Weathering the Extremes

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1. Introduction

At a speech to the United Nations in 2019, Greta Thunberg declaimed:

> "You have stolen my dreams and my childhood with your empty words. And yet I'm one of the lucky ones. People are suffering. People are dying…."[1]

Ms. Thunberg was not speaking of malnutrition and the diseases of poverty, which continue to ravage hundreds of millions of people around the world.[2] She was speaking of death and suffering caused by climate change. It was an emotive message, delivered with passion and conviction. But was it based on facts? Is manmade climate change causing more people to suffer and die? And, if so, what can be done about it?

This primer offers an overview of the likely effects that climate change has had on the incidence of extreme weather events, ranging from storms and floods to droughts and wildfires, and the extent to which those events have caused harm. In so doing, it addresses many (but not all) of the ways by which climate change might cause suffering and death. To do so, it describes the historical evidence for changes in the frequency and severity of extreme weather events, the mortality associated with such events, and their economic impact. It also discusses ways that humans have adapted to extreme weather events and strategies that will make humanity more resilient in the future.

The primer is organized according to type of extreme weather event, with successive sections focusing on: hurricanes (Section 2), tornadoes (Section 3), inland floods (Section 4), drought

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[1] *Transcript: Greta Thunberg's Speech At The U.N. Climate Action Summit*, National Public Radio, September 23, 2019, Available at: https://www.npr.org/2019/09/23/763452863/transcript-greta-thunbergs-speech-at-the-u-n-climate-action-summit

[2] Matthew M. Coates et al., "Burden of disease among the world's poorest billion people: An expert-informed secondary analysis of Global Burden of Disease estimates." *PLoS ONE 16(8)*, 2021. https://doi.org/10.1371/journal.pone.0253073

(Section 5), wildfires (Section 6), and extreme temperatures (Section 7). Section 8 considers extreme weather events as a whole, both in the US and globally. Each of these sections is organized in a similar fashion, beginning with an assessment of the change in frequency of the type of extreme weather event, followed by an assessment of changes in mortality and economic damage, and a brief discussion. Finally, Section 9 draws conclusions, offering insights regarding adaptive and resilient strategies that have been adopted and could be adopted in the future to reduce the harm resulting from extreme weather events.

1.1 A caveat regarding the data

One caveat is worth raising at the outset: the data is imperfect. Much of the data on the number of extreme weather-related natural disasters, as well as mortality and economic loss associated with such disasters is drawn from the EM-DAT database, which is maintained by the Centre for Research on the Epidemiology of Disasters at the Catholic University of Louvain in Belgium.[3] This is by any standards an excellent database. But it is neither complete nor unbiased. In particular, it suffers from selection bias resulting from its criteria for inclusion, which require that at least one of the following conditions are met:[4]

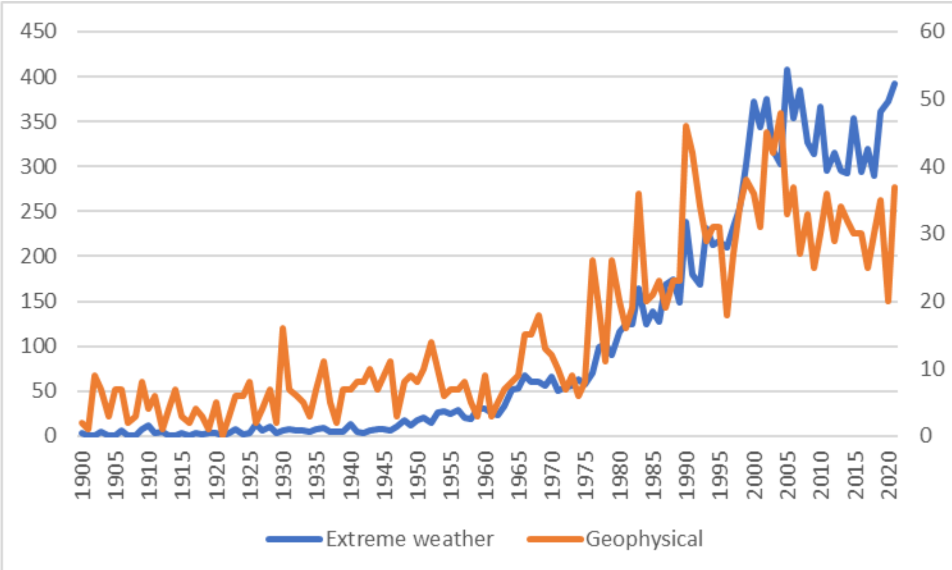
- 10 or more people dead
- 100 or more people affected
- The declaration of a state of emergency
- A call for international assistance.

Given the rapid increase in population density, improvements in communications, and improvements in government responses, many disasters that would not have met the EM-DAT criteria 100 years ago now do meet the criteria. As such, the number of weather-related natural disasters being reported over time very likely would increase even if underlying weather patterns remained unchanged. One way to test this is to compare the number of extreme weather-related natural disasters (climatic, hydrological, and meteorological) with the number of geophysical natural disasters (earthquakes, volcanoes, etc.). Figure 1 shows the number of both types of such disasters reported in EM-DAT from 1900 to 2021. While the absolute number of climate-related disasters has increased at a higher rate, the correlation between the two series is remarkably high

[3] https://www.emdat.be/
[4] *Id.*

($r^2 = 0.79$). Since geophysical disasters clearly are not caused by climate change, it seems likely that much of the documented increase in both is a result of other factors.

Figure 1: Extreme weather (left axis) and Geophysical (right axis) Disasters per year in EM-DAT



Source: EM-DAT

2. Hurricanes (Tropical Cyclones)

A hurricane is a rotating low-pressure weather system that has sustained surface winds of at least 74 mph. Hurricane intensity is categorized from 1 to 5 using the Saffir-Simpson Hurricane Wind Scale.[5] Category 1 and 2 hurricanes (sustained winds of 74 – 110 mph) are considered "minor." Category 3 to 5 hurricanes (sustained winds over 110 mph) are considered "major".

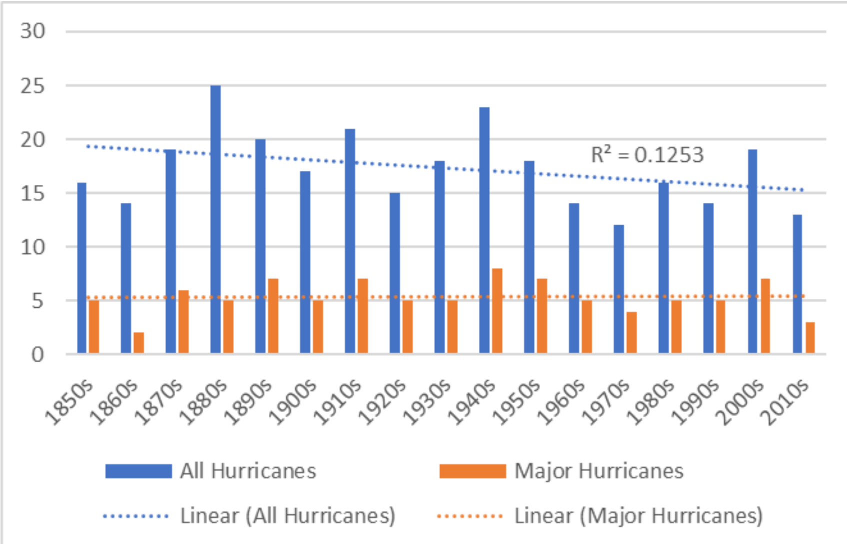
Note that outside the U.S., hurricanes often go by other names, such as typhoons. The more general term for all of these severe storms is tropical cyclones. For convenience, this study uses the term hurricane to refer to all tropical cyclones, except where indicated.

2.1 Hurricane Incidence and Severity

Figure 2.1 shows the number of Atlantic hurricanes that made landfall in the U.S. by decade from the 1850s to the 2010s. For all hurricanes, there is a modest downward trend—but the trend explains only about 12.5% of the variation in the number of hurricanes per decade. For major hurricanes, there is no significant trend ($R^2 = 0.001$).

[5] NOAA, *The Saffir-Simpson Hurricane Wind Scale*, National Oceanographic and Atmospheric Administration, May 2021. https://www.nhc.noaa.gov/pdf/sshws.pdf

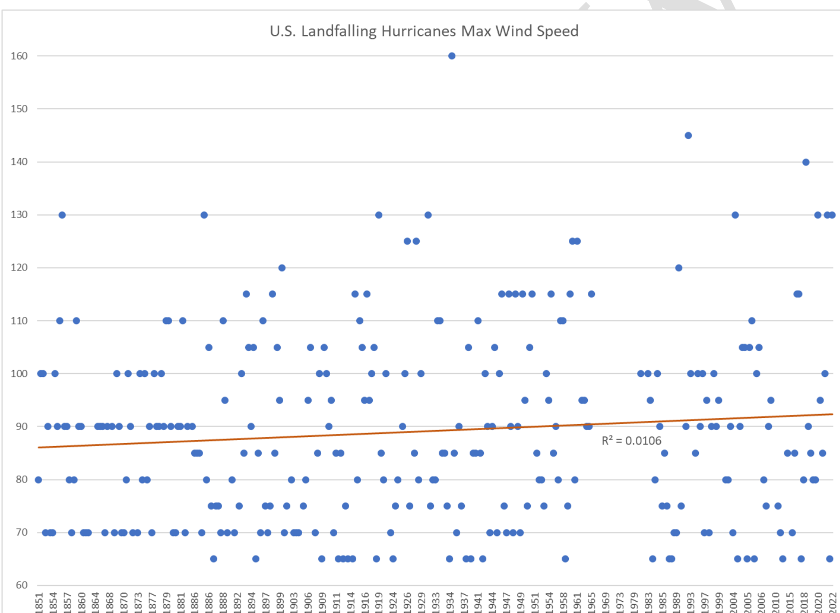
Figure 2.1 Atlantic Hurricanes that Made Landfall in the U.S. by Decade.



Source: NOAA, Continental United States Hurricane Impacts/Landfalls 1851-2019 (https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html)

Figure 2.2 shows the estimated maximum wind speed of all landfalling Atlantic hurricanes from 1851 to 2022. There is no significant trend ($R^2 = 0.01$).

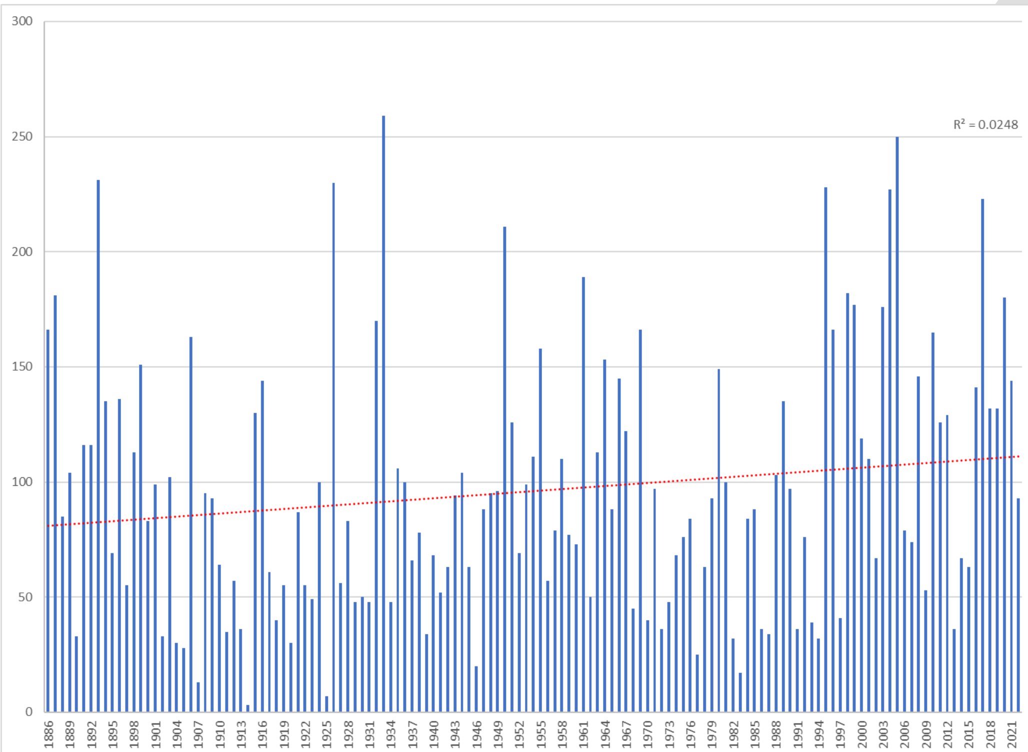
Figure 2.2 Maximum Wind Speed of U.S. Landfalling Hurricanes (Mph), 1851-2022



Source: NOAA, Continental United States Hurricane Impacts/Landfalls 1851-2022, (https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html)

Figure 2.3 shows the accumulated cyclone energy (ACE) of all landfalling hurricanes in the Atlantic Basin by year; ACE is a measure of the destructive potential of a hurricane.[6] There is a small but insignificant upward trend in ACE from 1886 to 2022 ($R^2 = 0.025$).

Figure 2.3 Accumulated Cyclone Energy, Atlantic Basin, All Hurricanes (10^4kn^2)



Source: NOAA (https://www.aoml.noaa.gov/hrd/hurdat/comparison_table.html)

Data on tropical cyclones at a global level is only available from 1970, but even over this shorter period, during which global mean temperatures have been more strongly affected by human emissions of GHGs, there is no discernable trend in tropical cyclone incidence (Figure 2.4).[7] Meanwhile, over the same period there is no discernable trend in ACE at a global level (Figure 2.5). By combining data from Atlantic hurricanes with those from the Western Pacific it is possible to see the pattern of about 70% of the world's hurricanes going back to 1945, which shows a significant downward trend for all hurricanes over the period and no trend for major hurricanes (Figure 2.6).

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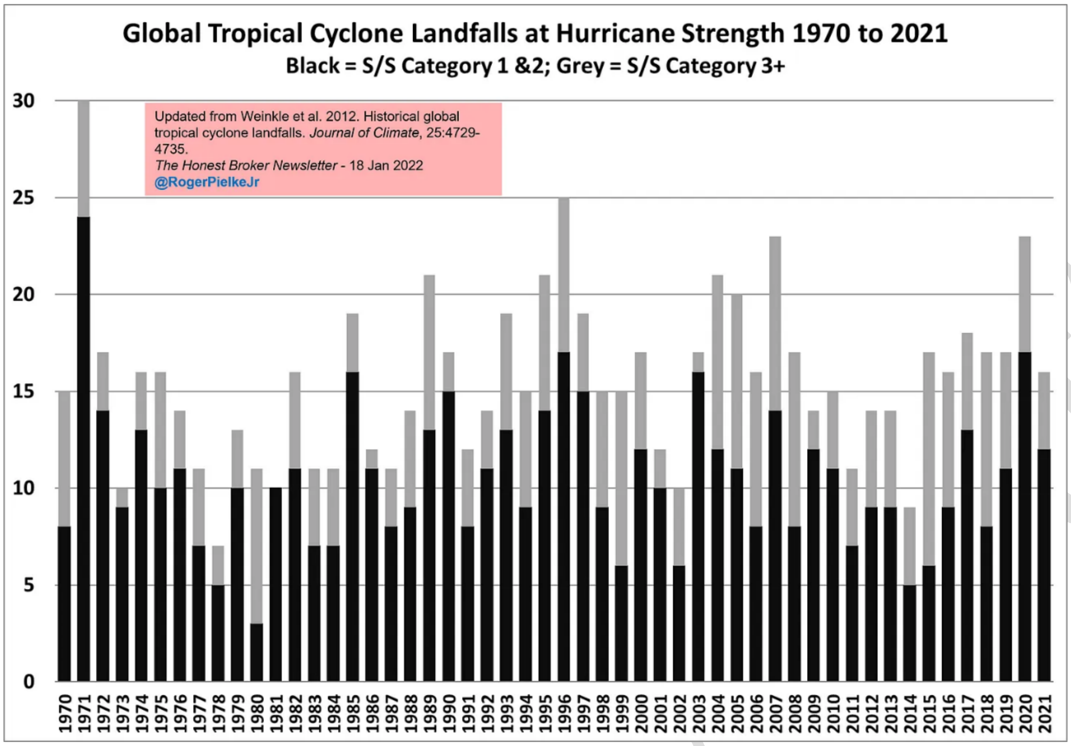
[6] ACE is calculated by taking the sum of the sum of the square of the maximum windspeed in nots and dividing by 10,000, to give a measure of kinetic energy whose units are kilonewtons squared (kn^2). (Left axis of Figure 2.3 is 10^4kn^2)

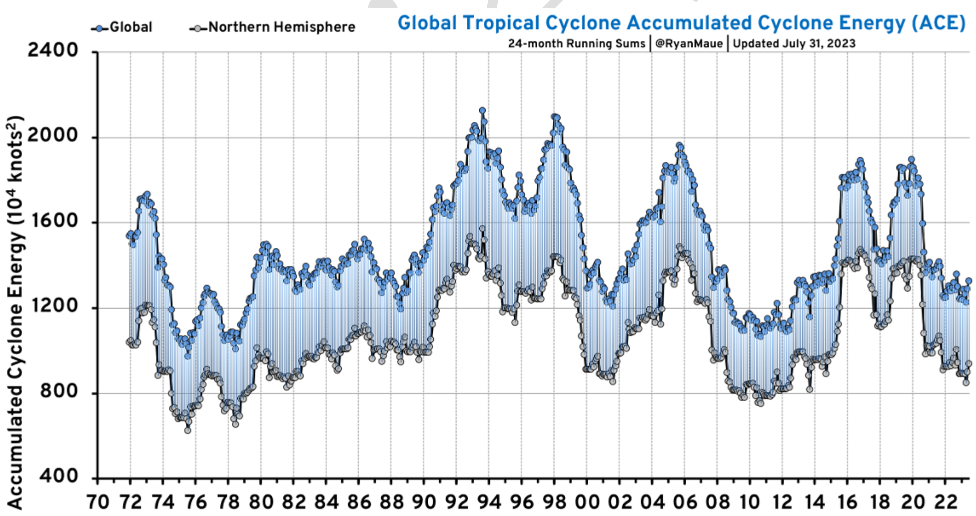
[7] https://open.substack.com/pub/rogerpielkejr/p/global-hurricane-landfalls-1970-to?utm_campaign=post&utm_medium=web

Figure 2.4 Global Incidence of Tropical Cyclones, 1970-2021



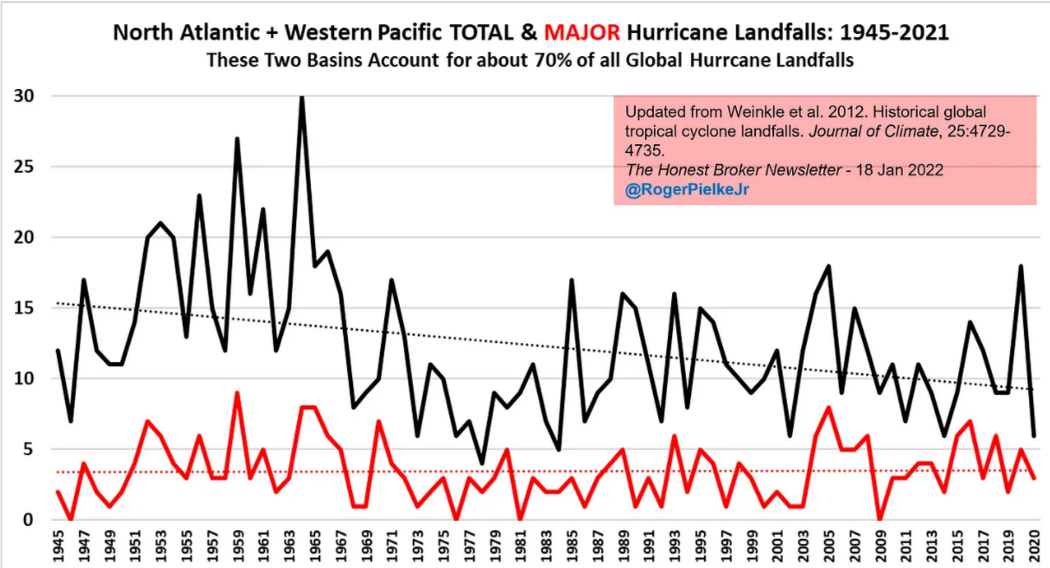
Source: Roger Pielke, Jr: https://open.substack.com/pub/rogerpielkejr/p/global-hurricane-landfalls-1970-to?utm_campaign=post&utm_medium=web

Figure 2.5: Global Tropical Cyclone Accumulated Cyclone Energy, 1970-2022



Source: Ryan Maue: http://climatlas.com/tropical/

Figure 2.6 North Atlantic and Western Pacific Total and Major Hurricanes, 1945-2021



Source: Roger Pielke,, Jr: https://open.substack.com/pub/rogerpielkejr/p/global-hurricane-landfalls-1970-to?utm_campaign=post&utm_medium=web

2.2 Hurricane Damage: Loss of Life

Hurricanes can cause death and destruction on a massive scale. In 2022, hurricane Ian caused an estimated $53 billion in total damage and 148 deaths.[8] The previous year, hurricane Ida caused nearly $40 billion in total damage and 91 deaths.[9] Meanwhile, in 2017, hurricane Maria caused over 3,000 deaths and over $50 billion in damage in Puerto Rico, while hurricanes Harvey, Irma and Maria caused approximately $110 billion in damage in the continental U.S..[10] But with the exception of Hurricane Katrina (2005), the number of lives lost in the continental U.S. has fallen quite dramatically over the past 120 years (Figure 2.7).

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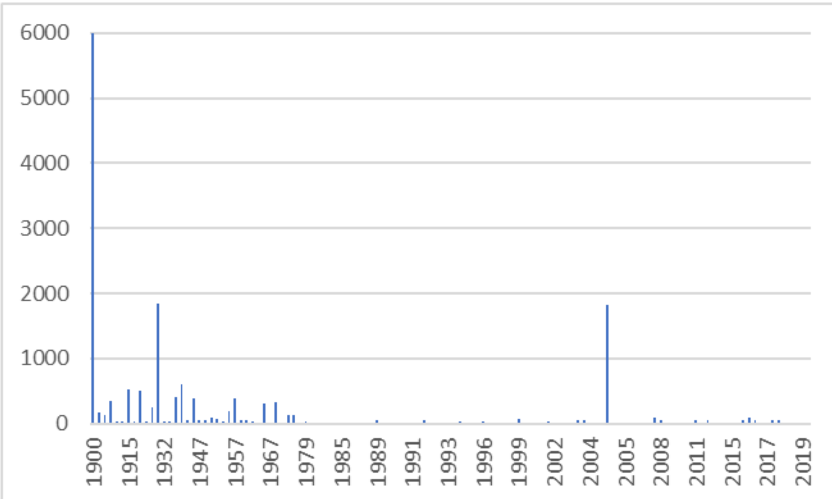
[8] *Facts + Statistics: Hurricanes*: *Top 10 Costliest Hurricanes In The United States* Insurance Information Institutes, no date: https://www.iii.org/fact-statistic/facts-statistics-hurricanes; https://www.nbcnews.com/news/us-news/hurricane-ian-florida-death-toll-rcna54069

[9] Facts + Statistics *supra* note 8; https://www.cdc.gov/mmwr/volumes/70/wr/mm7039a3.htm

[10] (Dollar values have been adjusted for inflation). Facts + Statistics *supra* note 8; Planning Board of Puerto Rico, *Economic Report to the Governor 2017*. Government of Puerto Rico, 2018. http://jp.pr.gov/Portals/0/Economia/Informes%20Econ%C3%B3micos%20al%20Gobernador/Informe%20Econ%C3%B3mico%20al%20Gobernador%20y%20Ap%C3%A9ndice%20Estad%C3%ADstico%202017.%20pdf.pdf?ver=2018-04-09-095004-193

Figure 2.7: Annual Deaths Due to Hurricanes, Continental U.S.,1900-2019



Source: EM-DAT

Taking into account the overall increase in U.S. population and the increase in the proportion of that population living in coastal areas susceptible to hurricane risk, the death rate has fallen even more dramatically. As a proportion of all people living in susceptible coastal counties, the number of deaths per decade has fallen from just over 600 per million in the 1900s to under 50 per million in recent decades (Figure 2.8). Indeed, the average death rate for the period 1980 to 2019 is 93% lower than the average death rate for 1900-1939.

