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ORIGINAL PAPER

Assessment of lightning mortality in the United States from 1979 to 2023

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Abstract
Climate change has been linked to an increased prevalence of lightning activity associated with hazardous storm formation. An increased frequency in lightning activity in the United States (US) would presumably increase the risk and incidence for lightning-related injuries and fatalities. Using cause of death data available from the US Centers for Disease Control (CDC) and Prevention via their WONDER online databases and the National Weather Service, the results showed a steady decline in the lightning-related mortality incidence and incidence rates in the US from 1979 to 2023. In the early 1980s, US death rates were near four per 10 million, and are now near one per 10 million. Death rates in the American South are higher, but have also experienced improvement, having fallen from near six per 10 million in the early 1980s to two per 10 million in recent years. A limitation of this study is a lack of data on lightning-related injuries. Overall, the steady decline in lightning-related deaths in the US likely is related to a multitude of factors including early storm reporting, improved risk communication, improved public education regarding the hazard, increased urbanization and mechanization of outdoor work, improvements in emergency medical care, among other weather-related risk reduction strategies. These results highlight the success of risk reduction strategies for reducing lightning-associated mortality in the US while the threat of hazardous lightning has likely continued to increase.

Keywords Fatalities · Mortality · Lightning · Trends · United States · Storms

1 Introduction

The Centers for Disease Control (CDC) and Prevention reports there were 444 deaths attributable to lightning strikes from 2006 through 2021 in the United States (CDC 2024) or 27.8 deaths per year. The latest 10-year average for lightning mortality is 18.6 deaths per year

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for the 2015–2024 period (National Weather Service 2025a) with 14 fatalities in 2025 as of the end of July. The decreased incidence is on track with the slight, but steady, decrease observed by Duclos and Sanderson (1990) when the incidence of lightning-related deaths fell from approximately 130 to 90 deaths per year between 1968 and 1985.

The decreased incidence in lightning-related mortality in the US is notable given presumed changes in climate that may have increased the frequency of hazardous lightning. Between 25 and 40 million lightning strikes hit the ground in the United States (US) annually according to the National Weather Service (2025b) and CDC (2025a), respectively. The prevalence of these lightning strikes is presumed to be increasing as both air temperatures (Williams et al. 2005; Price 2008; Romps et al. 2014; Price and Rind 1994) and nitrous oxides have increased (Schumann and Huntrieser 2007; Banerjee et al. 2014). Some uncertainty remains regarding if there has been or will be increased lightning prevalence everywhere due to the complexity involved with lightning formation with respect to changes in local atmospheric chemistry. For example, there may be decreases in lightning strikes in tropical regions, while there may be increases in lightning in non-tropical regions (Finney et al. 2018; Janssen et al. 2023).

For the continental US, Romps et al. (2014) predicted a 12% increase in lightning strikes for every one degree increase in global average air temperature. While not yet able to be thoroughly tested, only recently has a baseline been able to be set for characterizing the number of cloud-to-ground (CG) flashes and number of ground strikes points for the contiguous US (Vagasky et al. 2024). Vagasky et al. (2024) estimated the average number of CG flashes as 23.4 million per year with an average of 36.8 million ground contacts per year, which is expected since flashes consist of multiple strokes.

Given the ongoing prevalence of the lightning hazard, and potential increase for lightning strikes in portions of the US, we aim to present the results of lightning mortality using rates and trends to enable comparison with historical epidemiological studies on the topic. While there are valuable detailed analyses available for the 492 lightning fatalities that occurred in the US from 2006 through 2024 (Jensenius 2025; National Lightning Safety Council 2025) as well as mortality incidence data on citizen-oriented web sources (CDC 2025a); National Weather Service 2025a), there is limited reporting on mortality rates, which adjust for population size. Additionally, for building upon earlier epidemiological studies (Duclos and Sanderson 1990; Curran et al. 2000; Adekoya and Nolte 2005), we use death certificate data to present mortality rates by year for examining and comparing trends.

