is found from 1970 to 1999 and prior to 1930.

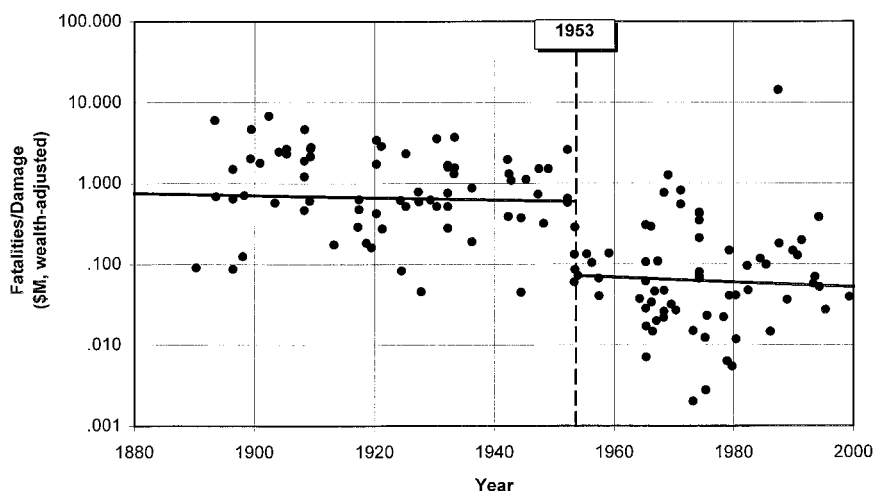


FIG. 4. Same as Fig. 3 except adjusted for wealth.

This is an encouraging result, in that it provides a baseline for the testing of catastrophe models that seek to estimate the likelihood of extreme events (Pielke et al. 1999). We have not considered the effects of changing population. The uncertainties associated with such effects could be very large. In order to deal with them, detailed tracks and population maps would be needed. Given that those details are lacking, we have left the population question unconsidered.

Using wealth and inflation adjustment, it seems clear that the most damaging tornado in U.S. history was the 1896 Saint Louis–East Saint Louis tornado, which produced damage equivalent to \$2.9 billion in modern terms. This is in the range of the 30th most damaging hurricane in the Pielke and Landsea (1998) study. One way to understand this value is in comparison to the total wealth of the United States. The 1896 tornado destroyed approximately 1/7000 of the total wealth of the nation. One change that has taken place in American society since that time is the “nationalization” of disaster recovery. Recovery efforts were primarily local in 1896, representing a huge burden for the local economies. Similarly, in the modern world, an event of this magnitude in a small or third world nation could have devastating effects in the absence of outside assistance.

We find nothing to suggest that damage from individual tornadoes has increased through time, except as a result of the increasing cost of goods and accumulation of wealth of the United States. Long-track, violent tornadoes through the heart of major cities are extremely rare events. Two of them, the 1896 and 1927 tornadoes that struck Saint Louis, stand out as the most damaging tornadoes in the U.S. record, with damages in modern terms of \$2.9 and \$1.8 billion, respectively. For comparison, the 1999 Oklahoma City tornado, which went primarily through residential areas but spent a significant portion of its path in open country, produced damage of about \$0.9 billion.

The Saint Louis events provide a historical analog to possible events in modern times. Equivalent tornadoes in a major city today could produce damage that would dwarf anything that has occurred since 1930. The recovery from the Oklahoma City tornado gives a small hint as to the challenges that a similar tornado would create. The fact that such an event has not occurred since 1927 is not likely to be evidence of any changes in meteorology, but simply reflects the small area that such vulnerable parts of cities cover. The question is not *if* a long-track violent tornado through the heart of the residential and industrial portion of a major metropolitan area will occur, but *when*. Given urban sprawl, such an event is more likely now than in the past. It seems prudent for local governmental agencies, especially in tornado-prone regions, to estimate their vulnerability to a long-track violent tornado. The North Texas Council of Governments, including the Dallas–Fort Worth area, has recently undertaken such an exercise (NTCOG 2000). They used the 3 May 1999 out-

break as a model and put the tornado tracks down on the Dallas–Fort Worth area. Engineers and economists then estimated the damage that would occur if the 3 May 1999 outbreak occurred in the Dallas–Fort Worth area. By moving the tornado tracks around, they were able to come up with a range of damage from both the individual tornadoes and from the outbreak. The maximum damage from a single tornado in this exercise was over \$3 billion.

Finally, we speculate that the presence of the pack of tornadoes with wealth-adjusted damage of around \$1 billion may be indicative of what happens when a violent tornado strikes the heart of a moderate-size community (e.g., the 1979 Wichita Falls, TX, or the 1924 Lorain and Sandusky, OH, tornadoes) or hits the suburbs of a larger city (e.g., the 1999 Oklahoma City tornado). Devastating events with damages on the order of \$1 billion or larger have occurred about once per decade in the United States. During that period, gaps of 20 years between successive events have occurred, as well as clusters of events in much shorter time, as would be expected from any random distribution of events. A major challenge to preparedness and recovery is maintaining a level of readiness during the gaps. Catastrophic events pose significant threats to the insurance and reinsurance industries (Keller 2000). Thus, accurate estimates of the threat are important for long-term planning both in the private and public sectors.

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