To make a slightly more direct comparison, the deadliest hurricane in U.S. history, the Galveston hurricane of 1900, resulted in between 6,000 and 8,000 deaths.[11] At the time, the population of Galveston was just under 38,000, implying a mortality rate of between 15 and 20 percent. By comparison, the deadliest hurricane of the past half-century in the continental U.S. was Katrina in 2005, which caused over 1,400 deaths, the vast majority of them in Louisiana.[12] Of those, the largest number, 767, occurred in Orleans Parish, which had a population of about 450,000, implying a mortality rate of 0.15%.

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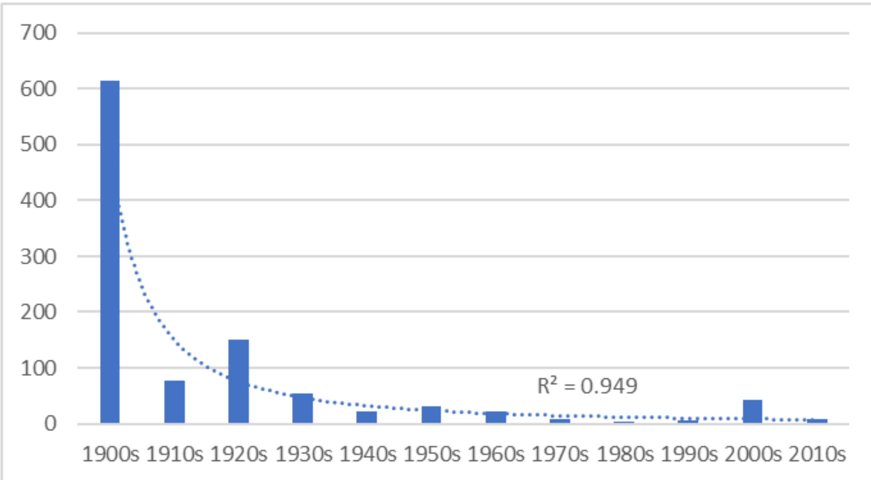
[11] U.S. Census Bureau History: *1900 Galveston Hurricane*, Washington, DC: U.S. Census Bureau, September 2015. https://www.census.gov/history/www/homepage_archive/2015/september_2015.html

[12] The precise total number of deaths varies depending on the source. Initial tallies suggested a total of 1145 in Louisiana and about 250 in other states, as well as up to 500 missing presumed dead. But subsequent analyses reduced the total number of deaths of Louisiana residents to 986 (https://ldh.la.gov/assets/docs/katrina/deceasedreports/KatrinaDeaths_082008.pdf) and the total number of missing to 135 (https://proceedings.esri.com/library/userconf/health06/docs/summary_report.pdf. That would imply a total death toll of around 1,400, rather than the 1,863 given in the EM-DAT dataset and used in the figures in this section.

Figure 2.8: Mortality Rate per Million, Counties in Hurricane Risk Zone, Continental U.S.



Source: EM-DAT, U.S. Census.

At a global level, data is patchier and hence less consistent. Nonetheless, over the past century, the death rate from tropical cyclones globally has fallen somewhat, especially since the 1970s (after which data has become increasingly reliable) (Figure 2.9). Note that Figure 2.8 divides deaths by total global population, rather than people living in coastal areas, which is why it is much lower than the rate for the U.S. Also since coastal populations have been rising disproportionately, the decline shown likely is lower than would be the case for affected populations.[13]

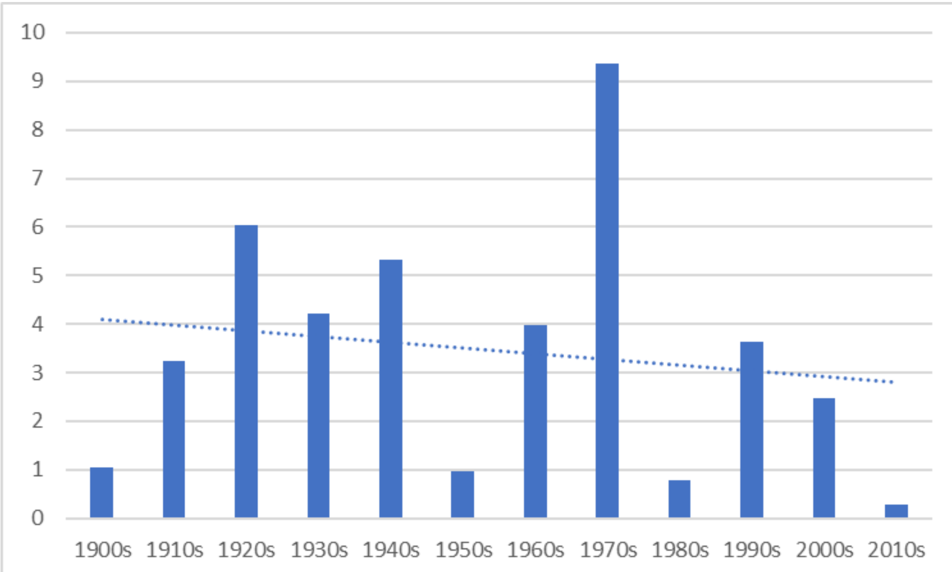
It is also worth noting that in each of the 1970s, 1990s, and 2000s, the death rate is dominated by a single cyclone that caused widespread devastation: Cyclone Bhola of 1971, which killed over 300,000 people, mostly in Bangladesh;[14] Cyclone Gorky of 1990, which killed about 140,000 people, also mostly in Bangladesh; and Cyclone Nargis of 2008, which killed about 140,000 people, mostly in Myanmar. It is also noteworthy that Cyclone Sidr in 2007, which was of a

[13] See also: Laurens M Bouwer and Sebastiaan N Jonkman, "Global mortality from storm surges is decreasing." *Environmental Research Letters* **13**(1), 2018. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aa98a3#erlaa98a3f4

[14] EM-DAT says 300,000; other sources say as many as 500,000. In addition, EM-DAT does not include Typhoon Nina in its list of Cyclones (it is included as a flood event), which is reported to have killed between 100,000 and 230,000 people in China. (Christopher C. Burt, *The Deadliest Weather-Related Catastrophe You Probably Never Heard Of*, Weather Underground, May 30, 2018, https://www.wunderground.com/cat6/deadliest-weather-related-catastrophe-you-probably-never-heard) (In the flood event data, EM-DAT lists only 20,000 deaths from Nina.)

similar magnitude to Bhola and Gorky and affected a similar region, killed fewer than 5,000 people.

Figure 2.9 Average Annual Mortality Rate per Million, Tropical Cyclones, Global



Source: EM-DAT (deaths), OurWorldInData (population)

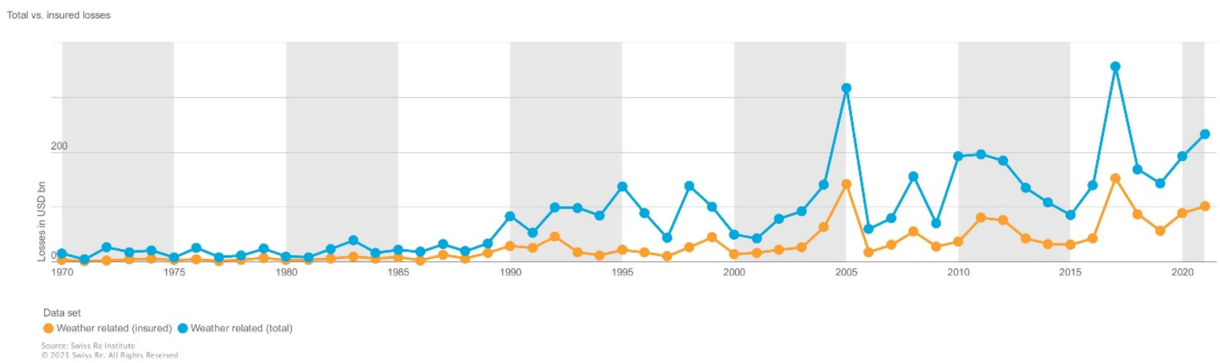
2.3 Hurricane Economic Damage

As noted, the number and severity of hurricanes have not changed significantly and the number of lives lost due to hurricanes has declined dramatically in the U.S. and globally. However, the economic losses caused by hurricanes and other weather-related natural disasters have *increased* dramatically over the past five decades (Figure 2.10).[15]

If the number and severity of hurricanes haven't increased, what is causing the increase in economic damage? The most plausible explanation is the dramatic increase in the value of infrastructure and property located in susceptible coastal areas. This is the conclusion of numerous studies that have sought to estimate "normalized" historic hurricane damage. These studies infer the effects that past hurricanes would have had if current societal conditions, such as population, wealth, and the value of real property, had prevailed when past hurricanes made landfall.

[15] AON, 2021 Weather, Climate and Catastrophe Insight, London: AON plc., 2021. https://www.aon.com/weather-climate-catastrophe/index.html Press Release, *Global insured catastrophe losses rise to USD 112 billion in 2021, the fourth highest on record, Swiss Re Institute estimates*, Zurich: Swiss Re. December 14, 2021. https://www.swissre.com/media/press-release/nr-20211214-sigma-full-year-2021-preliminary-natcat-loss-estimates.html

Figure 2.10 Economic Losses due to Weather-related Natural Disasters ($Billions).



Source: Swiss Re. Institute (https://www.sigma-explorer.com/)

The first such study was undertaken by Prof. Roger Pielke of the University of Colorado and Prof. Chris Landsea of the National Oceanographic and Atmospheric Administration (NOAA). Published in 1998 that study normalized the effects of hurricanes in the continental U.S. and found no evidence of an increase in normalized losses.[16] A major update and extension of that study published in 2018 also found no evidence of an increase in damage;[17] Figure 2.11 shows these normalized loss estimates

Normalization studies for Latin America and the Caribbean, India and China similarly show no trend in damages relating to tropical storms.[18] Meanwhile, a study by Laura Bakkensen and Robert Mendelsohn found that the normalized economic damage from hurricanes *fell* everywhere *except* the United States.[19]

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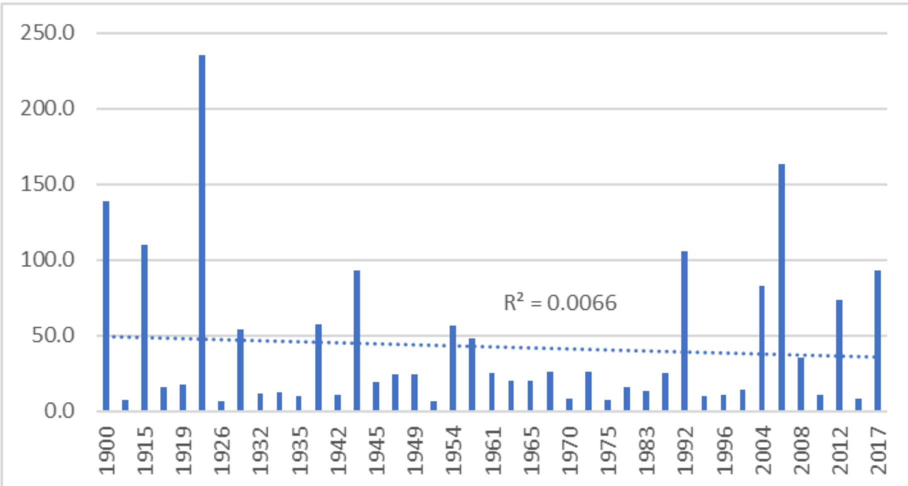
[16] Roger Pielke, Jr. & Chris Landsea, "Normalized hurricane damage in the United States: 1925–95." *Weather Forecasting* 13, 1998, 621–631.

[17] Jessica Weinkle et al. "Normalized hurricane damage in the continental United States 1900–2017," *Nature Sustainability* 1, 2018, 808–813. https://www.nature.com/articles/s41893-018-0165-2

[18] Roger Pielke, Jr. et al. "Hurricane vulnerability in Latin America and the Caribbean: Normalized damage and loss potentials." Natural Hazards Review, 4, 2003, 101–114; Raghavan, S., and S. Rajesh, "Trends in tropical cyclone impact: a study in Andhra Pradesh, India." Bulletin of the American Meteorological Society, 84, 2003, 635–644; Zhang, Q., L. Wu, and Q. Liu, "Tropical cyclone damages in China: 1983–2006." Bulletin of the American Meteorological Society, 90, 2009, 489–495.

[19] Laura A. Bakkensen and Robert O. Mendelsohn, "Risk and Adaptation: Evidence from Global Hurricane Damages and Fatalities." Journal of the Association of Environmental and Resource Economists **3**(3), 555-587.

Figure 2.11 Normalized Hurricane Damage in the Continental U.S., $billions, 1900-2017



Source: Jessica Weinkle et al. "Normalized hurricane damage in the continental United States 1900–2017," *Nature Sustainability* 1, 2018, 808–813.

2.4 Discussion

The reductions in mortality from hurricanes have many causes, among the most important of which are:

- better forecasts, more effective early warning systems, and improved evacuations;[20]
- more robust buildings and infrastructure;[21] and
- maintaining and improving sea defenses, including natural systems such as mangroves.[22]

Improvements in buildings, infrastructure, and sea defenses have also reduced the economic effect of hurricanes. A Recent study showed that after accounting for factors such as the age of a

[20] Fakhruddin, Bapon S.H.M.; Schick, Lauren (2019) "Benefits of economic assessment of cyclone early warning systems - A case study on Cyclone Evan in Samoa" https://www.preventionweb.net/quick/48966; Rogers, David and Tsirkinov, Vladimir (2010) "Costs and benefits of early warning systems" *Global Assessment Report on Disaster Risk Reduction* 2011. https://www.preventionweb.net/english/hyogo/gar/2011/en/bgdocs/Rogers_&_Tsirkunov_2011.pdf; Maria Apergi, Emily Wilkinson and Margherita Calderone, The 'triple dividend' of early warning systems Evidence from Tanzania's coastal areas, London: Overseas Development Institute, 2020. https://cdn.odi.org/media/documents/202006_odi_triple_dividend_wp_final.pdf

[21] Ian M. Giammanco, William H. Pogorzelski, Milad Shabanian, and Tanya D. Havlicek, *Do Modern Building Codes Mitigate Mortgage Delinquency Following Landfalling Hurricanes? The Influence of Building Codes on Mortgages*, CoreLogic and IBHS, 2023. https://www.corelogic.com/intelligence/building-codes-impact-mortgage-delinquency/

[22] Siddharth Narayan, Michael W. Beck, Borja G. Reguero, Iñigo J. Losada, Bregje van Wesenbeeck, Nigel Pontee, James N. Sanchirico, Jane Carter Ingram, Glenn-Marie Lange, Kelly A. Burks-Copes, *The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences,* PlosONE, May 2, 2016. https://doi.org/10.1371/journal.pone.0154735;

building and borrower characteristics, the likelihood of default on a mortgage for a building in a hurricane-prone area in the U.S. was significantly lower for properties in jurisdictions that had adopted more recent standards for their building codes.[23] Meanwhile, the levees built to protect New Orleans after the devastations of hurricane Katrina did just that during hurricane Ian, while neighboring parishes lacking the protection of levees suffered much greater damage and loss of life.[24]

However, in the U.S., a dramatic increase in the development of land in hurricane/storm-surge-prone areas has led to an increase in the cost of damage associated with hurricanes. To some extent, this increase has been driven by market forces, as Americans choose to locate in warmer regions and/or close to sunny beaches. At the same time, public policies have also created perverse incentives. In particular, federal- and state-subsidized flood insurance programs have reduced the cost of insuring against hurricane-related risks, creating hundreds of billions of dollars in moral hazard.[25]

Going forward, among the most cost-effective ways to increase U.S. resilience to hurricanes would be to remove these perverse subsidies and consequent realignment of incentives on the part of the owners and developers of buildings. Some steps have been taken along that road – but much more could be done.[26]

3. Tornadoes

Tornadoes are among the most devastating storms. Unlike hurricanes, which form over the warm water in the tropics, tornadoes form over land and are typically attached to the base of a thunderstorm from which they are spawned. They also build quickly and rarely last for more than

[23] Giammanco et al. *supra note* 21.
[24] https://fic.tufts.edu/newsroom/marina-lazetic-and-karen-jacobsen-discuss-how-hurricanes-impact-low-income-communities-in-the-conversation/
[25] Sadie Frank, Eric Gesick and David G. Victor, *Inviting Danger: How federal disaster, insurance and infrastructure policies are magnifying the harm of climate change*, Brookings Institution, March 2021. https://www.brookings.edu/wp-content/uploads/2021/03/Inviting_Danger_FINAL.pdf
[26] Ray J. Lehmann, *Perverse Incentives and Preparing for Managed Retreat: The Case to Reform the NFIP*, Testimony to the U.S. Senate Committee on Banking, Housing, and Urban Affairs “Reauthorization of the National Flood Insurance Program, Part I” May 18, 2021. https://www.banking.senate.gov/imo/media/doc/Lehmann%20Testimony%205-18-21.pdf

15 minutes. But the energy tornadoes release during their brief life can be phenomenal, with winds sometimes reaching 300 mph.[27]

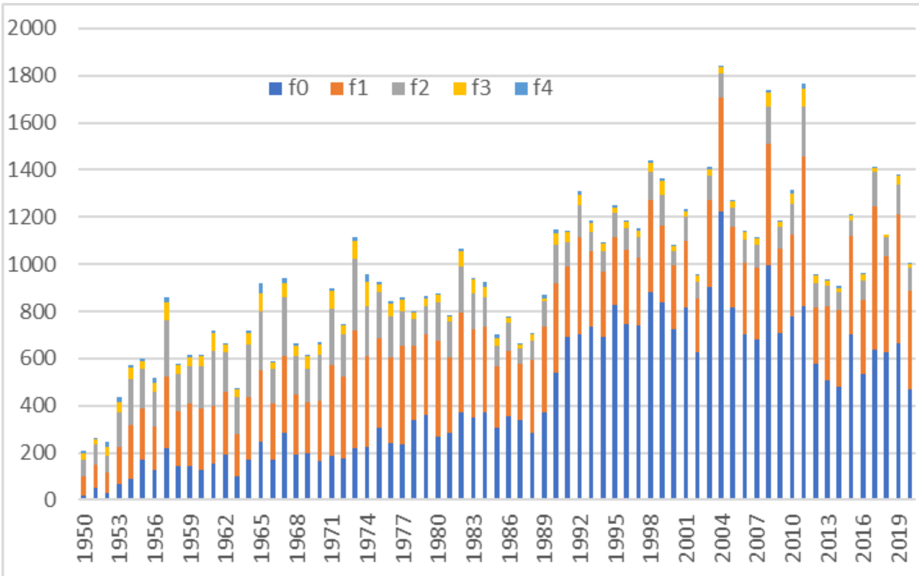
The strength of a tornado is measured on the Enhanced Fujita ("EF") scale, a six-point scale that can be characterized by the maximum wind speed of a 3-second gust. Thus, an EF0 tornado would have 3-second gust speed of between 65 and 85 mph, while an EF5 tornado would have 3-second gusts of over 200 mph.[28] Another way to distinguish tornadoes is between those that are "light" (EF 0) and "moderate" (EF 1) and those that are "major" (EF 2-5).

3.1 Number, Intensity, and Incidence of Tornadoes

Researchers have been recording tornado strength with reasonable accuracy since about 1950. Over that time, the number of tornadoes recorded in the U.S. each year has increased significantly (Figure 3.1). However, the increase in recorded U.S. tornadoes has all occurred in light-moderate tornadoes, while the number of recorded intense tornadoes has declined slightly (Figure 3.2). In addition, the distribution of recorded tornadoes has shifted somewhat from the more traditional "Tornado Alley" of the Great Plains (primarily across the states of Texas, Louisiana, Oklahoma, Kansas, South Dakota, Iowa and Nebraska) to "Dixie Alley" of the South-East (primarily eastern Texas and Arkansas, Louisiana, Mississippi, Tennessee, Alabama, Georgia, western Kentucky, South Carolina, western North Carolina, and southeast Missouri).[29]

[27] National Weather Service, *Definition of a Tornado*, No Date. https://www.weather.gov/phi/TornadoDefinition
[28] *Enhanced F Scale for Tornado Damage*, NOAA, 2007. https://www.spc.noaa.gov/efscale/ef-scale.html
[29] Vittorio A. Gensini and Harold E. Brooks, "Spatial trends in United States tornado frequency," *Climate and Atmospheric Science* **1**: 38, 2018. https://www.nature.com/articles/s41612-018-0048-2

Figure 3.1 U.S. Tornadoes per Year, 1950-2020

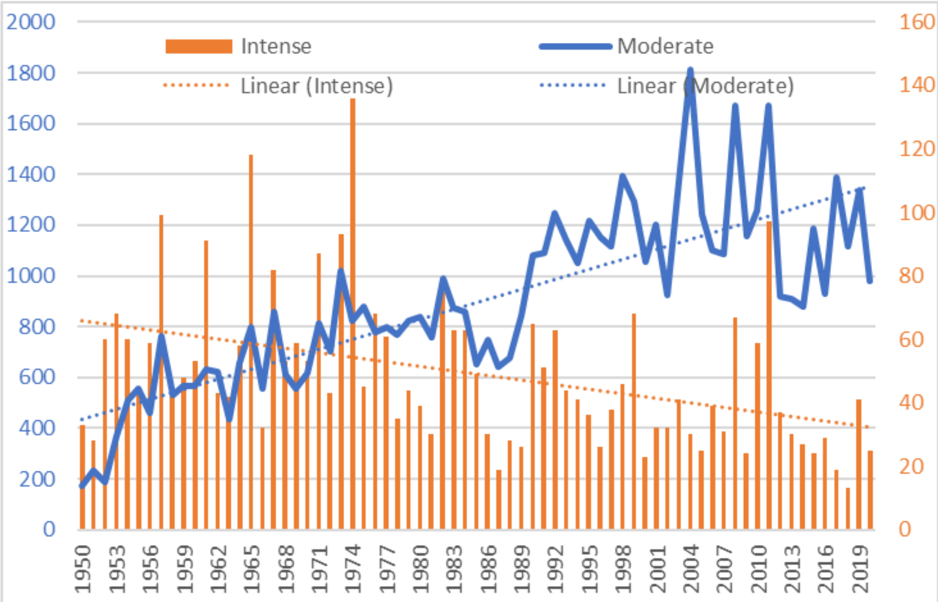


Source: NOAA (https://www.spc.noaa.gov/wcm/data/1950-2020_all_tornadoes.csv)

Numerous possible explanations for these changes in the recorded incidence and distribution of tornadoes have been postulated, including changes in population density, improvements in measurement, and climatic effects. A study published in the journal *Scientific Reports* in January 2021, undertaken by scientists at City University New York and NOAA, concluded that the long-term trend in Dixie Alley can be explained by an increase in population density in that region, resulting in an increase in the number of people affected. Meanwhile, the long-term trend in Tornado Alley can be explained by the installation of Doppler radar systems for monitoring tornadoes.[30] Meanwhile, climatic factors, such as El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO) affect non-trend related variations in tornado incidence.

[30] Niloufar Nouri et al. "Explaining the trends and variability in the United States tornado records using climate teleconnections and shifts in observational practices." *Scientific Reports* **11**: 1741, 2021. https://www.nature.com/articles/s41598-021-81143-5

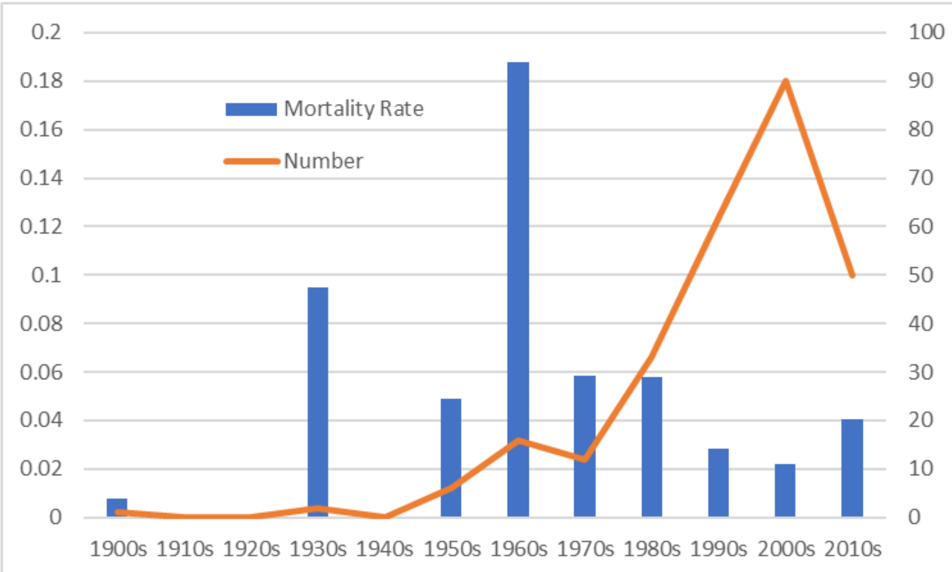
Figure 3.2 Trends in “Moderate” (EF 0 – EF 2) and “Intense” (EF 3 +) U.S. Tornadoes, 1950-2000



Source: NOAA (https://www.spc.noaa.gov/wcm/data/1950-2020_all_tornadoes.csv)

At a global scale, records are far less reliable than for the U.S. The EM-DAT database includes fewer than 300 storms labeled as a “tornado”. The vast majority of those are from the past four decades and exhibit a strong upward trend (Figure 3.3). Given what we know from the U.S. data, this trend is almost certainly driven mainly by increases in population density and improvements in monitoring, as well as the restrictive conditions EM-DAT requires disasters to meet to be included in the database, rather than any change in the underlying number of tornadoes. In spite of the increase in the number of tornadoes meeting the EM-DAT criteria, the mortality rate per million per decade has declined since peaking in the 1980s.

Figure 3.3: Average Annual Mortality Rate from Intense Tornadoes (Left axis) and Number of Intense Tornadoes (Right axis), Global

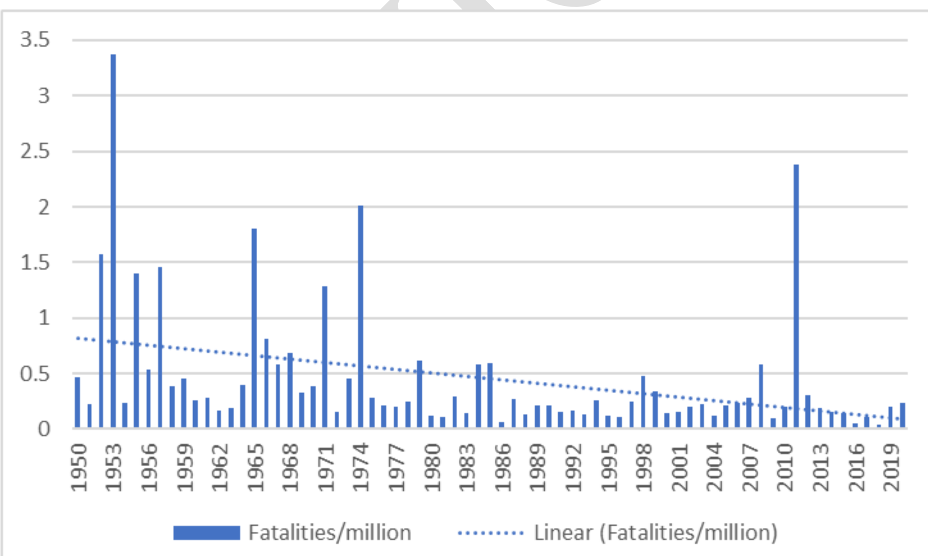


Source: EM-DAT

3.2 Mortality from Tornadoes

Given the decline in the number of intense tornadoes in the U.S., it is perhaps not surprising that the mortality rate from tornadoes has been declining (Figure 3.4).

Figure 3.4: Annual Mortality Rate per Million from Tornados, U.S.



Source: NOAA (https://www.spc.noaa.gov/wcm/data/1950-2020_all_tornadoes.csv) ; U.S. Census

A 2019 study that looked in more detail at the relationship between fatalities and the population density of countries where tornadoes are prevalent confirms this finding. It argues that beyond changes in the number of intense tornadoes, other factors such as better weather prediction and communications, as well as stricter building codes also contributed to the decline in mortality.[31]

3.3 Economic Consequences of Tornados

In 2013, Kevin Simmons, Daniel Sutter and Roger Pielke calculated normalized losses from tornadoes in the US from 1950 to 2011, using a methodology similar to the one Pielke and Landsea developed for hurricane damage. In that study, they found that normalized losses from tornadoes had declined over the study period. In a follow-up analysis published at the end of 2021, Pielke found that the trend had continued (Figure 3.5).[32] A recently-published paper by Jinhui Zhang and colleagues at Macquarie Business School in Australia took a similar approach and confirmed the results of the earlier work, finding a downward trend in normalized damage nationally, but they found a small upward trend for Alabama—reflecting the effects of the shift in the distribution of tornadoes.[33]

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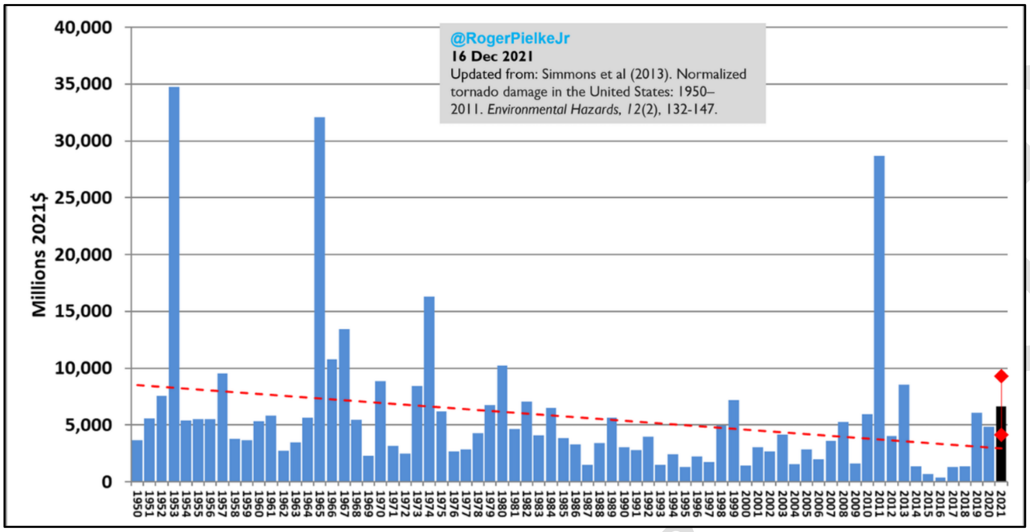
[31] Ernest Agee and Lindsey Taylor, "Historical Analysis of U.S. Tornado Fatalities (1808–2017): Population, Science, and Technology," *Weather, Climate and Society* **11**(2), 2019, 355–368. https://journals.ametsoc.org/view/journals/wcas/11/2/wcas-d-18-0078_1.xml

[32] Roger Pielke Jr., "US Tornado Damage 1950 to 2021: How much damage from tornadoes would occur in 2021 for each of the past 72 years," The Honest Broker, Dec 16, 2021. https://rogerpielkejr.substack.com/p/us-tornado-damage-1950-to-2021

[33] Jinhui Zhang, Stefan Trück, Chi Truong , David Pitt, "Time trends in losses from major tornadoes in the United States," *Weather and Climate Extremes*, Vol 41, September 2023, 100579. https://www.sciencedirect.com/science/article/pii/S2212094723000324

Figure 3.5 Normalized US Tornado Damage, 1950-2021.



Source: https://rogerpielkejr.substack.com/p/us-tornado-damage-1950-to-2021

3.5 Discussion

The decline in mortality from tornadoes in the U.S. and globally is likely due to factors similar to those that have reduced mortality from hurricanes: improved monitoring, better communications, and stronger buildings. But in the case of tornadoes, it may also reflect a secular decline in the number of the most intense tornadoes, as documented clearly for the United States. The decline in normalized losses from tornadoes likely reflects similar factors.

4. Inland Floods, Landslides, and Related Dangers

Inland floods occur when streams, rivers, and other watercourses overflow their banks due to excessive precipitation or snowmelt. Since the dawn of civilization, population centers have developed along the banks of rivers.[34] Over time, as population densities have increased, the number of people affected by such flooding has thus increased.[35] ?

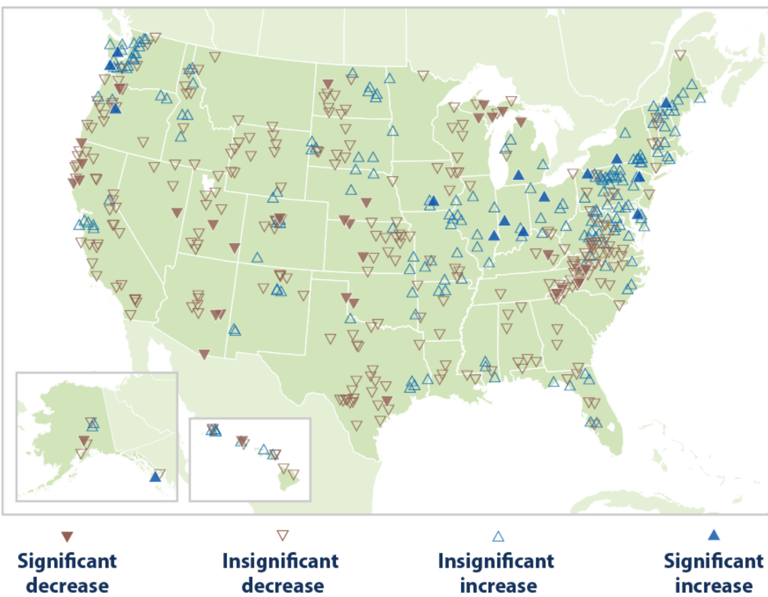
[34] "The rivers of civilization" https://doi.org/10.1016/j.quascirev.2015.02.004
Quaternary Science Reviews
Volume 114, 15 April 2015, Pages 228-244
Guo, Rongxing. (2016). Rivers, Cyclical Floods and Civilizations. 10.13140/RG.2.1.1386.9046.
https://www.researchgate.net/publication/305639882_Rivers_Cyclical_Floods_and_Civilizations
[35] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020WR027744

"Floodplains in the Anthropocene: A Global Analysis of the Interplay Between Human Population, Built Environment, and Flood Severity" https://doi.org/10.1029/2020WR027744

4.1. Flood Incidence

Although precipitation has increased both globally and in the U.S. over the past century, this does not appear to have translated into an overall increase in flood risk. Rather, the distribution of flooding appears to have changed somewhat. In the U.S., the Northeast and Northwest have seen an increase in flooding, while the West, Midwest, South and Southeast have seen a decline (Figure 4.1).[36]

Figure 4.1 Changing Magnitude of River Flooding in the U.S., 1965-2015.



Source: https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding
https://www.epa.gov/sites/default/files/2016-07/river-flooding-download1-2016.png

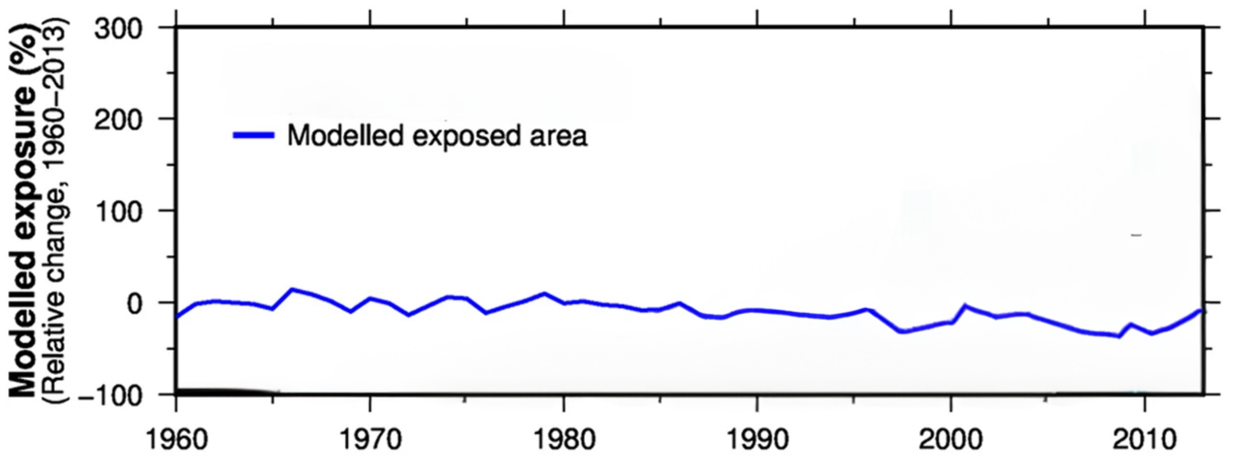
A 2016 paper by Masahiro Tanoue and colleagues from the University of Tokyo published in Scientific Reports analyzed EM-DAT data on flood incidence since 1960 and found that despite an increase in reported number of floods, the implied area exposed to flooding had not increased (Figure 4.2).[37]

Figure 4.2 Change in Area Exposed to Flooding (Modelled), Global, 1960-2013.

Towards understanding the dynamic behaviour of floodplains as human-water systems https://doi.org/10.5194/hess-17-3235-2013

[36] EPA, *Climate Change Indicators: River Flooding* https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding

[37] Masahiro Tanoue, Yukiko Hirabayashi & Hiroaki Ikeuchi, "Global-scale river flood vulnerability in the last 50 years." *Scientific Reports* **6**: 36021, 2016. https://www.nature.com/articles/srep36021

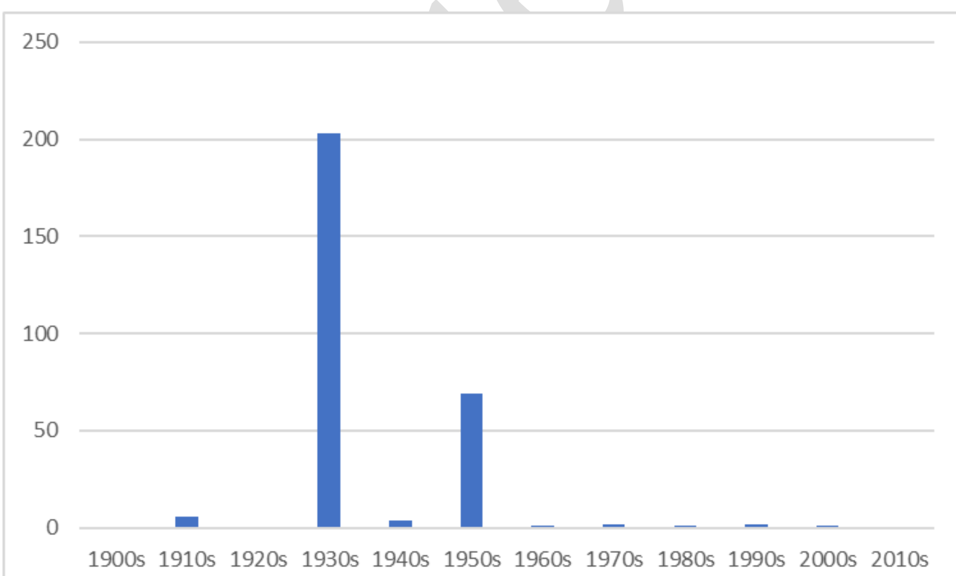


Source: Modified from Tanoue et al. (original is Figure 4.5 below)

4.2 Mortality from Floods

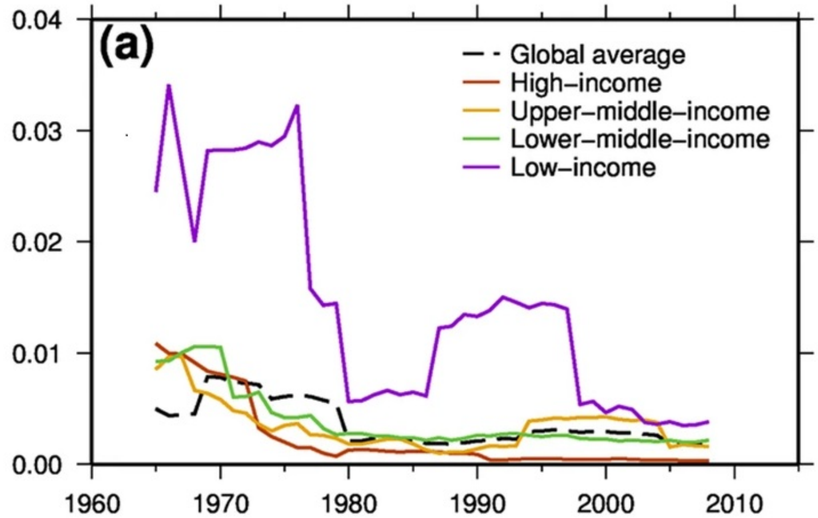
Floods and related dangers, such as landslides, have historically been second only to droughts among weather-related natural disasters in terms of their deadliness. But over the past half-century, the decadal mortality rate from floods has declined precipitously at the global level (Figure 4.3). Looking at the period since 1960, mortality rates have continued to fall, especially in low-income countries (Figure 4.4).

Figure 4.3 Annual Average Mortality per Million from Floods, Global, 1900- 2019



Source: EM-DAT

Figure 4.4: Mortality Rate from Flooding, 11-Year Moving Average, 1960-2013

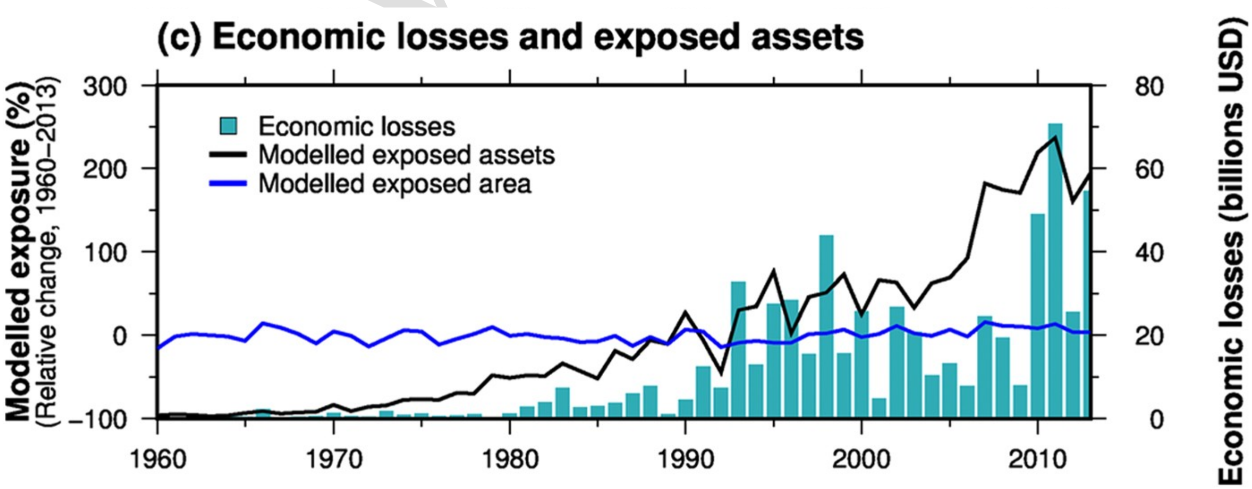


Source: Tanoue et al. https://www.nature.com/articles/srep36021/figures/2

4.3 Economic Effects of Floods.

In the above-mentioned study, Tanoue et al. estimated economic losses from flooding based on EM-DAT data and found that these are similar to "modelled losses", which are based on changes in population density and the value of assets in flood-prone areas, taking into account the very modest changes to the "modelled exposed area." (Figure 4.5) The implication is clear: as with losses from hurricanes, the increase in economic losses from flooding is driven entirely by the increase in construction in exposed areas and the increased value of the assets (buildings, roads, bridges, etc.).

Figure 4.5 Modelled and Estimated Economic Losses from Floods, Global, 1960-2013.



Source: https://www.nature.com/articles/srep36021/figures/1

4.4 Discussion

Flooding events still occasionally make headlines. For example, in late June 2022, a combination of heavy rain and rapid snowmelt caused a dramatic flood in parts of Yellowstone National Park. Some houses near the park and parts of some roads collapsed, leading to the closure of the park.[38] But there were no deaths as a result of the flood.[39] Moreover, the park soon reopened.[40] And by July 13, almost the entire park was open to tourists.[41]

While climate change is likely changing the distribution of precipitation and hence shifting flood patterns, there is no evidence that it is leading to an increase in damage from flooding. Rather, as with hurricanes, it is increased building in floodplains that is causing an increase in economic losses.

5. Droughts

A drought is a period of drier-than-normal weather. The extent to which a region experiences drought is a function of water availability, which in turn is related to the amount of water that falls from the sky (precipitation) and the amount that evaporates from the land (evapotranspiration). One way to measure the extent of drought is by using the ratio of precipitation to evapotranspiration. A standardized metric based on this ratio is called the Standardized Precipitation Evapotranspiration Index (SPEI).[42]

5.1 The Incidence of Drought

Figure 5.1 shows the 5-year SPEI for the U.S. from 1900 to 2020. The prolonged drought of the 1930s, which contributed to the "dust bowl", can be seen clearly. By contrast, the past few years have on average been less drought prone. However, averages can mask important variability; in this case, the Western U.S. has mostly become drier over the past century, while the Eastern US has mostly become wetter (Figure 5.2).

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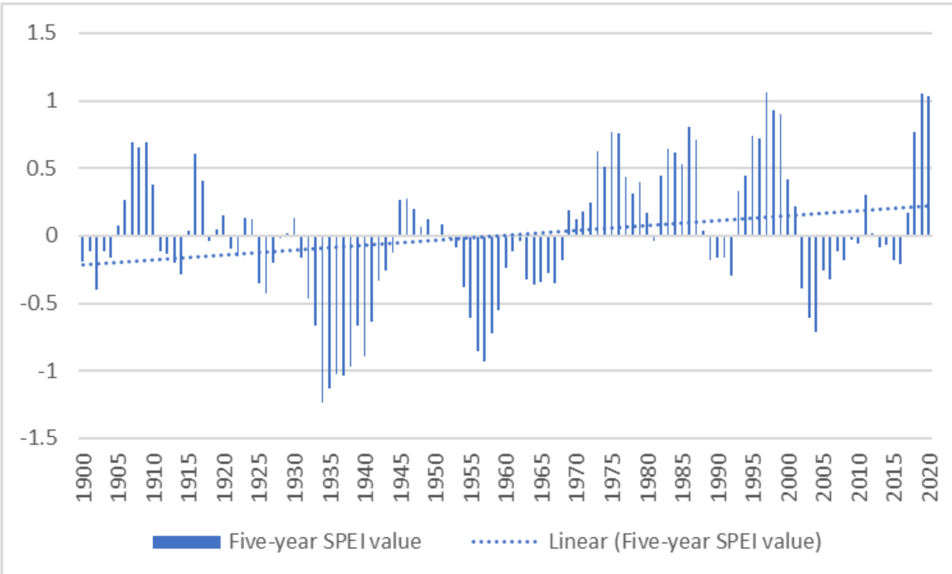
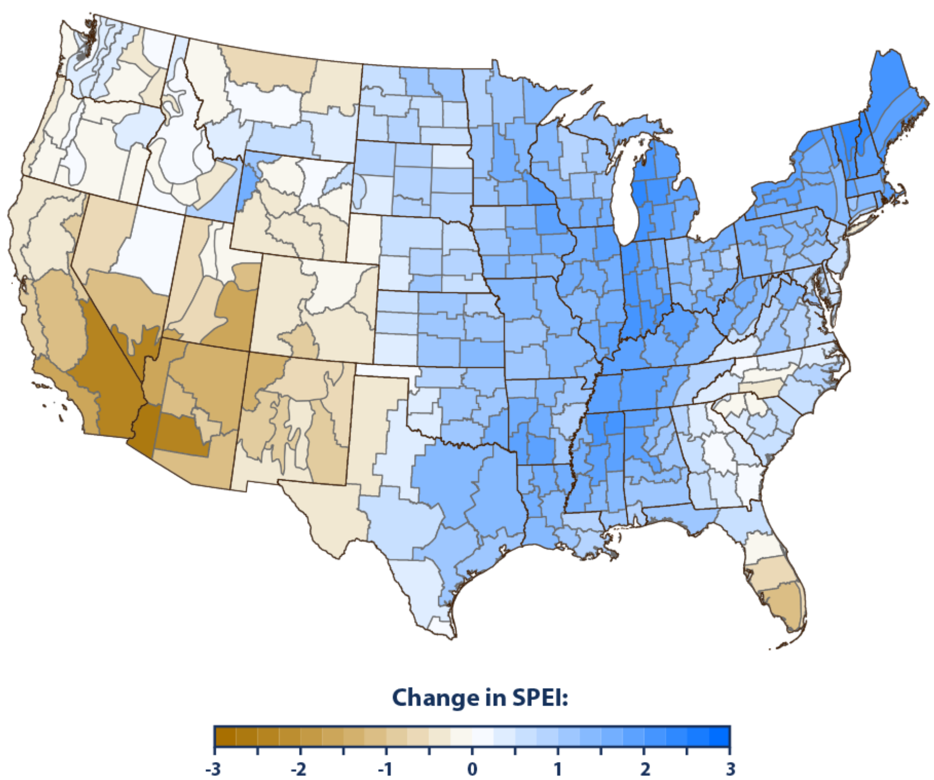
[38] https://earthobservatory.nasa.gov/images/150010/catastrophic-flooding-in-yellowstone
[39] https://cowboystatedaily.com/2022/06/15/yellowstone-flooding-no-death-only-destruction/
[40] https://www.reuters.com/world/us/yellowstone-national-park-partly-reopen-after-rare-closure-forced-by-floods-2022-06-19/#:~:text=%22While%20the%20park's%20north%20loop,Service%20said%20late%20on%20Saturday.
[41] https://www.nps.gov/yell/learn/news/220613.htm
[42] https://spei.csic.es/home.html

Figure 5.1 5-Year SPEI Values for the U.S., 1900-2020



Source: https://www.epa.gov/climate-indicators/climate-change-indicators-drought

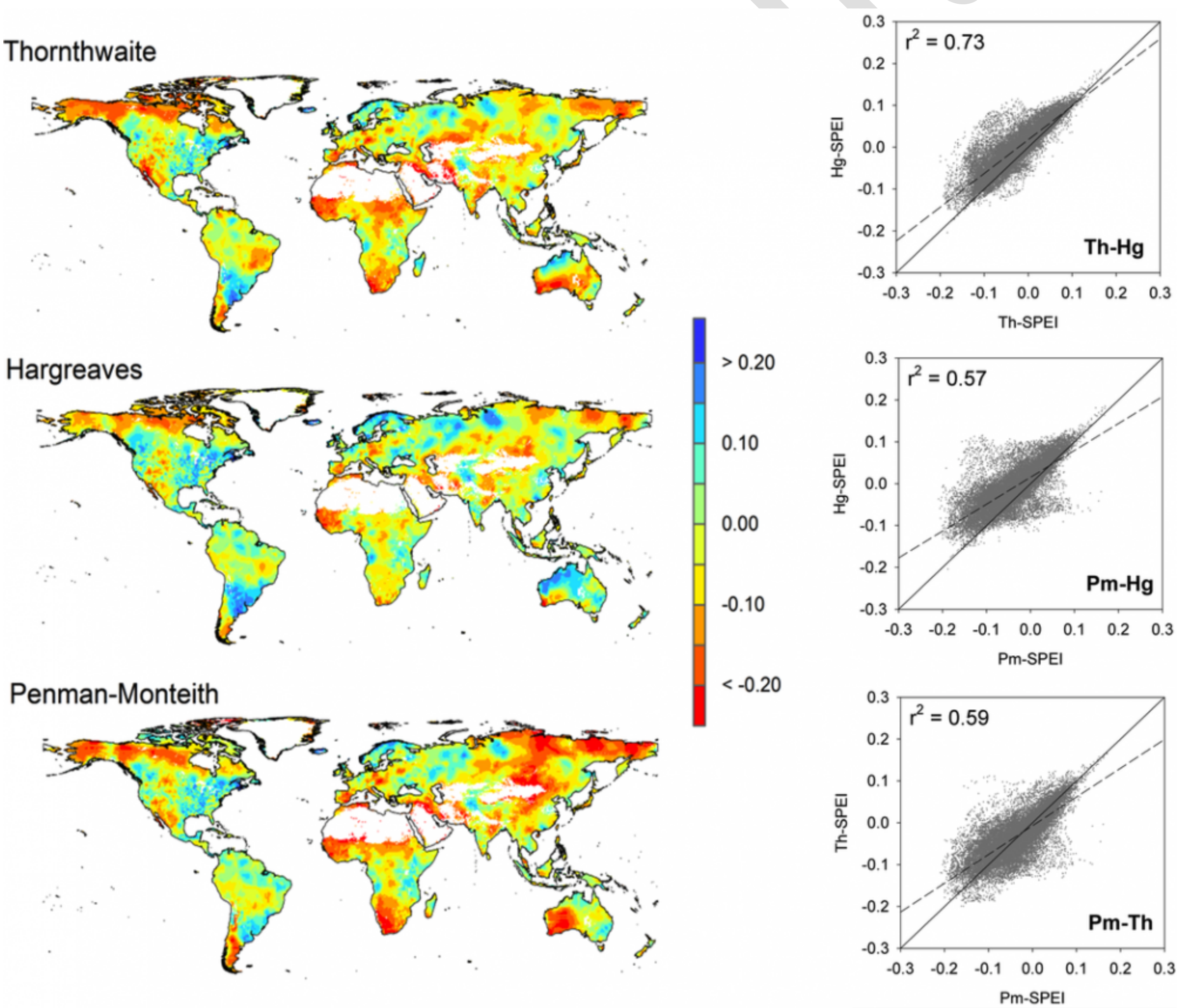
Figure 5.2 Average Change in Five-Year SPEI in the Contiguous 48 States, 1900-2020.



Source: https://www.epa.gov/climate-indicators/climate-change-indicators-drought

A similar picture can be painted for the world as-a-whole. Or perhaps I should say *pictures*: Figure 5.3 shows three different comparisons of decadal SPEI data over the period 1950-2009. The differences arise because of inadequacies in historic SPEI data, so modelers interpolate based on available data. The correlation between available data (Hg-SPEI) and the modeled results in each case ("Thornthwaite", "Hargreaves" and "Penman-Monteith" – corresponding to the names of the modellers) is shown in the black and white figure on the right. Thus, the "best" fit appears to be the Thornthwaite model, which has an r^2 of 0.73, compared with 0.57 and 0.59 for the other models. Nonetheless, the variation in potential fit is very large and somewhat unhelpful in terms of determining any relationship between draught and long-term changes in temperature, precipitation, and evapotranspiration.

Figure 5.3 Global Change in Decadal SPEI, 1950-2009, Under Different Modelling Scenarios

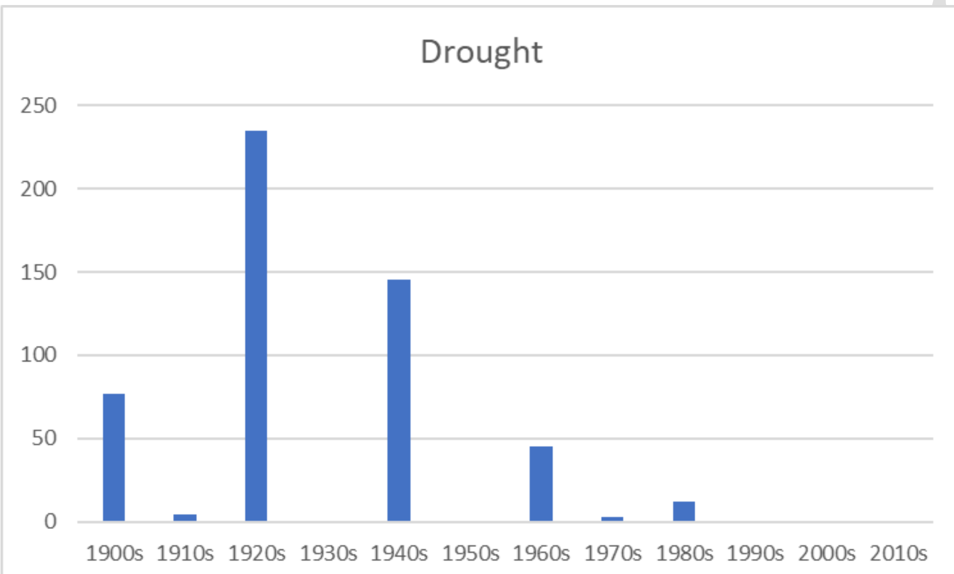


Source: Sergio Vicente-Serrano and National Center for Atmospheric Research Staff (Eds), 2015, **"The Climate Data Guide: Standardized Precipitation Evapotranspiration Index (SPEI)."** Available at: https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-evapotranspiration-index-spei.

5.2 Mortality from Drought

During the 20th century, and likely throughout history, droughts were responsible for more deaths than any other weather-related natural disaster.[43] But over the past few decades, the harm caused by droughts has diminished so dramatically that the mortality rate since 1980 (fewer than three per million per decade) is barely visible in Figure 5.1.

Figure 5.4 Average Annual Mortality Rate per Million from Droughts, Global



Source: EM-DAT

The reason for the dramatic decline in deaths from drought is not that droughts themselves have disappeared, as is clear from the section above. Rather, it is that humanity has become better adapted to drought, through a combination of factors such as: improved water management, improved food production and distribution, and the adoption of early warning systems.

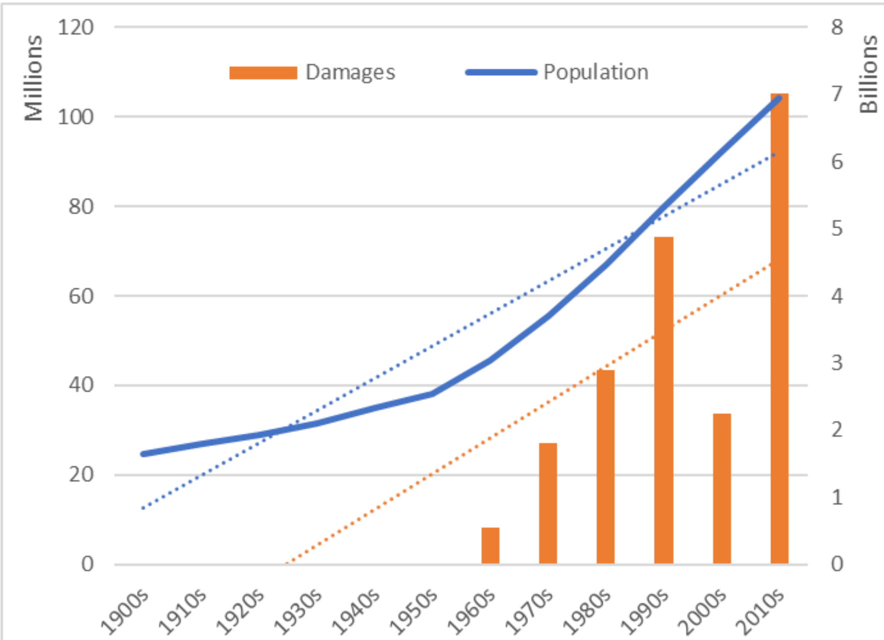
5.3 The Economic Cost of Drought

While mortality from droughts has been falling, EM-DAT data suggests that associated economic damage has been rising. However, economic damage has been rising in parallel with increases in population (Figure 5.5). Since the amount of economic damage from drought was

[43] https://ourworldindata.org/natural-disasters#number-of-deaths-by-type-of-natural-disaster [how to cite]

recorded as “zero” until 1960 in the EM-DAT database, it seems highly likely that the increasing economic damage seen in the data is an artefact of the criteria for reporting – combined with a lack of credible estimates of economic damage from drought until recently.

Figure 5.5: Economic Damage from Drought (left axis, $) and Global Population (right axis).



Sources: EM-DAT (Damages), OurWorldInData (population)

5.4 Discussion

While physical droughts continue to pose a challenge, they are far less of a threat to human life. The improvement is largely a consequence of peace and free markets. Throughout human history, droughts caused loss of life when, as a result of wars and/or restrictions on trade, people in drought-prone areas were not able to obtain food grown elsewhere. In the past 60 years, despite a recent uptick, mortality associated with war has declined and barriers to trade have been dramatically reduced.[44] It is no coincidence that droughts have been transformed from widespread catastrophes into locally acute problems that in most cases can be managed through markets and technology. Meanwhile, the economic cost of droughts is, all things considered, relatively modest.

[44] https://ourworldindata.org/war-and-peace; https://ourworldindata.org/grapher/globalization-over-5-centuries-km

6. Wildfires

Wildfires are unplanned and uncontrolled woodland fires. Evidence suggests that prior to human occupation, woods were subject to frequent, often large, wildfires.[45] As human populations expanded, they typically made clearings in the woods, either by cutting trees down or undertaking (relatively) controlled burns. These actions changed the nature of woodlands.

From the sixteenth Century onwards, war and disease caused some areas of the U.S. that had previously been inhabited to become depopulated. One consequence, according to several accounts, was that woodlands in those areas reverted to a more "natural" state.[46] This is corroborated by evidence of "fire scarring."[47] Thus, by the mid-nineteenth Century, when settlers began to repopulate the Western U.S., the conditions had been established for infrequent but catastrophic woodland fires.

6.1 Wildfires Incidence

Prior to the late nineteenth Century, there are few reliable records of the number or extent of U.S. wildfires, so frequency and scale must be inferred from proxies such as pollen and charcoal.[48] Records kept by the U.S. Forest Service show that the area of National Forest burned each year fell dramatically after the 1910s, continued to fall until the late 1950s, and then started to rise again in the early 1980s (Figure 6.1).

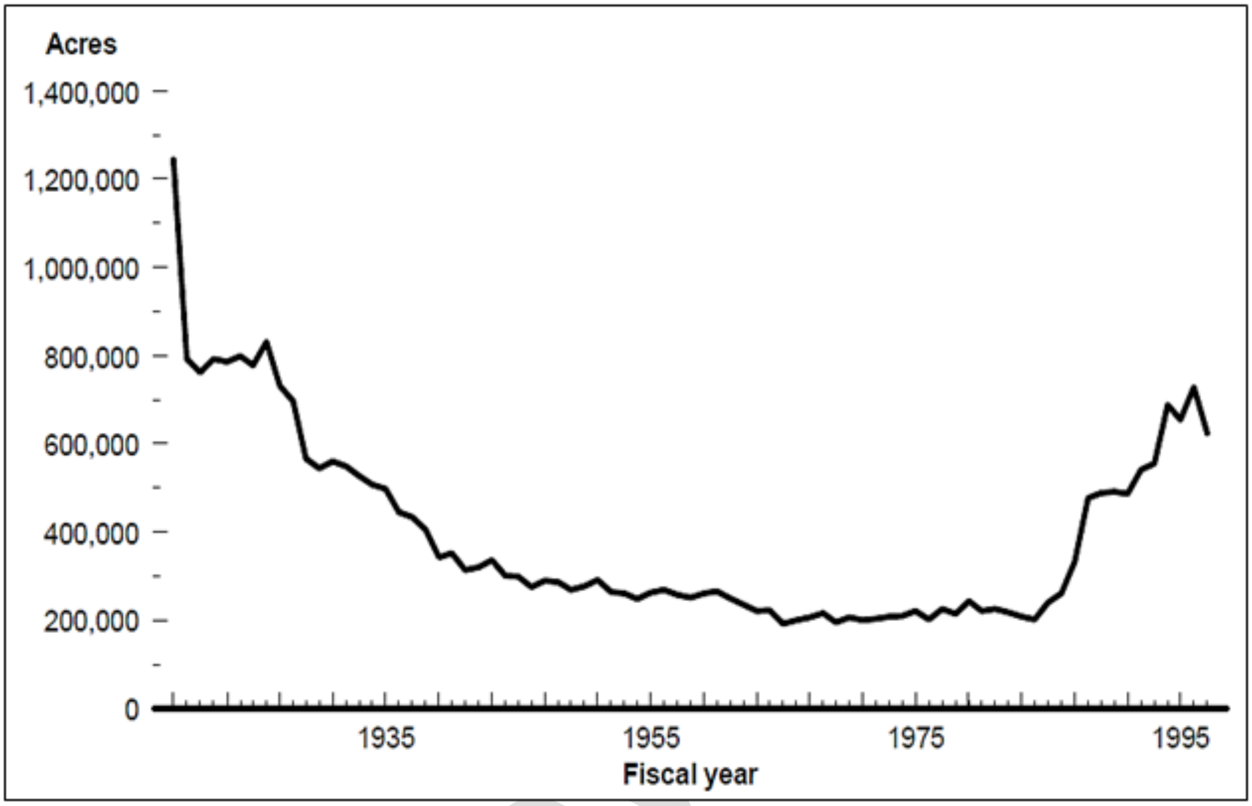
[45] Andrew C. Scott, David M. J. S. Bowman, William J. Bond, Stephen J. Pyne, and Martin E. Alexander, *Fire on Earth – An Introduction*, Wiley-Blackwell, 2014, Figure 5.7. https://higheredbcs.wiley.com/legacy/college/scott/1119953561/PPT/Chapter_5.pptx.

[46] William Cronon, *Changes in the land: Indians, colonists, and the ecology of New England*, New York: Hill and Wang, 1983; Stephen Pyne, *Fire in America: A cultural history of wildland and rural fire*, Princeton, NJ: Princeton University Press, 1982; Timothy Silver, *A new face on the countryside: Indians, colonists, and slaves in South Atlantic forests, 1500-1800*, Cambridge: Cambridge University Press, 1990.

[47] Scott et al., supra note 45, figure 5.8.

[48] Id. and https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4302794/

Figure 6.1: Area of National Forest Burned, 1910s-1990s[49]

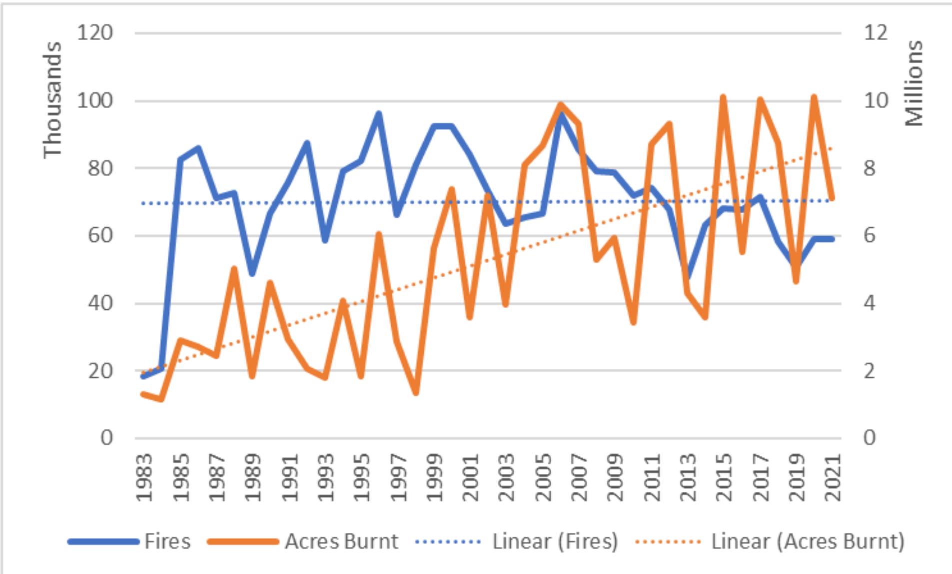


Source: U.S. Forest Service via: http://www.gao.gov/assets/110/107694.pdf

Since 1960, the National Interagency Fire Center and its predecessors have kept records of both the number of fires and the area burnt. Until recently, these data were all publicly available. But NIFC now only shares data on the number and size of fires since 1983, on the grounds that data prior to that date also include fires that were intentionally set. Figure 6.2 shows the data from 1983 to 2021.

[49] The original figure is headed "Number of National Forest Acres Burned by Fire, 1910-97." However, based on the dates on the x-axis, it would appear that the figure actually starts in 1919.

Figure 6.2 U.S. Wildfires: Number of Fires (Left Axis) and Acres Burnt (Right Axis) 1983-2021



Source: NIFC

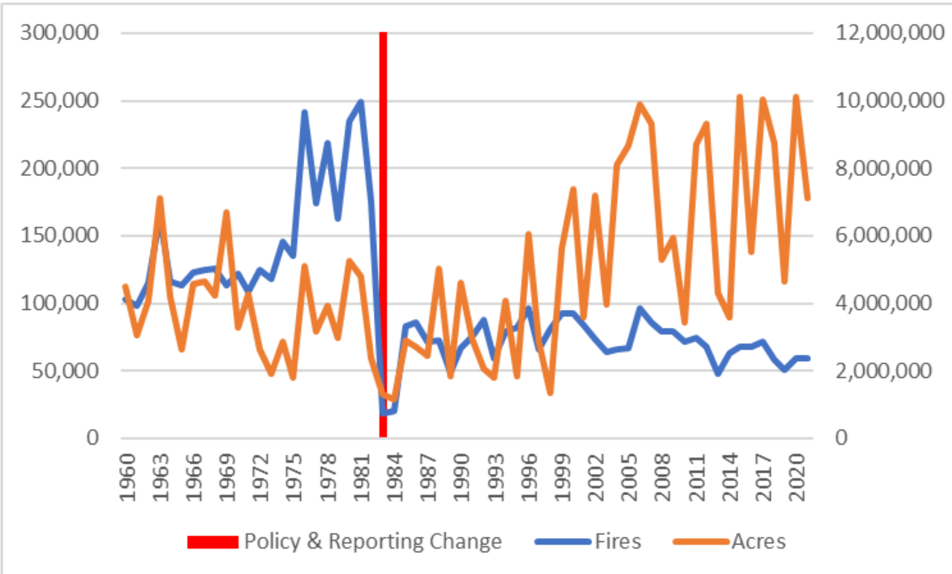
However, I had previously downloaded the data going back to 1960, so we can compare those data too. The number of wildfires in the 1983-2021 dataset (Figure 6.3) is lower than the total number of woodland fires in the 1960-1982 dataset, but the total area burnt is considerably larger. Figure 6.2 shows, more clearly, that the average annual area burnt has risen dramatically over the past four decades, while the number of wildfires has remained relatively stable. This coincides with a significant increase in the number of catastrophic wildfires.

While there has been an increase in woodland acreage burnt in the U.S. in recent decades, the international picture is less clear. Satellite data from the Global Fire Emissions Database (GFED) show that from 1997 to 2016 (the last year for which comparable data is available), the average area burnt per year fell by about 20% (Figure 6.4).[50] By contrast, a study from 2022 found a significant increase in woodland area burnt from 2001 to 2019 (Figure 6.5).[51]

[50] Methodology: Louis Giglio et al. "Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4)" JGR Geosciences **118** (1), 317-328, 2013. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/jgrg.20042

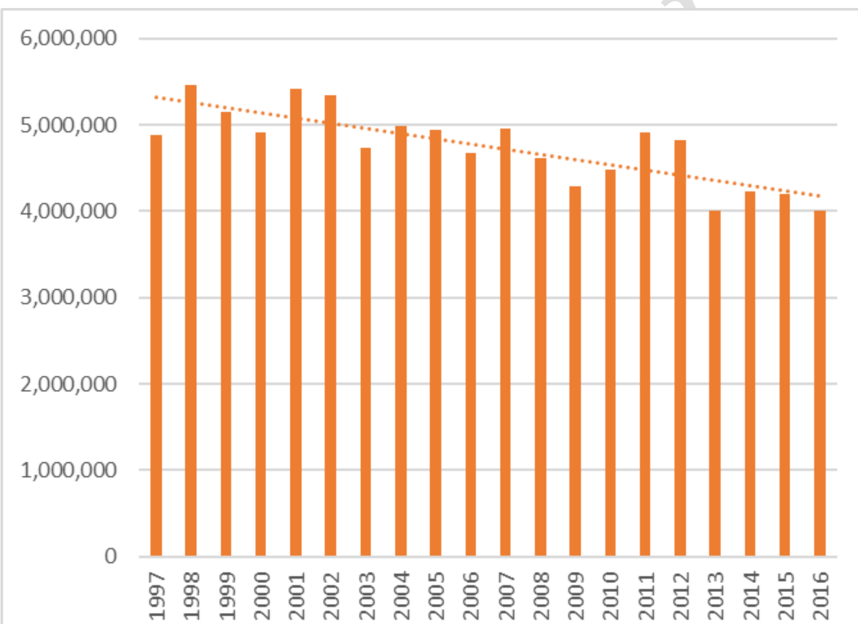
[51] https://www.frontiersin.org/articles/10.3389/frsen.2022.825190/full

Figure 6.3 U.S. Woodland Fires: Number (left axis) and Acres Burnt (right axis) 1960-2021.



Source: NIFC.

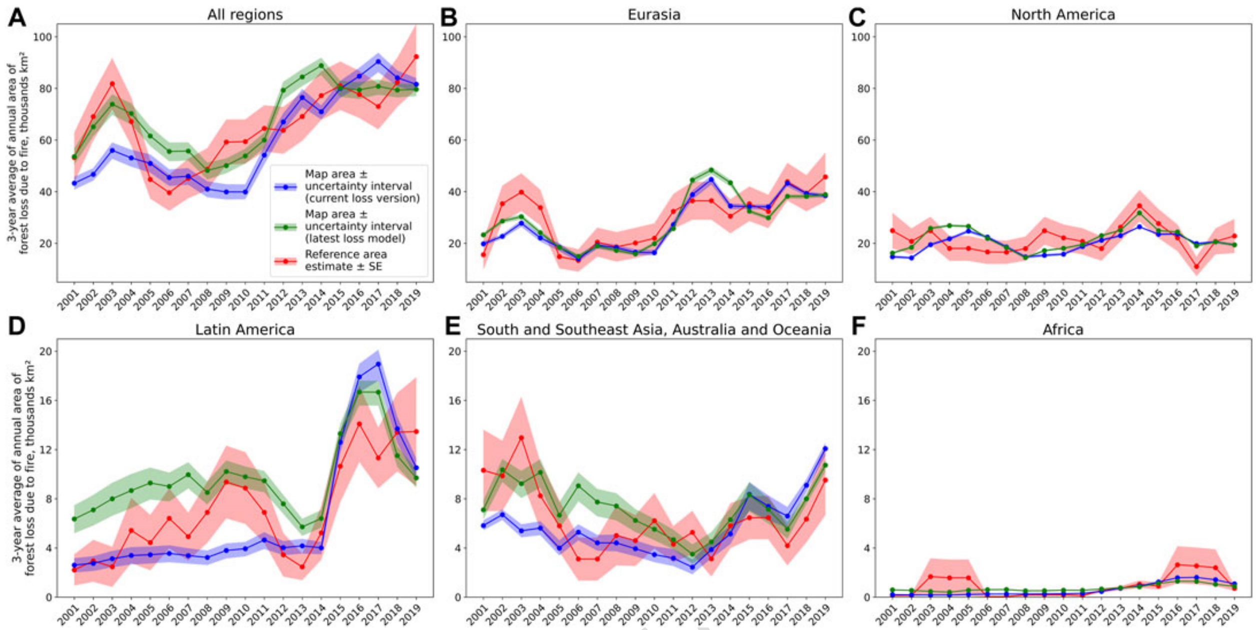
Figure 6.4 Area of land burnt (square kilometers), Global, 1997-2016



Source: Global Fire Emissions Database (http://www.globalfiredata.org/analysis.html)

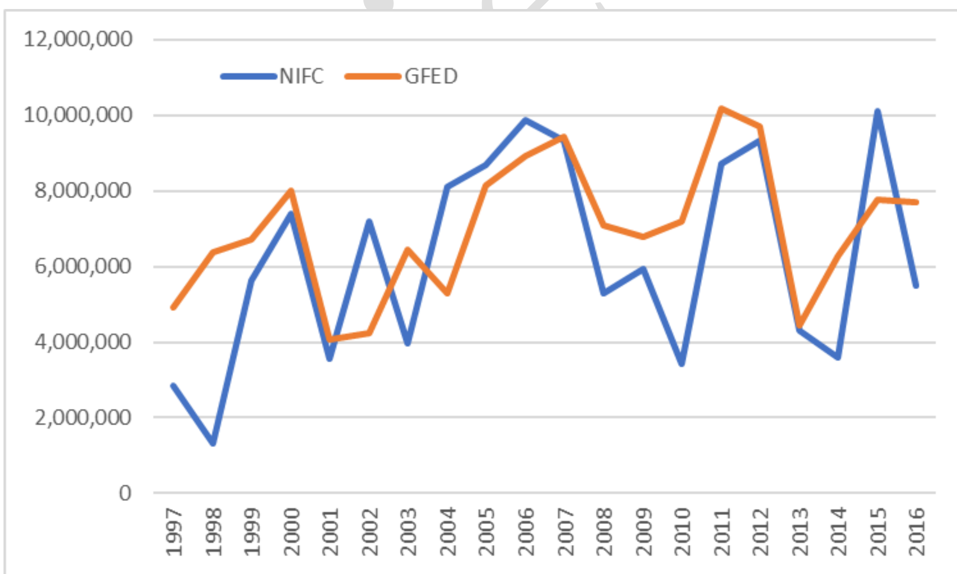
It is also noteworthy that the GFED satellite estimates of area burnt in North America quite closely match the estimates from the NFIC (Figure 6.6), suggesting that the area of wildfires burnt is actually the same as the area of woodland burnt (for the simple reason that the area burnt using intentionally lit fires is tiny by comparison), arguably validating the entire series for area burnt shown in figure 6.3.

Figure 6.5 Forest loss due to fire (thousands of square kilometers), global and by region, 2001-19



Source: https://www.frontiersin.org/articles/10.3389/frsen.2022.825190/full

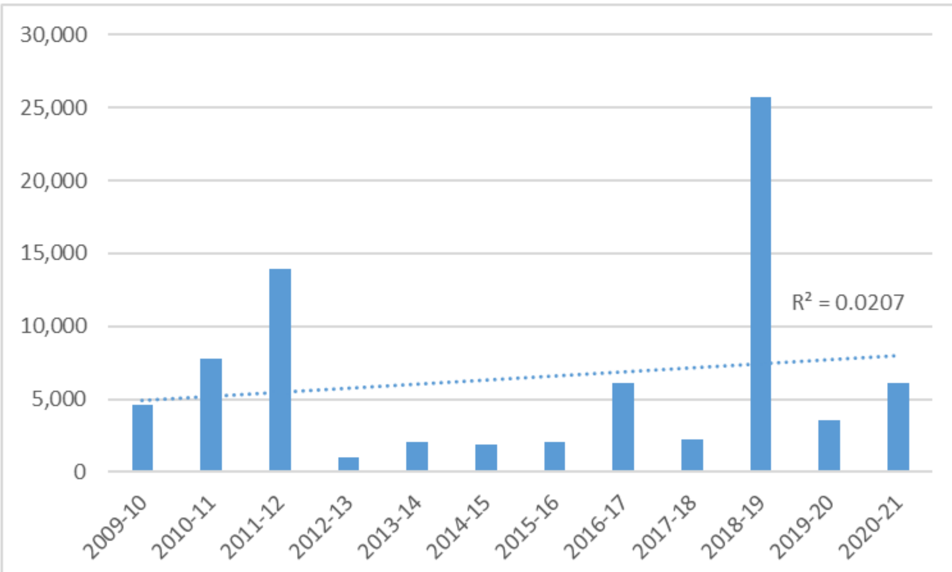
Figure 6.6 Area of Woodland Burnt, U.S., based on NFIC and GFED (satellite) data, Acres



Source: NFIC, GFED.

In England, 2018 was the country's *annus horibilis* for wildfires. Looking at comparable data for the decade to 2020, however, that year was an outlier with no statistically significant trend over the poriod (Figure 6.7). This is reinforced when looking at longer datasets for the UK as a whole (Figure 6.8).

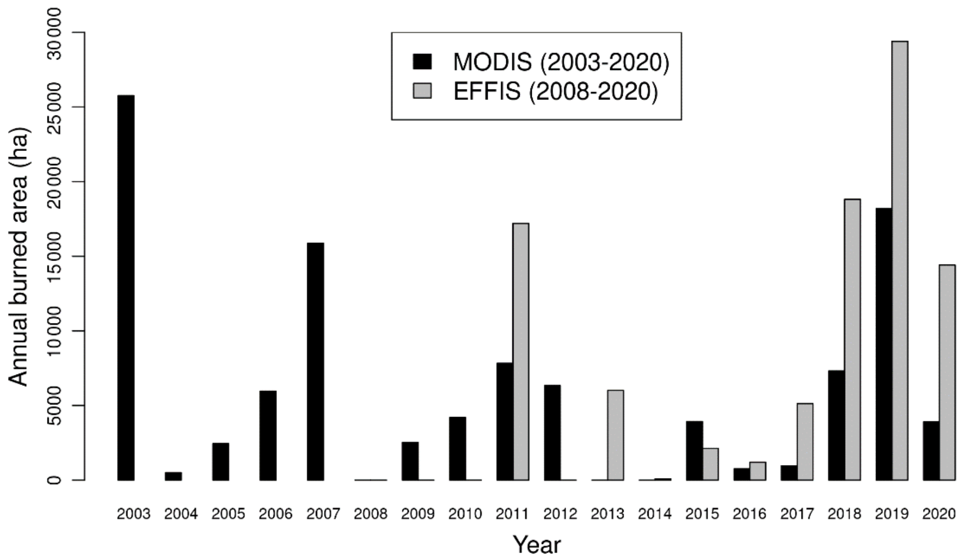
Figure 6.7 Woodland Area Burnt in England, Hectares, Financial Years 2009-10 to 2020-21



Source: Forestry Commission Wildfire statistics for England: Report to 2020-21 Supporting data[52]

[52] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1136808/FC-Wildfire-statistics-for-England-Report-to-2020-21-Supporting-Data.xlsx

Figure 6.8 Woodland Area Burnt in the UK, Hectares, 2003-2020.



Source: Perry et al. [53]

6.2 Mortality from Wildfire

Over the course of the past few decades, communities living close to woodlands – an area known as the "wildland-urban interface" (WUI) – have expanded considerably. A 2018 study published in the Proceedings of the National Academy of Sciences found that between 1990 and 2010, the number of new houses built in the WUI had increased from 30.8 to 43.4 million (a 41% increase), while the land area deemed to be WUI had increased from 581,000 square kilometers to 770,000 square kilometers (a 33% increase).[54] The study also found that the number of houses within the perimeter of recent wildfires had increased from 177,000 in 1990 to 286,000 in 2015.

This expansion of the WUI, combined with the increase in the number of wildfires in the U.S., explains the documented increase in mortality from wildfire in the U.S. over the past few decades (Figure 6.9). The very high figure in the 1910s is due to a single fire in 1918 that according to EM-DAT caused approximately 1,000 deaths (higher than some other sources).[55]

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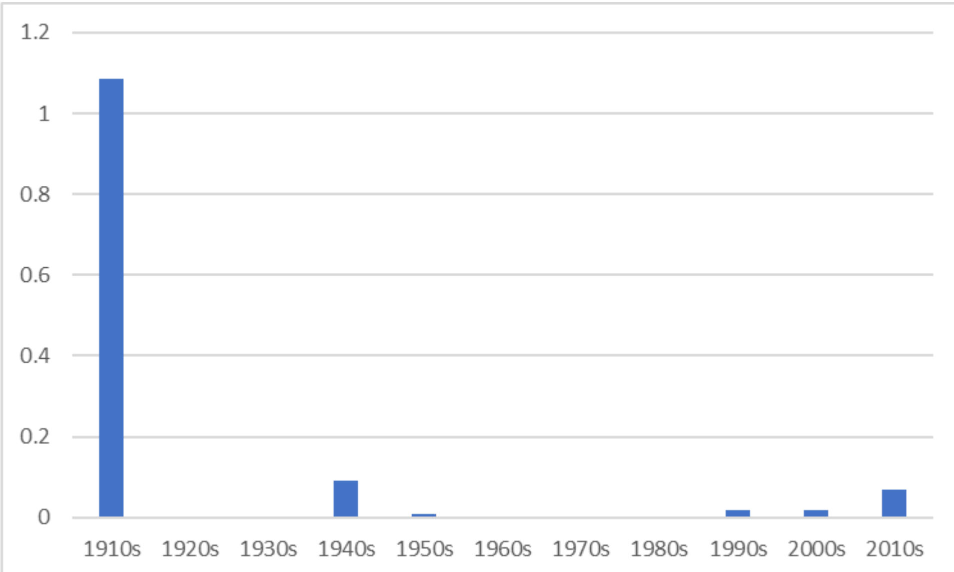
[53] Matthew C. Perry, Emilie Vanvyve, Richard A. Betts, and Erika J. Palin, Past and future trends in fire weather for the UK, Nat. Hazards Earth Syst. Sci., 22, 559–575, https://doi.org/10.5194/nhess-22-559-2022, 2022.
[54] https://www.pnas.org/doi/10.1073/pnas.1718850115
[55] This appears to refer to the Cloquet-Duluth Fire in Northern Minnesota, the worst natural disaster in Minnesota history. Other sources estimate caused about 450 deaths (e.g. Paul Nelson, "Cloquet, Duluth, and Moose Lake Fires, 1918," MNOpedia. https://www.mnopedia.org/event/cloquet-duluth-and-moose-lake-fires-1918).

(Intriguingly, the EM-DAT database does not include the 1910 "Big Burn", which led to 86 documented deaths.[56])

Figure 6.9 Average Mortality per Million per Decade from Wildfire, U.S., 1900-2019

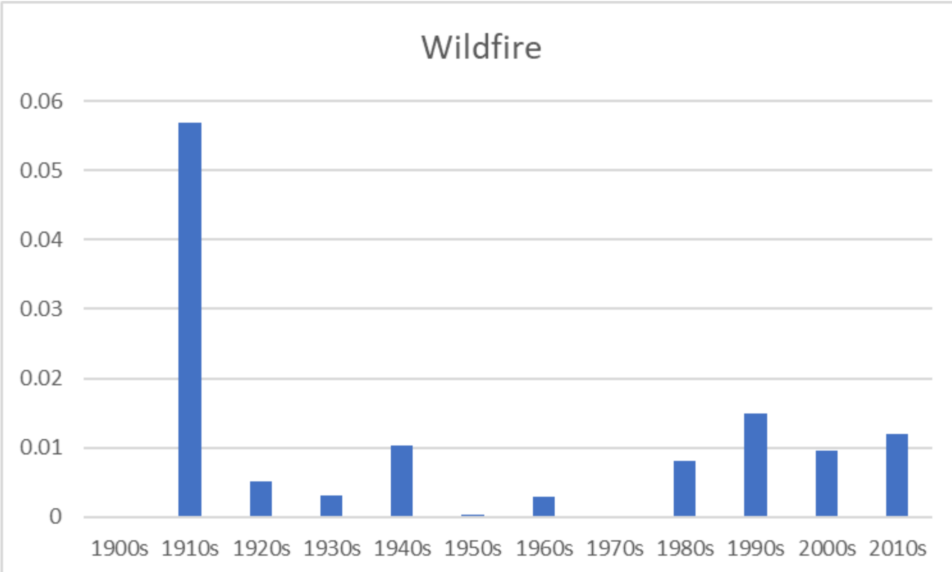


Source: EM-DAT

Figure 6.10 shows the mortality rate per million per decade from wildfires globally. Meanwhile, Figure 6.11 shows the raw mortality figures for the US and the world, as well as the proportion of global mortality represented by the U.S. While these data probably evince a reporting bias, they reinforce the concerns regarding the expansion of the WUI in the U.S. and internationally during the past three decades.

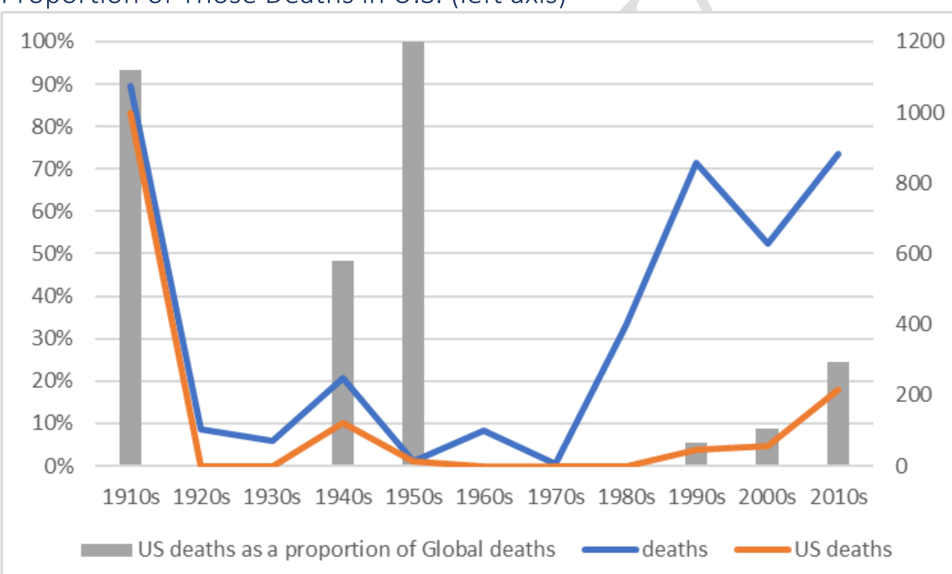
[56] Stephen Pyne, *Year of the Fires: The Story of the Great Fires of 1910*. New York: Viking, 2001.

Figure 6.10 Average Mortality Rate per Million per Decade from Wildfire, Global



Source: EM-DAT

Figure 6.11 Comparing Mortality from Wildfires: Global Deaths per Decade (Right axis) and Proportion of Those Deaths in U.S. (left axis)

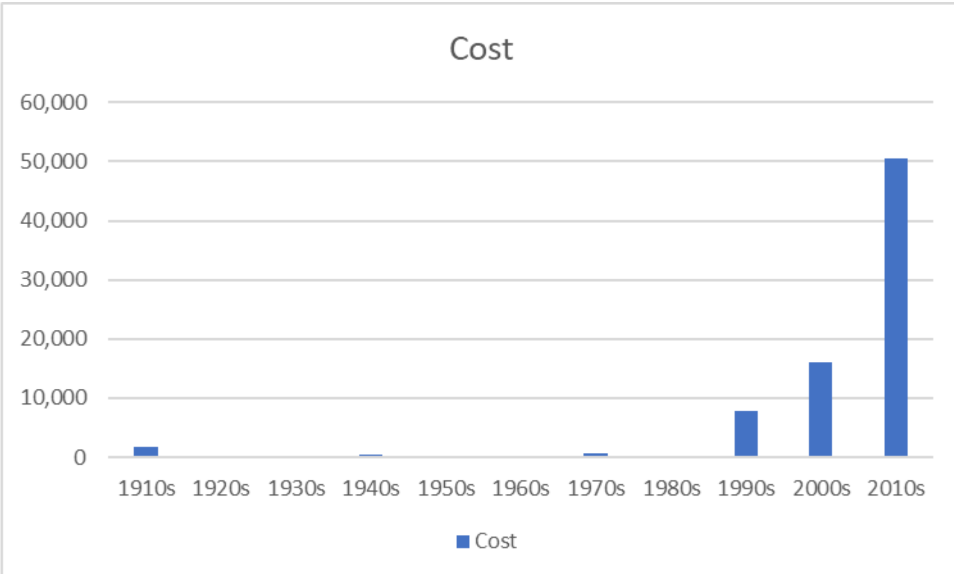


Source: EM-DAT

6.3 Economic Effects of Wildfire

The expansion of the WUI has exacerbated not only mortality risk but also economic risk. Figure 6.12 shows estimates of damage from U.S. wildfires, which in the 2010s topped $50 billion.

Figure 6.12 Damage Caused by Wildfires per Decade, U.S. ($millions)



Source: EM-DAT

6.4 Discussion

In the past five years, forest fires have had devastating effects in many places, including: Alaska (2022),[57] California (2017, 2018, 2020, 2021),[58] Chile (2023),[59] England (2018),[60] Greece (2018 and 2023),[61] Scotland (2019), and Sweden (2018).

In some cases, these fires may have been exacerbated by global warming and associated climatic changes, such as the ratio of precipitation to evapotranspiration (see section 5). However, overall the evidence regarding trends in woodland fires is ambiguous.

What is not ambiguous is the growing problem of the Wildland-Urban-Interface, driven almost entirely by increases in the number of people living in or close to wild areas that are at risk of fire. This is exacerbated in many places by inadequate forest/fire management, which has increased the risk of catastrophic fires.

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[57] https://akfireinfo.com/2022/07/21/wildfires-burn-more-than-3-million-acres-in-alaska/
[58] https://www.reuters.com/graphics/CALIFORNIA-WILDFIRES/gdpzyjxmovw/
[59] https://www.reuters.com/world/americas/chile-battles-deadliest-wildfires-record-heatwave-grips-2023-02-06/
[60] Supra note 52
[61]

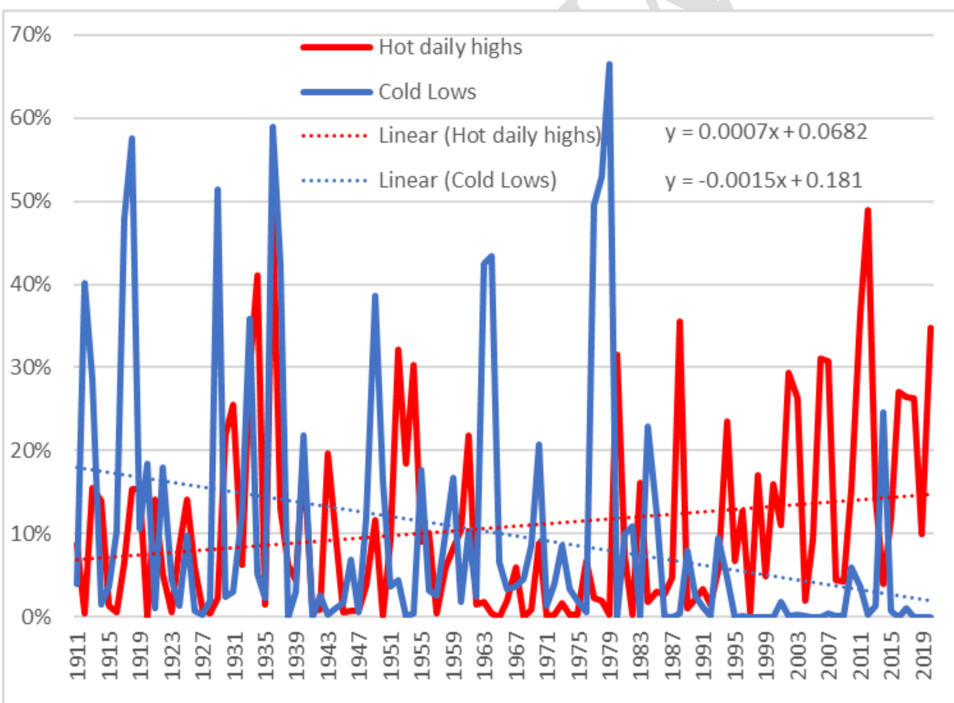
7. Extreme Temperatures

Humans are not well adapted to extreme temperatures. Extreme cold can cause hypothermia in a few minutes and death shortly thereafter.[62] Extreme heat can cause hyperthermia, heat stroke, and death.[63] Extreme heat and cold also cause problems for other animals, as well as plants, if they are not well adapted to such environments. Because human, animal, and plant populations are adapted to different temperatures, "extreme temperature" tends to be defined in a relative rather than absolute sense. As such, there is no objective definition.

7.1 Changing Incidence of High and Low Temperatures

As temperatures have risen both globally and in the U.S., the number of very hot days has increased and the number of very cold days has declined. Figure 7.1 shows that although the proportion of the contiguous 48 states experiencing very hot days has increased on average over the past century, the percentage of cold days has fallen twice as fast.

Figure 7.1 Proportion of Contiguous US Experiencing Very Hot and Very Cold Days



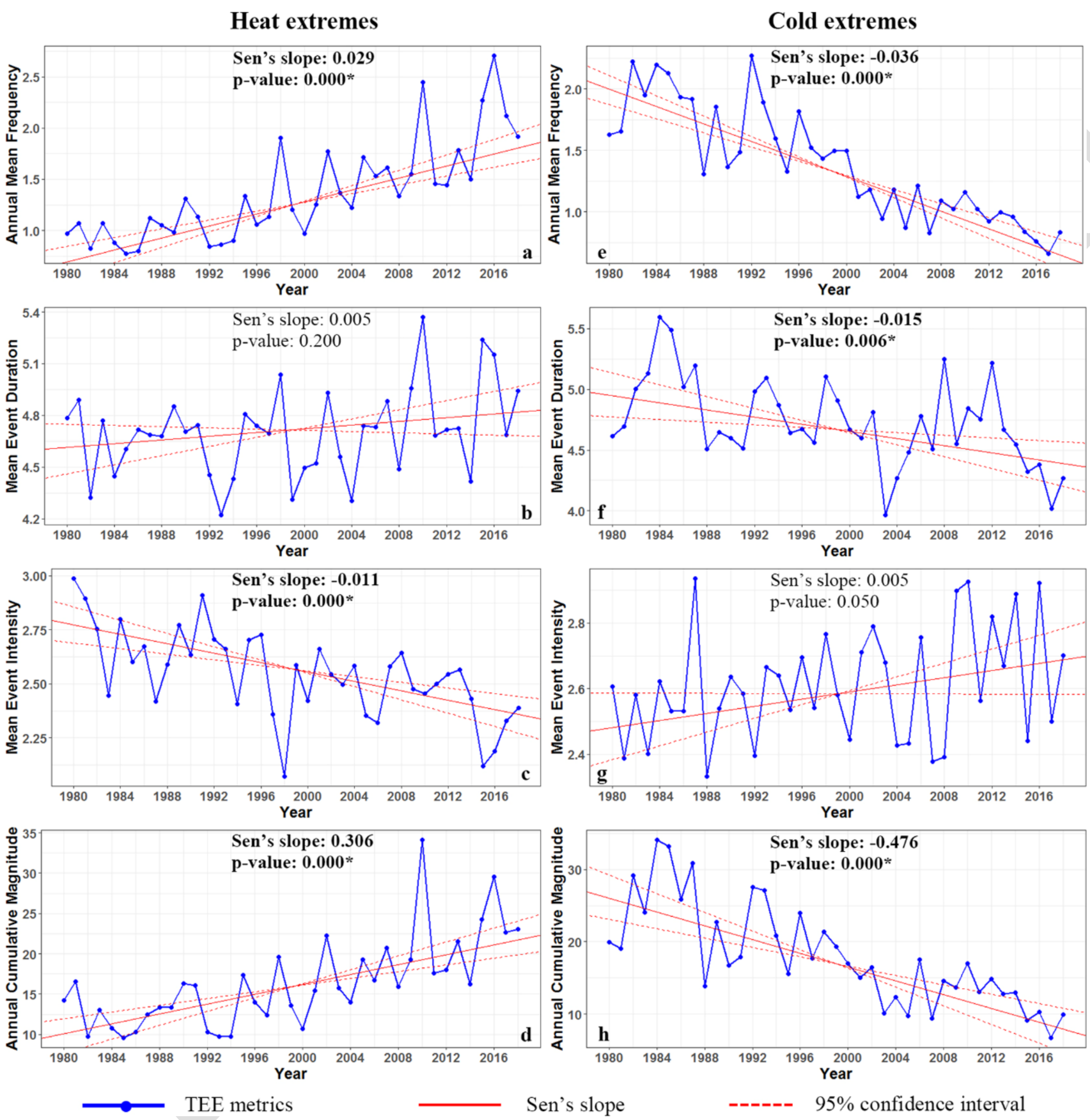
NOAA, U.S. Climate Extremes Index, www.ncdc.noaa.gov/extremes/cei

[62] Henry Guly, "History of accidental hypothermia," *Resuscitation*, Vol. 82(1), 2011pp. 122–125. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3060344/

[63]

A recent study by Yuan Zhang and four colleagues at the Chinese Academy of Sciences shows a similar pattern at the global level (Figure 7.2).[64]

Figure 7.2: Global Temperature Extremes, 1980-2018



Source: Zhang et al. *Communications Earth & Environment* 3: 73, 2022

Looking at global temperature extremes from 1980 to 2018, the researchers found that while heat extremes had become more frequent, their length had not increased and they had become less

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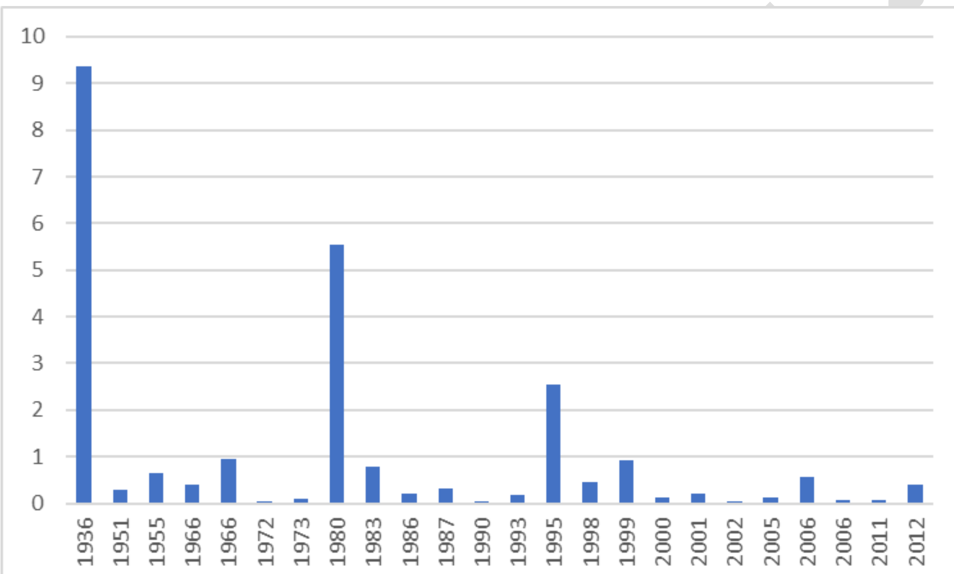
[64] Yuan Zhang et al., "Growing prevalence of heat over cold extremes with overall milder extremes and multiple successive events." *Communications Earth & Environment* 3: 73, 2022. https://www.nature.com/articles/s43247-022-00404-x#citeas

intense. Meanwhile, cold extremes had decreased at about the same rate and become shorter, but not changed in intensity. Overall, the researchers concluded that the "cumulative magnitude" of heat events increased by less than the decrease in cumulative magnitude of cold events. In other words, the net effect was a decline in "cumulative magnitude" of the two types of extreme temperature events.

7.2 Mortality from Extreme Temperatures

Despite the increase in the number of very hot days over the course of the past century, mortality from heatwaves has declined in the U.S. (Figure 7.3).

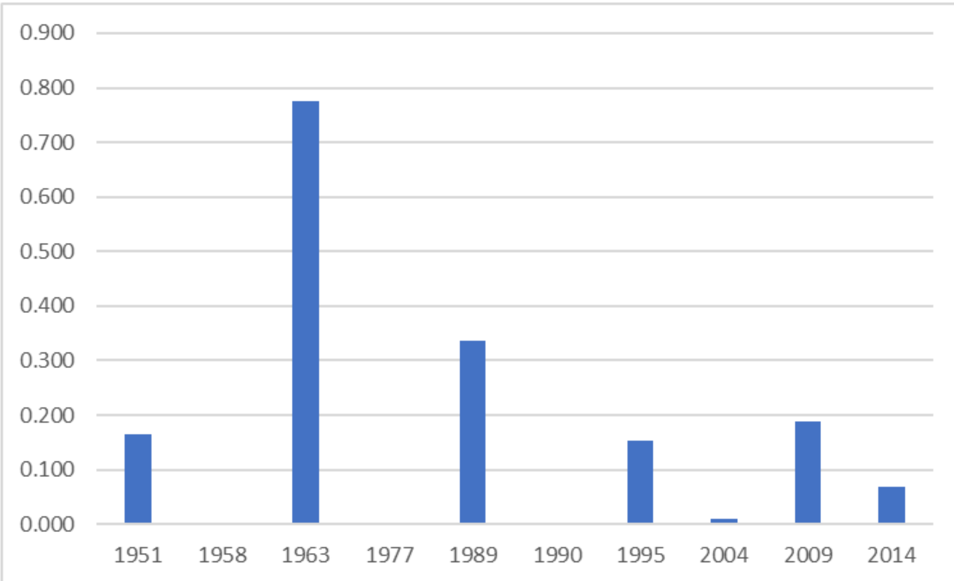
Figure 7.3: Mortality Rate per Million, Heatwaves, U.S.



Source: EM-DAT

A similar pattern can be seen in figure 7.4 for mortality from coldwaves in the U.S.

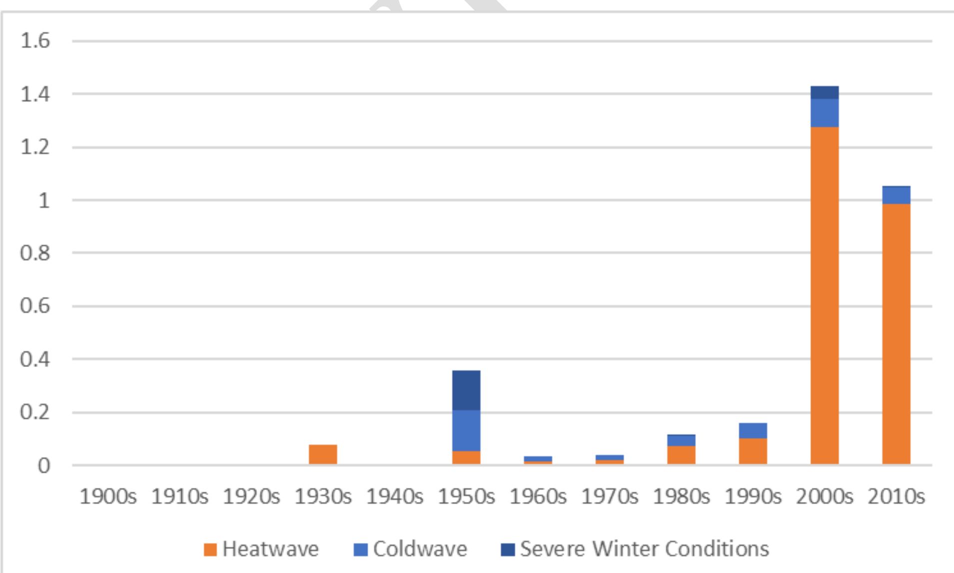
Figure 7.4: Mortality Rate per Million, Coldwaves, U.S.



Source: EM-DAT

Looking at the picture globally, a rather different pattern emerges, with mortality from both heatwaves and coldwaves *rising* over time. Indeed, the mortality from heatwaves appears to have reached extremely high levels in the 2000s and 2010s (Figure 7.5). Most of these deaths have occurred in Europe.[65]

Figure 7.5 Average Annual Mortality Rate per Million, Extreme Temperatures, Global



[65] EM-DAT data.

Source: EM-DAT

However, this focus on "extreme temperatures" may give a misleading impression regarding the overall effects of changes in temperature on human mortality over the past few decades. In a 2015 paper published in *The Lancet*, Professor Antonio Gasparrini of the London School of Hygiene and Tropical Medicine described the outcome of a study conducted by a team he had led. They analysed the cause of over 74 million deaths over the period 1985–2012 in 384 locations in Australia, Brazil, Canada, China, Italy, Japan, South Korea, Spain, Sweden, Taiwan, Thailand, UK and USA. They found that cold weather caused nearly 20 times more deaths than hot weather.[66] Since warming has led to a decline in cold temperatures at a faster rate than the increase in warm temperatures, the net effect *should* be a reduction in temperature-related mortality.

Looking more narrowly at Europe, a similar picture emerges. A study by a team of researchers led by Pierre Masselot of the London School of Hygiene and Tropical Medicine and published this year in *Lancet Planetary Health* considered the incidence of deaths associated with heat and cold across 854 European cities (including 103 in the UK) from 2000 to 2019. In spite of the large increase in deaths from heatwaves in Europe seen in the EM-DAT data, the researchers estimated that while heat caused around 20,000 excess deaths annually, cold caused ten times that number—over 200,000 excess deaths annually.[67]

In contrast to these estimates of deaths from heat and cold, the EM-DAT data *extreme* temperatures caused a total of about 400 documented deaths per year on average in Europe over the past 20 years. However, extreme temperatures tend to grab headlines because their deadly effects are concentrated over a very short time period. The 2022 heatwaves in the UK, for example, were the second most deadly weather-related natural disaster in Britain in the past century, killing in the space of a few weeks an estimated 2,985 people.[68] (Although a recent re-

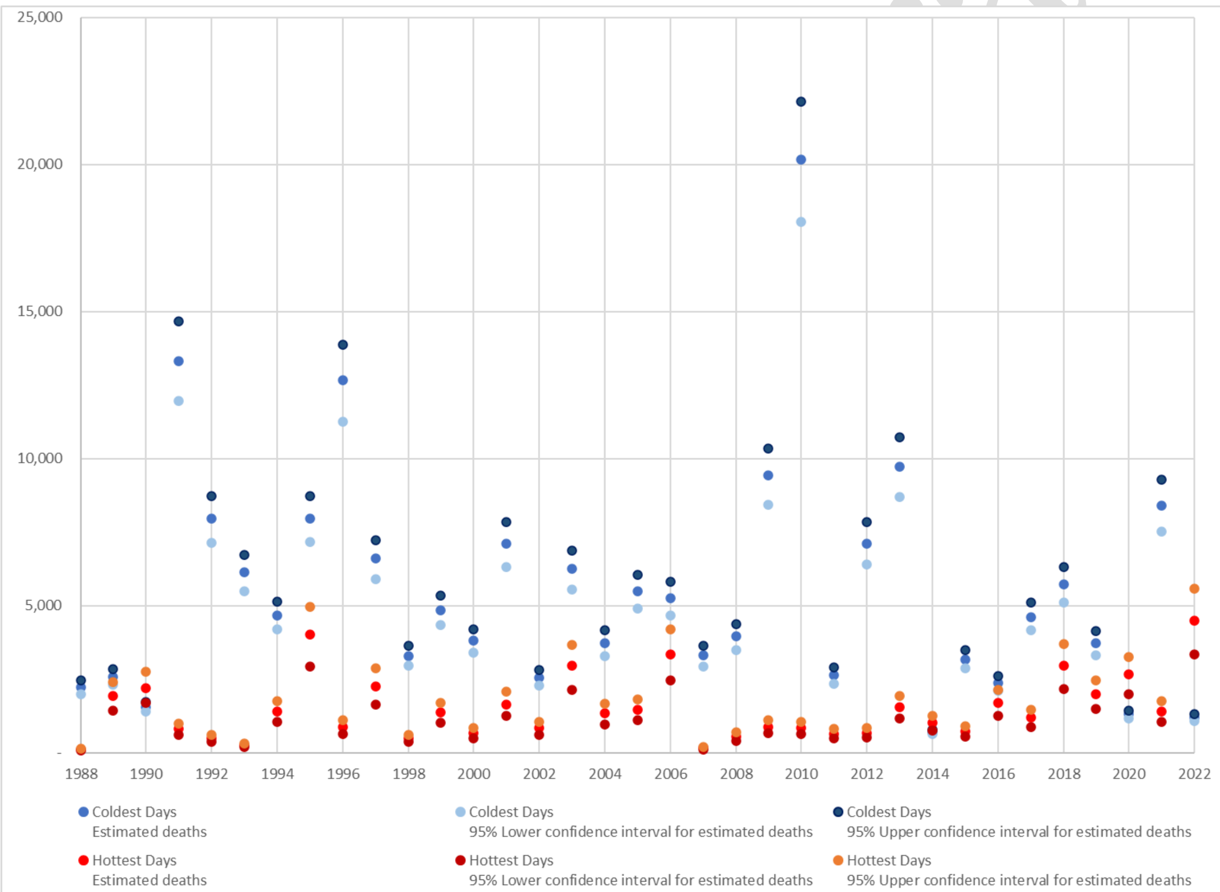
[66] See: Gasparrini, Antonio et al. "Mortality associated with high and low ambient temperature: a multicountry observational study." *The Lancet* 386 (9991). 369–375. July 2015. Available at: http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(14)62114-0/fulltext.

[67] Pierre Masselot et al., "Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe," *Lancet Planetary Health*, Vol. 7(4), E271-E281, 2023. https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(23)00023-2/fulltext

[68] https://www.gov.uk/government/publications/heat-mortality-monitoring-reports/heat-mortality-monitoring-report-2022

analysis suggests that the total may have been even higher – at 4507.[69] If so, that might, sadly, top the previous most deadly single episode, the smog of December 1952, which is estimated to have killed at least 4,000 people.[70]) This—and the almost-as-deadly heatwaves of 2020, which killed an estimated 2,556 people—*is* considerably higher than the 750 people estimated by Massenet et al. to have died from heat on average each year in UK cities over the period 2000 to 2019. However, this should be set against the 43,000 people estimated to die of cold in UK towns *each year*.

Figure 7.6 Deaths on the Hottest Days and Coldest Days in England and Wales, 1988-2022.



Source: ONS (https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/articles/climaterelatedmortalityandhospitaladmissionsenglandandwales/1988to2022)

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69 https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/articles/climaterelatedmortalityandhospitaladmissionsenglandandwales/1988to2022

70 https://www.metoffice.gov.uk/weather/learn-about/weather/case-studies/great-smog

A recent analysis of data covering the period 1988 to 2022 found that while approximately 50,000 people died of *extreme heat* in the UK over the 35 year period, four times as many—approximately 200,000 people—died of *extreme cold*. Moreover, in every single year except 2022, the number of deaths on the coldest days was greater than the number of deaths on the hottest days (Figure 7.6).

Finally, it is worth noting that the vast majority of people who die from both heat and cold are elderly. In the ONS data for the UK, in 2020 and 2022, 88% and 95% of deaths were people over 65 (respectively), while 72% and 84% were over 75.[71] The purpose of pointing this out is not to diminish the tragedy of these deaths. Rather, it is to observe that since life expectancy has increased dramatically over the course of the past century, one reason for the increased mortality from extreme heat is simply that there are more old people.

7.3 Economic Effects of An Increase in Warm Days & Reduction in Cold Days

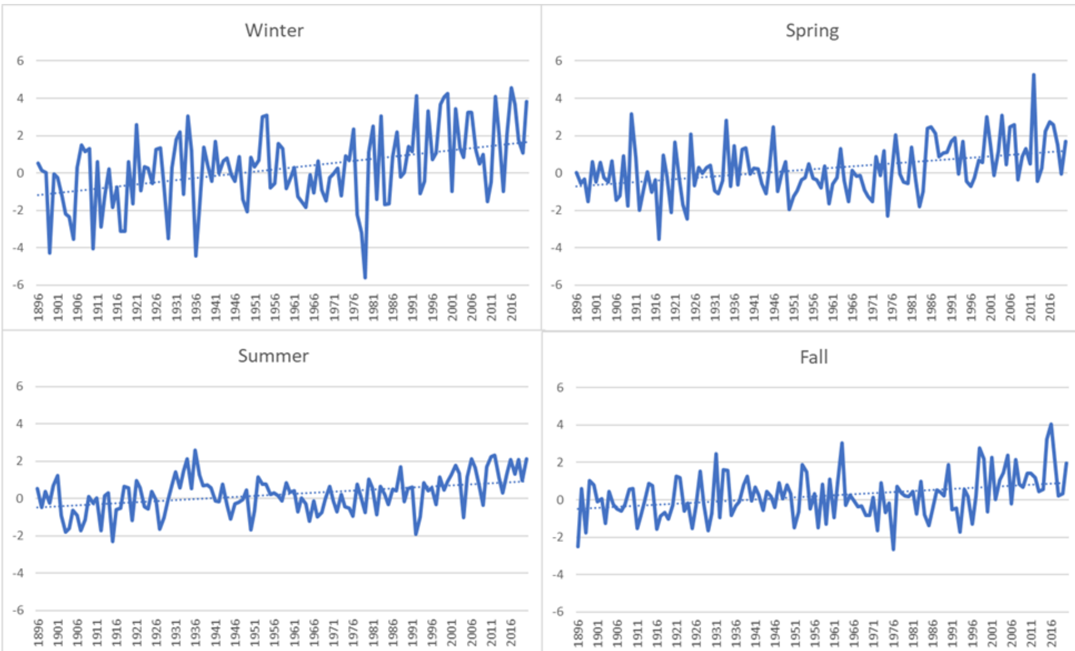
In the U.S., between 1896 and 2020, temperatures rose in winter (December, January, February) by 80% more than the average of spring (March, April, May), summer (June, July, August), and fall (September, October, November) (Figure 7.7). Meanwhile, the number of annual heating degree days fell by about 1,000, while the number of annual cooling degree days rose by fewer than 500 (Figure 7.8).

Since it requires about the same amount of energy to heat or cool a building by 1C using the same technology (i.e. a heat pump[72]), the total amount of energy required to maintain an acceptable ambient temperature in an average building in the U.S. has declined over the past century. (If the most popular technologies in the U.S. are used –i.e. a furnace or boiler for heating and an AC for cooling—AC is actually more efficient.[73]) Similarly, using data for 157 countries over three decades, Sebastian Petrick and Katrin Rehdanz of Kiel Institute for the

[71] https://www.gov.uk/government/publications/heat-mortality-monitoring-reports/heat-mortality-monitoring-report-2022
[72] However, air-source heat pumps are less efficient when outside temperatures are very low: https://www.sciencedirect.com/science/article/pii/S2542435123003513?dgcid=rss_sd_all
[73] https://iopscience.iop.org/article/10.1088/1748-9326/8/1/014050

World Economy and Richard S. J. Tol of the Economic of the Social Research Institute in Dublin found that net energy use decreases with rising temperatures (albeit at a declining rate).[74]

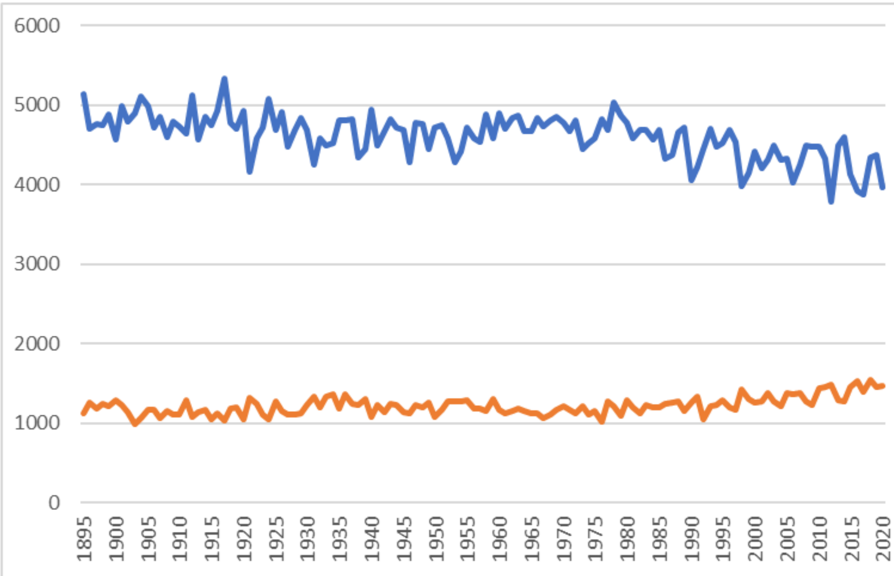
Figure 7.7. Changes in Average Seasonal Temperatures, U.S., 1895-2020.



Source: EPA:

[74] Petrick, Sebastian, Katrin Rehdanz and Richard S. J. Tol. *The Impact of Temperature Changes on Residential Energy Consumption.* Kiel Working Paper No. 1618. April 2010.

Figure 7.8 Heating Degree Days (Blue) and Cooling Degree Days (Orange), U.S., 1895-2020



Source: EPA: https://www.epa.gov/climate-indicators/climate-change-indicators-heating-and-cooling-degree-days

7.4 Discussion

While some types of extreme temperature events may have worsened over the past century, the overall effects of rising average temperatures on health and on expenditure on energy, both in the U.S. and globally, appear to be beneficial. In other words, rising temperatures have resulted in a reduction both in deaths and financial outlays.

It is also worth noting again that both mortality from and costs of heatwaves have fallen in the U.S., in spite of an increase in the number of extreme temperature days. This raises an obvious question: what has the U.S. done that has enabled it to reduce the harm of high temperatures? Most obviously, it has much more widespread adoption of air conditioning than any other country. By 1990, nearly 90% of U.S. households had some form of air conditioning, up from 12% in 1960, and two-thirds now have central AC.[75] In a 2016 study published in the Journal of Political Economy, Alan Barreca and colleagues found that mortality associated with days when

[75] https://ourworldindata.org/grapher/technology-adoption-by-households-in-the-united-states?facet=entity&country=~Home+air+conditioning; US Energy Information Administration – " Nearly 90% of U.S. households used air conditioning in 2020", 31 May 2022. https://www.eia.gov/todayinenergy/detail.php?id=52558

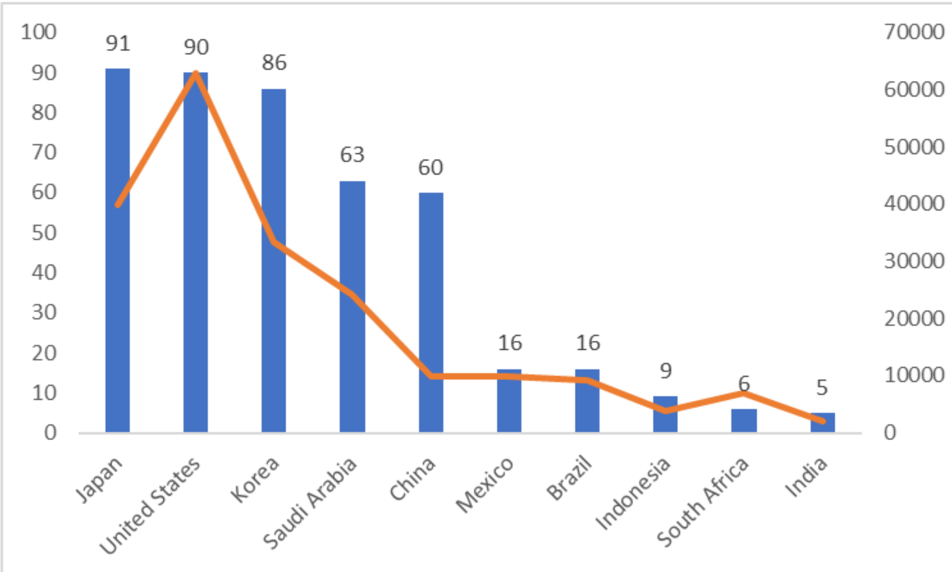
temperatures exceeded 80F (26.7C) declined by 75% during the 20th century, that nearly all of the decline followed the widespread residential adoption of AC after 1960, and (by considering differential rates of installation of AC systems) that adoption of AC was causally related to the decline in mortality.[76] The authors estimate that the adoption of AC generated an aggregate of between $5 to $10 billion in consumer surplus per year (2012 US$).[77]

By contrast, air conditioning is relatively uncommon in Europe – so uncommon, in fact, that there are apparently no reliable estimates of its prevalence. The International Energy Agency simply says "less than 10%", while industry bodies assert similar numbers and notes that in Germany and the UK it is below 5%.[78] Estimates suggest that fewer than 10% of European households have AC.[79]

Lack of AC is also a problem in many poor and middle-income countries.[80] But the IEA estimates that as of 2018 sixty percent of Chinese households had AC, while in Mexico and Brazil only 16% of households had AC, even though the three countries had similar levels of GDP/capita (Figure 7.9). Since Brazil and Mexico generally have climates that would justify the installation of AC, factors other than climate and income clearly affect the decision to install AC.

[76] Alan Barreca, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S. Shapiro, "Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century," *Journal of Political Economy*, Volume 124, Number 1, February 2016, pp. 105-159. (https://eml.berkeley.edu/~saez/course131/barrecaetalJPE16.pdf)
[77] Barreca et al. supra note 76, at 156.
[78] https://heatiq.co.uk/blog/how-much-does-it-cost-to-install-air-conditioning-and-is-it-worth-it/
[79] IEA:
[80] https://www.iea.org/data-and-statistics/charts/percentage-of-households-equiped-with-ac-in-selected-countries-2018; https://eprints.lse.ac.uk/113643/1/1_s2.0_S0959378021000789_main.pdf

Figure 7.9 Proportion of Households with AC (Columns, Left Axis, %) and GDP/Cap (Line, Right Axis, USD), Select Countries (2018)



Source: IEA https://www.iea.org/data-and-statistics/charts/percentage-of-households-equiped-with-ac-in-selected-countries-2018 and World Bank

Some commentators have worried about the consequences of increasing adoption of air conditioning.[81] There are two problems with such concerns: first, they implicitly assume that the immediate health benefits of air conditioning are of less value than the long-term effects of associated emissions, which seems at best questionable. Second, such analyses ignore the reductions in emissions that result from the warmer winters, which as noted more than offset the increase in cooling due to warmer summers.

8. Overall Changes in Extreme Weather Events & Their Effects

This section draws together evidence regarding the incidence and effects of extreme weather events as a whole, providing some context regarding the relative

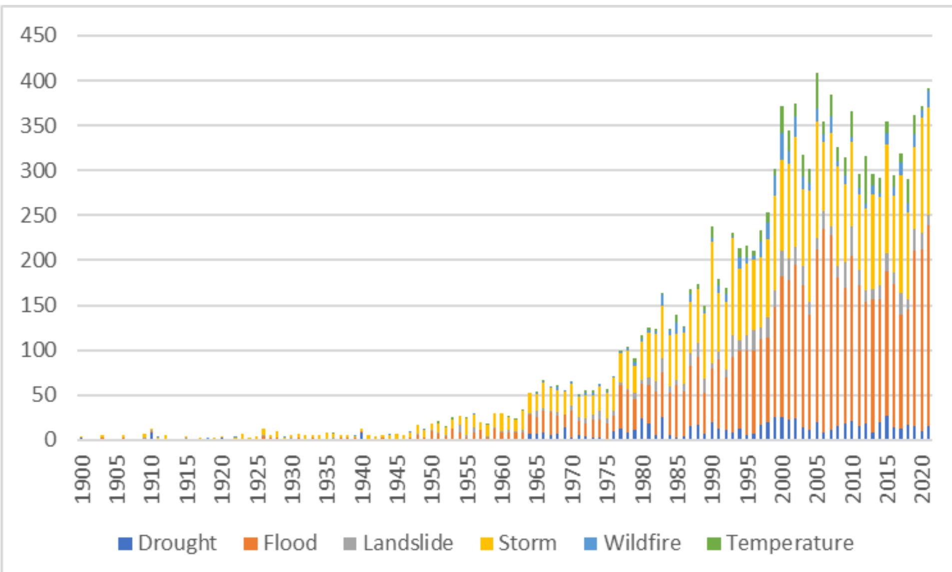
8.1 The Incidence of Extreme Weather Events

As noted in the introduction, the incidence of extreme weather events as recorded in the EM-DAT database has increased dramatically over the past century. The majority of that increase has

[81] Olivier Deschenes The Impact of Climate Change on Mortality in the United States: Benefits and Costs of Adaptation, NBER Working Paper No. 30282, July 2022 https://www.nber.org/system/files/working_papers/w30282/w30282.pdf

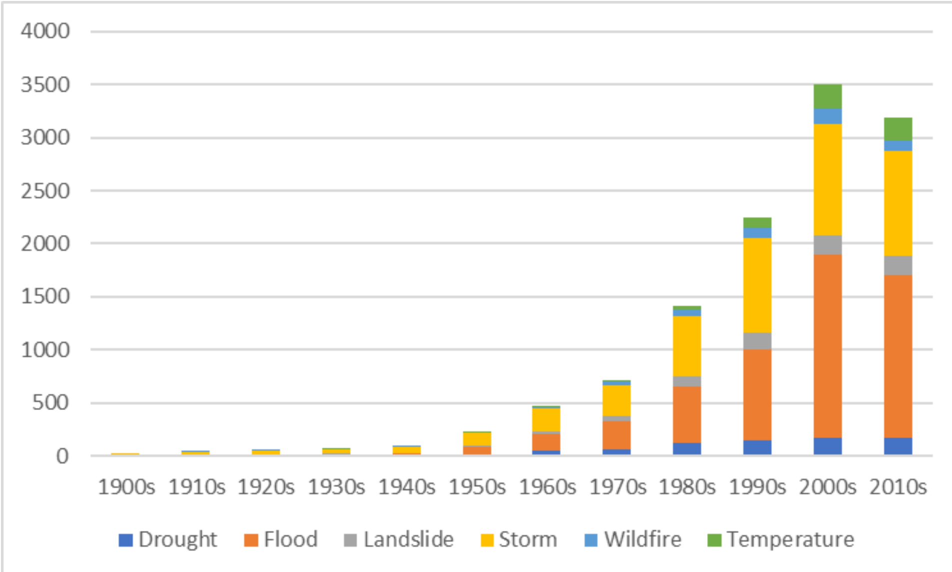
come from floods and storms (Figures 8.1 and 8.2). As noted in section two, major storms such as hurricanes and tornadoes have not increased significantly over the past 100 years. While the number of floods may have increased, it is unlikely that they have increased by nearly the rate implied in the EM-DAT data. In other words, a better understanding of the broader patterns of extreme weather events (as documented in this study) reinforces the concern that there is a reporting bias in EM-DAT data, leading to an apparent increase in the number of extreme-weather events that is disproportionate to the *actual* increase.

Figure 8.1: Incidence of Extreme Weather Events per Year, 1900-2021



Source: EM-DAT

Figure 8.2 Incidence of Extreme-Weather Events per Decade, 1900-2019

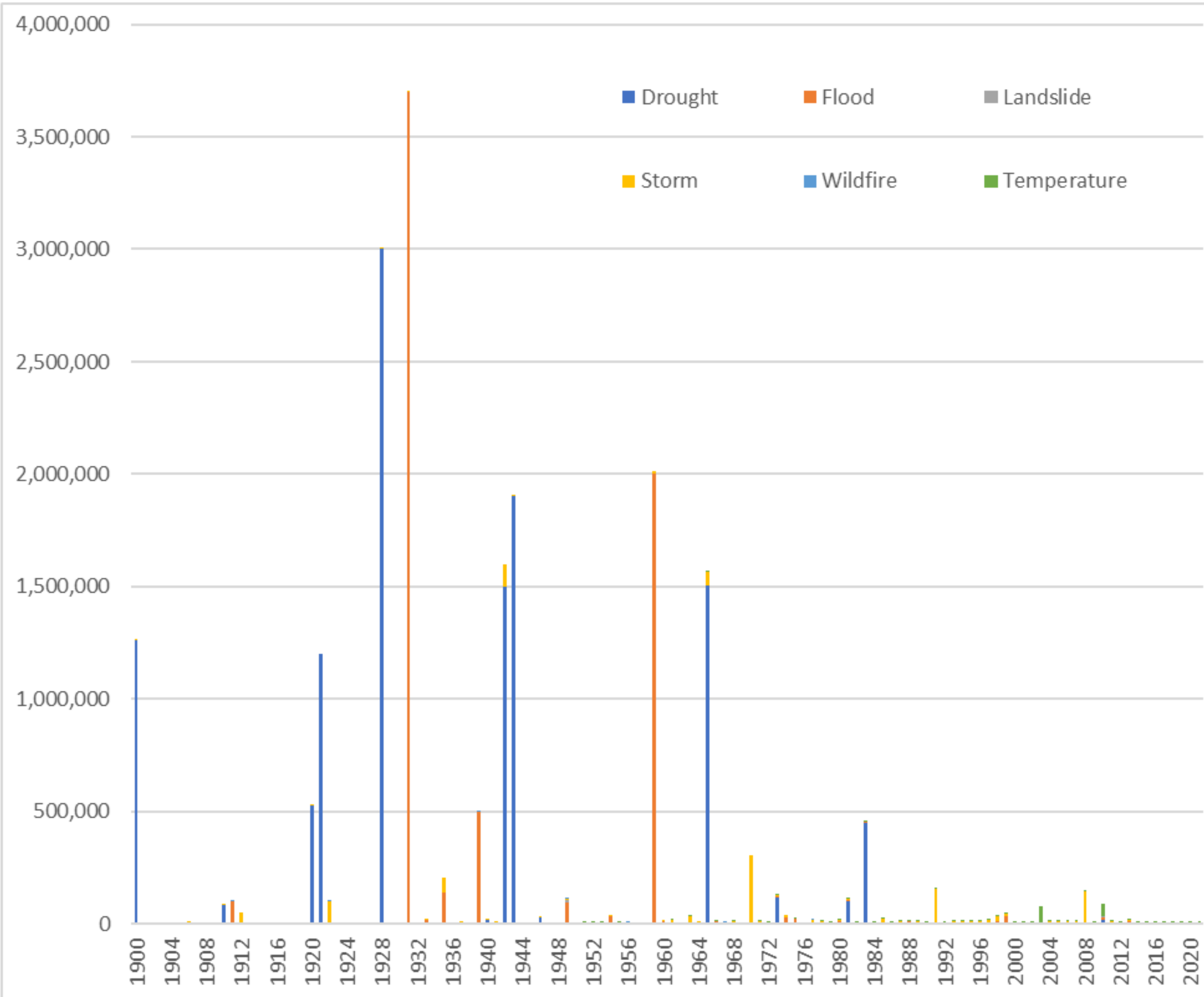


Source: EM-DAT

8.2 Mortality From Extreme Weather Events

Figure 8.3 shows the mortality from all extreme weather events, as documented by EM-DAT, for each year from 1900 to 2021 using stacked bar charts. More than perhaps any other figure in this study, it shows just how dramatically mortality from such events has declined— even with the recent increase in mortality from extreme temperatures in Europe. It also shows that this decline has come mainly from reductions in mortality due to droughts, floods, and storms.

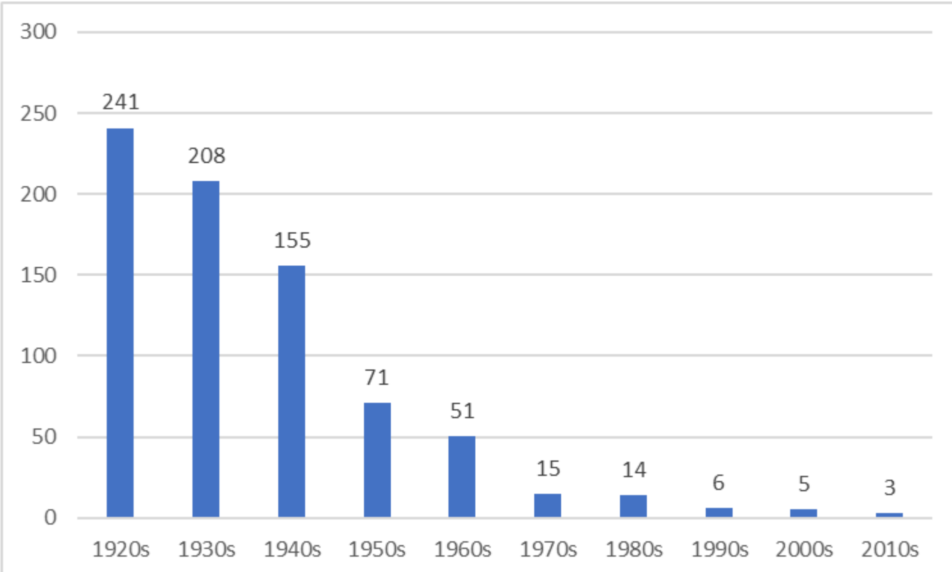
Figure 8.3 Annual Mortality from Extreme Weather Events, Global, 1900-2021



Source: EM-DAT

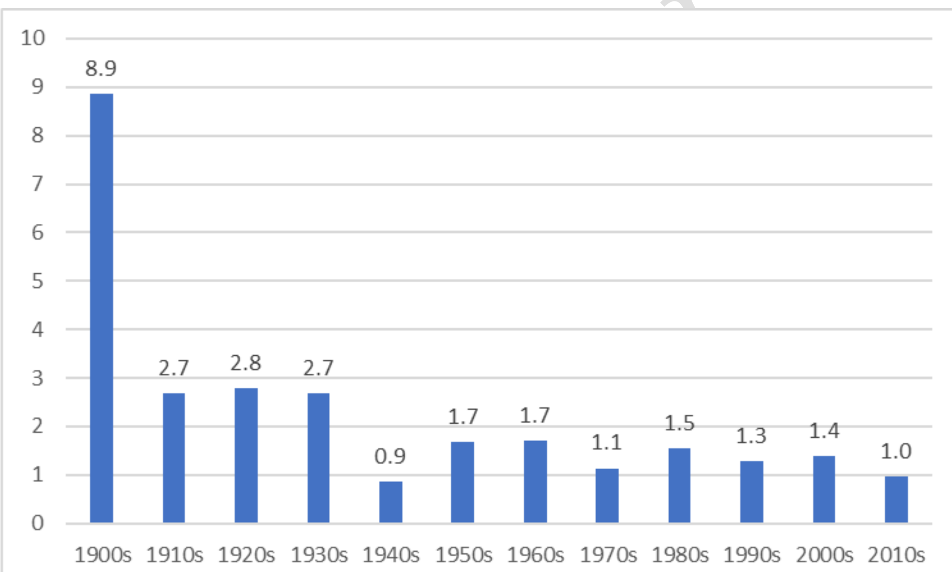
Figures 8.4 and 8.5 show the trend in overall average annual mortality from extreme weather events globally and for the U.S., respectively. These trends are remarkable in several respects. First, they confirm that despite a dramatic increase in population density (which as already noted has contributed to an increase in the number of natural disasters that meet the EM-DAT criteria), the mortality rate from extreme weather events had declined precipitously. Indeed, the average annual mortality rate from such events in the 2010s was 99% lower than in the 1920s. Second, by the 1910s, the average annual mortality rate for extreme weather events in the U.S. was already lower than the current global average and has continued to fall ever since.

Figure 8.4 Average Annual Mortality Rate per Million from Extreme Weather, Global



Source: EM-DAT

Figure 8.5 Average Annual Mortality Rate per Million from Extreme Weather, U.S.

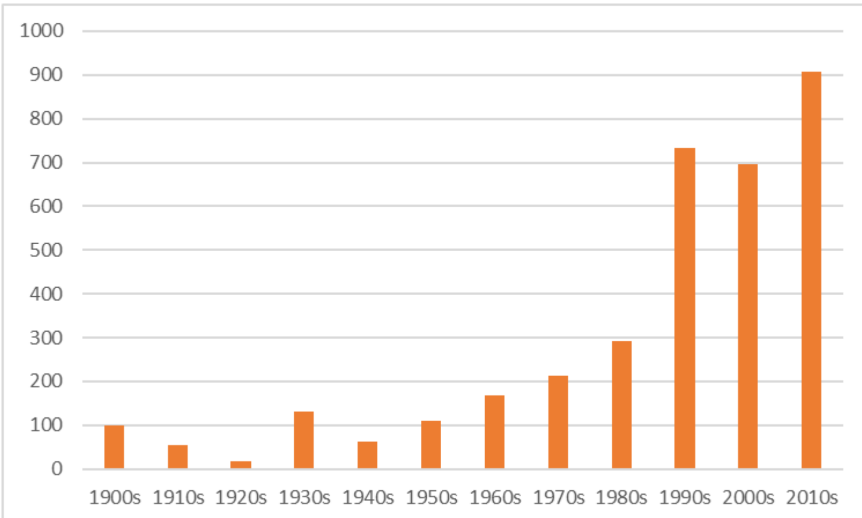


Source: EM-DAT

8.3 Economic Consequences of Extreme Weather Events

At a global level, even adjusting for inflation, economic growth, and population growth, the economic damage from extreme-weather-related events has grown nine-fold since the 1900s, based on EM-DAT data (Figure 8.6). However, as noted in the introduction, the EM-DAT database is subject to selection bias, so it is possible that a good part of this rise is a result of the increase in the proportion of disasters that meet the EM-DAT criteria.

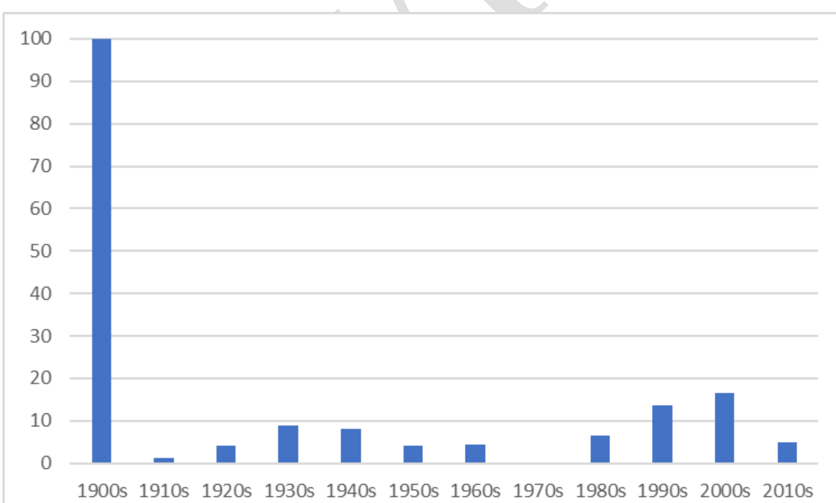
Figure 8.6: Damage Caused by Extreme Weather, Rebased (1900s = 100), Global



Sources: EM-DAT, OurWorldInData

In contrast to the global picture, in the U.S., similarly adjusting for inflation, economic growth and population growth, damage per decade from extreme-weather related events have fallen by about 95% since the 1900s (Figure 8.7). Meanwhile, if we exclude the first decade of the 20th century, damage per decade has not changed significantly.

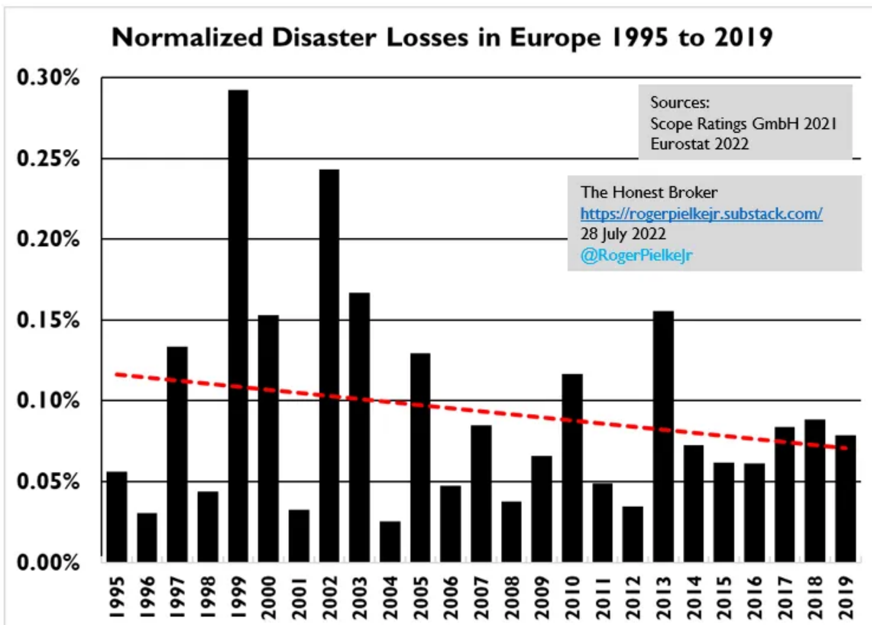
Figure 8.7: Damage Caused by Extreme Weather, Rebased (1900s = 100), U.S.



Sources: EM-DAT, World Bank

In Europe (the 34 countries that are covered by the European Environment Agency, which includes the UK), nominal losses from weather-related natural disasters rose during the period 1995-2019.[82] But when these losses are normalized to account for increases in the value of assets, they actually fell considerably (Figure 8.8).[83]

Figure 8.8: Normalized Losses from Weather-Related Natural Disasters in Europe 1995-2019.



Source: Roger Pielke Jr: https://rogerpielkejr.substack.com/p/making-sense-of-trends-in-disaster-ced

8.4 Discussion

The decline in mortality from extreme weather events despite the increase in their documented incidence is a remarkable good news story. To my knowledge, the first publication on the subject was by Indur Goklany.[84] Four years' later, I oversaw the publication of an update from Goks while I was a Vice President at Reason Foundation. Since then, numerous authors have published papers utilising and/or updating Goklany's work in various ways, perhaps most notably Bjorn

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[82] https://www.scopegroup.com/dam/jcr:eb50a1cd-7bcd-46db-a2fe-80fa9b1d76da/Scope%20Ratings_Extreme%20climate%20events_2021%20Nov.pdf (Countries included: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom.)

[83] https://rogerpielkejr.substack.com/p/making-sense-of-trends-in-disaster-ced

[84] https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=c0405c0e8dff048677d9b72fe10dd93a2891da69; see also https://reason.org/wp-content/uploads/files/deaths_from_extreme_weather_1900_2010.pdf

Lomborg[85] and Hannah Ritchie, Pablo Rosado and Max Roser at OurWoldInData.[86] Even the World Meteorological Organisation (WMO) has noted the trend.[87]

The lack of evidence of an increase in economic harm from most weather-related natural disasters would also seem to be a good news story. As noted in section 2, Roger Pielke and Chris Landsea published their first paper on normalized damage from hurricanes in 1998.[88] That work led to many subsequent studies, most of which have come to broadly similar conclusions. And when there was some debate on the matter, the Intergovernmental Panel on Climate Change (IPCC) agreed with Pielke's assessment.[89]

Given that the WMO and the IPCC are so often cited by activists and the media as authorities on climate change, it may seem odd that their views on the effects of extreme weather events are not regularly cited by those groups when it comes to extreme weather events. Although the media has occasionally covered this good news story, it seems to be forgotten as soon as there is a hurricane, tornado, flood, forest fire, or heatwave. Then, the focus shifts to the immediate problem; meanwhile, the PR departments at climate alarmist organizations (as well as the climate alarm departments at PR companies) reel out the usual mantra that "this is evidence of climate change".

Of course, extreme events *may* be evidence of climate change, so it is understandable that the media would repeat the mantra. The problem is that there is rarely if ever any sense of perspective. Journalists typically seek to ensure "balance"; so, if one group claims an event is symptomatic of climate change, a journalist might try to find another group that says it is not a sign of climate change. Rarely will they seek out someone who says, "Well, it's true, this heatwave that is killing hundreds of people could be a consequence of climate change, but that same climate change is reducing the severity and extent of cold weather, which on net is saving thousands of lives every year. Moreover, in some countries—most notably the US—heatwaves

85 Lomborg has published dozens of articles on the theme (https://lomborg.com/news?field_category_target_id=21&field_area_target_id%5B0%5D=16&field_language_target_id%5B0%5D=136&page=4),
86 Ritchie et al.'s work is at: https://ourworldindata.org/natural-disasters.
87 https://public.wmo.int/en/media/press-release/weather-related-disasters-increase-over-past-50-years-causing-more-damage-fewer
88 Roger Pielke, Jr. & Chris Landsea, "Normalized hurricane damage in the United States: 1925–95." *Weather Forecasting* 13, 1998, 621–631.
89 https://thebreakthrough.org/issues/energy/ipcc-sides-with-roger-pielke-jr

are killing fewer people because of widespread adoption of air conditioners in homes; maybe Britons should be encouraged to do likewise."

Unfortunately, the lack of such nuanced perspectives magnifies the impression that discussions of climate change are "polarized".

9. Conclusions

At the outset, this paper asked whether the evidence supported Greta Thunberg's assertion that "People are suffering. People are dying" as a result of climate change. The somewhat surprising answer is that although some people *might* be suffering and dying in part as a result of climate change, far *fewer* people are suffering and dying today of the kinds of problems most associated with climate change than were dying in decades past. So, while climate change might have changed the pattern of extreme weather events, humanity has implemented technologies that have so dramatically diminished the consequences that we are now arguably at less risk from most weather-related natural disasters than at any time in human history.

There are exceptions, however. In particular, wildfires and extreme heat seem to be causing more death and destruction (albeit still in relatively small amounts compared to other weather-related disasters).

In the case of the former, the problem does not seem to be primarily climate-related: evidence suggests that the area burnt by wildfire has not been increasing—indeed from 1996 to 2016 it declined at a global level. The main problem appears to be an increase in the number of people living in the Wildland-Urban Interface (WUI) and the failure to adjust forestry management practices to limit the risks associated with this change in habitation. This is likely being exacerbated by climate change in places such as the Western US, which appears to have become both hotter and drier. But the most straightforward and effective way to reduce the risk is by rectifying the underlying management issues.[90]

When it comes to extreme heat, perspective matters. Global warming appears to be reducing net deaths from extreme temperatures because rising temperatures during winter months are

[90] Julian Morris, *Devastating Fires Show Forest Management Reforms Are Badly Needed*, Los Angeles: Reason Foundation. https://reason.org/policy-brief/forest-fires-management-reform/

reducing the (much larger) number of people who die each year from cold at a greater rate than rising temperatures during summer months are leading to additional deaths from heat. However, many people continue to die from both cold and heat despite the existence of ample technologies that could prevent most of these deaths, as evidenced by the decline in deaths from both cold and heat in the U.S. Improving access to better technologies—ranging from insulation to heating and cooling systems—would dramatically reduce these deaths.

Some other weather-related natural disasters cause more economic damage in nominal terms today than in the past. However, as with wildfires, this appears to be due to increased building in affected areas (hurricane zones, flood plains, etc.), not to an increase in the severity of the underlying hazards. When increases in population density and the value of assets are taken into account, there is no increase in the thus-normalized loss over the past century.

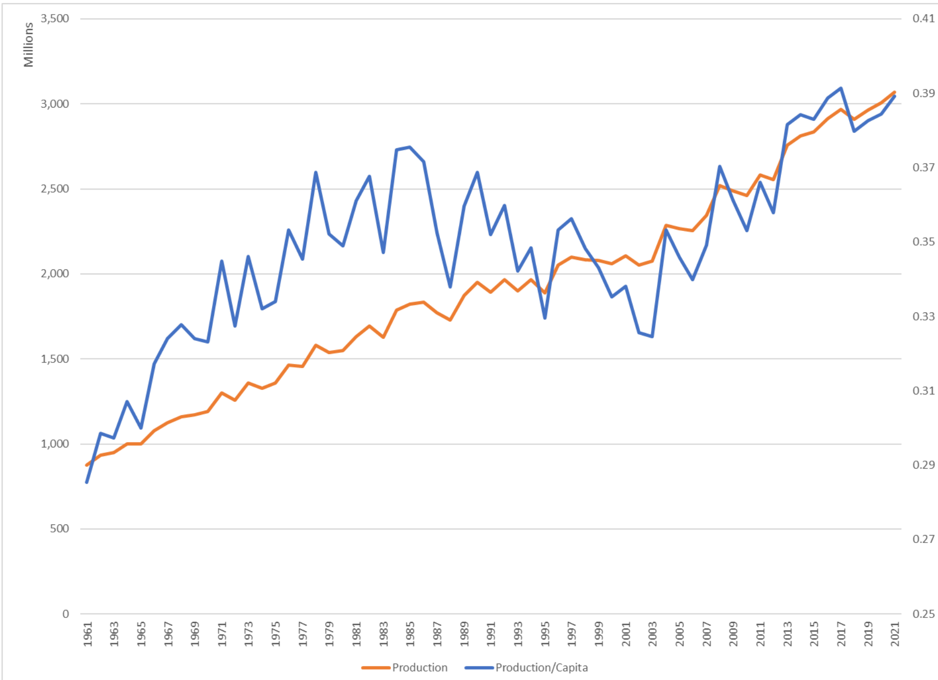
9.1 Technologies to Weather Climate Change

Global warming may be changing the patterns of extreme weather events but humanity has shown that—so far at least—it can outwit these changes. Indeed, it has done better than that, as this study shows it has dramatically reduced mortality from such events. But it could do more both with technologies that already exist and also through future innovations.

It would be easy to produce an entire study devoted to technologies that reduce mortality and economic loss from extreme weather events but a few deserve a brief mention:

Improvements in agricultural technologies, including new crop varieties, better fertilisers, modern pest management technologies, systems for targeted application of fertiliser and pesticide, mechanisation, and automation have dramatically increased yields of cereal crops. Indeed, yields have increased so much that the world is now producing more than three times as much as it was in 1961, which means that although the world's population has increased from 3 billion to 8 billion, per capita cereal yields have gone up by about 30% (Figure 9.1).

Figure 9.1: Global Cereal Production (Orange, left axis) and Production Per Capita (Blue, right axis), tonnes/year, 1961-2021.



Source: Author based on FAO (production) and World Bank (population)

Yields per hectare have risen dramatically across the world, but there remain wide differences, some but not all of which can be explained by variations in environmental conditions (soil, climate, etc.) (Figure 9.2). There thus remain significant opportunities to increase adoption of such technologies more widely.

Technologies already in development and those likely to be developed in the near future also promise dramatic increases in yields, even in countries where yields are already high. For exampe, the application of modern biotechnology (including gene editing) has the potential to produce crops that are better adapted to higher temperatures and more arid climates.[91] Meanwhile, the use of advanced sensors, machine learning and robotics can help improve targeting of nutrients and pest management, further increasing yields and reducing waste.[92] Genetically enhanced crops may also result in reductions on greenhouse gas emissions.[93]

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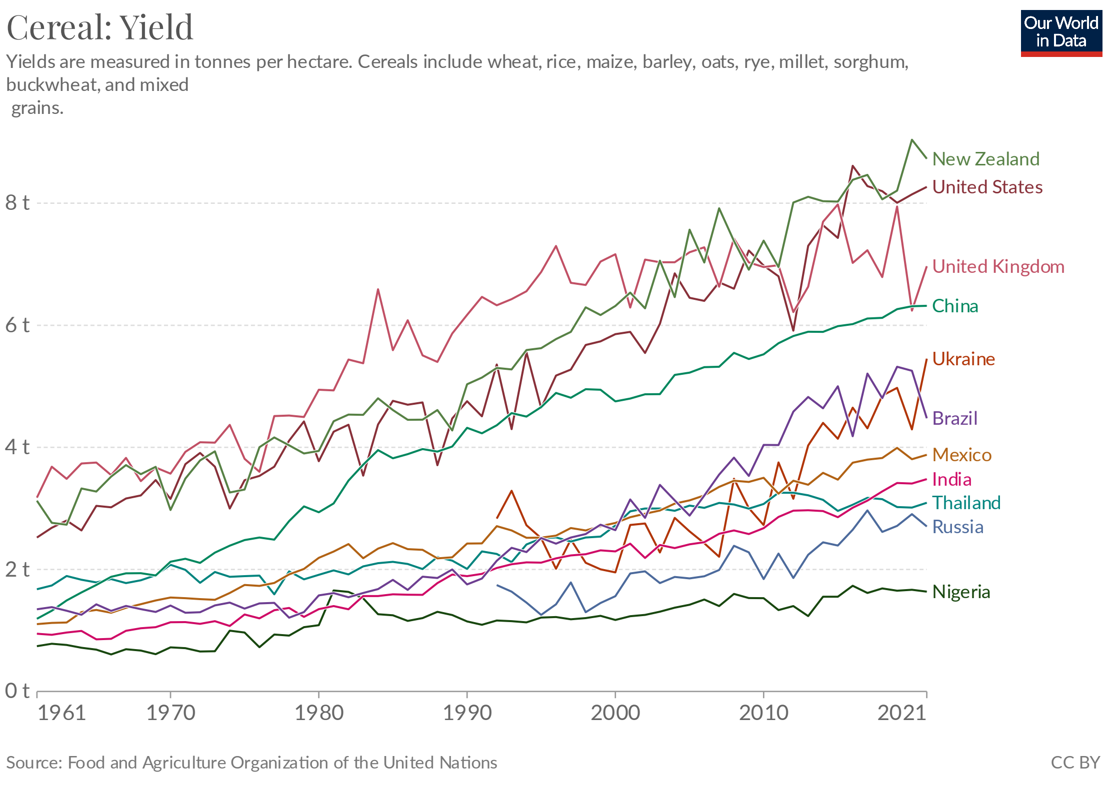
91 https://www.frontiersin.org/articles/10.3389/fsufs.2021.685801/full;

92 https://www.mckinsey.com/industries/agriculture/our-insights/agricultures-connected-future-how-technology-can-yield-new-growth

93 https://www.researchgate.net/publication/358436513_Genetically_modified_crops_support_climate_change_mitigation

Figure 9.2: Cereal Yields in Select Countries, tonnes/hectare, 1961-2021



Improvements in building technologies have helped reduce both mortality and economic loss from storms, floods, and other weather-related natural disasters, as well as other non-weather-related disasters such as earthquakes.[94] More widespread adoption of such technologies would further reduce those losses.[95]

Likewise, improvements in physical infrastructure (including roads, rail, bridges, water pipes, sewers, pylons, ducts, cables, ports, levees, sea walls, and dams), related facilities (such as pumps, substations, and repeaters), and natural barriers such as mangroves, have reduced the impact of weather-related natural disasters.[96] But, again, much more could be done, especially in lower-income countries.[97]

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[94] https://www.fema.gov/emergency-managers/risk-management/building-science/building-codes-save-study
[95] Id.
[96] https://www.oecd-ilibrary.org/sites/800b0352-en/index.html?itemId=/content/component/800b0352-en; https://www.oecd.org/environment/cc/policy-perspectives-climate-resilient-infrastructure.pdf;
[97] https://www.adb.org/publications/quality-infrastructure-and-natural-disaster-resiliency

As noted, air conditioning has dramatically reduced mortality from heat in the U.S., including during extreme heat events. About 90% of U.S. households have AC installed, which is among the highest AC adoption rates in the world (Figure 7.9). By contrast, many countries—even wealthy countries in Europe—have very low adoption rates. Perhaps surprisingly, about 60% of households in China have AC, suggesting that middle- and high-income countries could have much higher adoptions rates if households chose to prioritise their adoption.

Of course, there are many, many other technologies, in existence and yet to be invented, that have the potential to reduce mortality, morbidity and economic loss from weather-related natural disasters. For example, floating garages might offer a low-cost way for people living in flood-prone areas to protect their vehicles.[98] It is even conceivable that in the future, technologies might be developed that turn some extreme weather events to our benefit—for example by harnessing the power of storms.[99]

9.2 Policies to Weather Climate Change

While improvements in specific technologies have undoubtedly driven the decline in mortality from weather-related natural disasters, these improvements have formed part of, and been underpinned by, broad-based technological improvements. For example, improvements in agricultural technologies have often coincided with innovations in other areas such as chemical engineering (for example, the development of the Haber-Bosch process for manufacturing ammonia from natural gas),[100] automotive engineering (the tractor was invented by Victor Froelich who adapted the gasoline engine that had initially been developed to transport people and goods),[101] and—more recently—AI and robotics (the development of sensor-based precision agriculture and autonomous farm machines has been underpinned by developments in various technologies that are broadly part of the AI/robotics revolution).[102]

Over the course of the past century, these broad-based technological innovations have led to economic growth and a diversification of employment away from agriculture that have

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[98] https://www.topgear.com.ph/features/feature-articles/flood-proof-floating-garage-a4354-20201126
[99] https://www.smithsonianmag.com/innovation/can-we-capture-energy-hurricane-180960750/#:~:text=So%20while%20wind%20is%20only,gold%20mine%20of%20clean%20energy.
[100] https://www.thechemicalengineer.com/features/cewctw-fritz-haber-and-carl-bosch-feed-the-world/
[101] https://www.froelichtractor.com/the-tractor.html#:~:text=In%201892%20in%20the%20tiny,were%20used%20to%20thresh%20wheat.
[102] https://www.sciencedirect.com/science/article/pii/S2667318523000016

dramatically reduced the extent to which most citizens in most countries are directly susceptible to the effects of extreme weather on income-generating activities.[103] As Figure 9.3 shows, countries whose citizens are less reliant on agriculture tend to score higher on the UNDP's Human Development Index.

Figure 9.43 Share of Employment in Agrifood Systems and Human Development Index score.

Source: https://www.fao.org/3/cc4337en/cc4337en.pdf

The implication is clear: policies that facilitate broad-based innovation and economic diversification are important, nay essential to create societies that are both adaptive to and resilient in the face of extreme weather events—and climate in general. Since this not a paper about what begets such innovation and economic diversification, a subject on which there are thousands of books and research papers, it will not address the problem in detail.

In some cases, government policies have had the perverse effect of encouraging people to live in locations that are prone to extreme weather events. In the U.S., for example, the National Flood Insurance Program has encouraged people to live in flood-prone areas, including those subject to hurricane-driven tidal surges.[104] Such programs should obviously be scrapped.

Finally, there is the question of which policy approaches are best suited to address the aftermath of a natural disaster. After Hurricane Katrina, the Mercatus Center at George Mason University

103 https://www.fao.org/3/cc4337en/cc4337en.pdf
104 https://www.insurancebusinessmag.com/us/news/catastrophe/national-flood-insurance-program-incentivises-perverse-behaviour-59779.aspx

launched a massive, multiyear, multidisciplinary research programme to understand which types of collective action were most effective in addressing the aftermath of the storm and facilitating reconstruction.[105] Since the work produced dozens of articles and at least seven books, it would not be fair to summarize it in a few words. Having said that, in very, very broad terms, the researchers found that decentralized governance and free markets worked better than centralized governance and controlled markets.

105 https://www.mercatus.org/hayekprogram/economic-insights/expert-commentary/mercatus-disaster-recovery-research