2 Methodology

Mortality data were extracted from the CDC using their publicly accessible "Wide-ranging ONline Data for Epidemiologic Research" (WONDER) database (CDC 2025b). The data were retrieved from WONDER using the underlying cause of death files contained within the database. For this study, there were twelve data retrievals. Four data retrievals were related to the 2018–2023 timeframe, four were related to the 1999–2017 and the other four retrievals were regarding the 1978–1998 timeframe. For each timeframe, there was one retrieval for lightning mortality data for the entire US grouped by year, and there was one retrieval for lightning mortality data grouped by Census region and year. For the remaining two retrievals for each of the three timeframes, mortality data were obtained by age category and sex. Specifically, for each timeframe there was one retrieval for lightning mortality data for the US by age categories, and similarly, a final retrieval with mortality data grouped by sex (male and female).

The lightning mortality and total population data for 1999–2017 and 2018–2023 were extracted from the CDC WONDER data sources labeled as 1999–2020 underlying cause of death by bridged-race categories and 2018–2023 underlying cause of death by single-race categories, respectively. These two mortality databases use coding specific to the International Classification of Diseases of Diseases and Related Health Problems, 10th Revision (ICD-10). Data for 1999–2023 were extracted for deaths coded by ICD-10 as X33 (victim of lightning), which is contained within X30-39 (exposure to forces of nature). The mortality data for 1978–1998 were extracted from the CDC WONDER 1968–2016 compressed mortality database, upon selecting for mortality data from 1978 to 1998 with ICD 9th Revision (ICD-9) codes. Data were extracted for 1978–1998 cases coded by ICD-9 as E907 (lightning), which is contained in E900-E909 (accidents due to natural and environmental factors). For data extracted from CDC WONDER, if any cell resulted in fewer than 10 deaths, the data were suppressed in accordance with CDC policy. For optimizing available data, age categories were pulled or combined into 10-year categories to increase the number of cells with 10 deaths or more to enable the calculation of mortality rates since data rows with less than 10 deaths are suppressed.

The underlying cause of death data available through CDC WONDER are based upon death certificates for US residents and are made available by place of residence which can be organized for the total US, region, state, and county (CDC 2025c). The ICD-10 manual (World Health Organization 2019) excludes from the X33—victims of lightning, the victims of fire caused by lightning as well as victims impacted by the fall of a tree or other object(s) caused by lightning, designating those events to ICD-10 codes (X00-09 and W20, respectively). Similarly, from 1978 to 1998, ICD-9 (UK Data Service 2025) used the same exclusions from E907. ICD codes and CDC WONDER do not detail the mechanism of lightning contact (e.g. direct strike, flashover over, etc.) responsible for fatalities.

Data were analyzed with Stata 15 (StataCorp 2017). Crude mortality rates per 10 million persons were calculated as the number of deaths divided by the population at-large multiplied by 10 million. For years with death counts below 16, CDC WONDER reported the crude rate results as unstable due to having poor reliability (Brillinger 1986). Despite this limitation, the mortality rates were calculated for inclusion in the regression models and averages.

Scatterplots incorporating linear regression analysis results were generated for visualizing and evaluating the change in lightning mortality rates by year for the whole US and for the US-South Census Region. Given the low prevalence (less than 10 cases) of lightning-related deaths by year in Census regions beyond the South, most Census region data by year were suppressed, which prevented time-trend analyses of lightning mortality by regions other than the South. In the years of 2011 and 2021, there were less than 10 deaths from lightning in the South, resulting in suppressed data in CDC WONDER. Given that fatality data by state, which correspond closely with CDC WONDER data, are available from the National Weather Service (2025a), the results for 2011 and 2021 were able to be determined and incorporated as an estimate of the suppressed values below 10 cases.

For analyzing the data, scatterplots with lines of best fit were able to be generated for the aggregated data (1978–2023) and for the data obtained by ICD-9 (1978–1998) and data obtained by ICD-10 (1999–2023). Annual and average mortality rates for the US and South Census region were obtained for 1978–2023, 1978–1998, and 1999–2023. Paired t-tests comparing lightning mortality rates by year between the South Region and US inclusive of the South, were performed. Additional analyses using barcharts were performed for assessing changes in mortality rates by 10-year age groups and sex across three time periods. These analyses were performed using the cumulative number of lightning deaths during three time periods (1979–1998, 1999–2017, and 2018–2023) and dividing by the multi-year population sizes to enable mortality rate comparisons across the three time periods. Data retrievals for age categories and sex by annual years rather than multi-year time periods resulted in a large number of rows with less than 10 cases (suppressed data) and were thus not used for analysis. The three time periods used for lightning mortality rates by 10-year age categories and sex relate to the years of the three data files in CDC WONDER.

Lastly, an empirical analysis was performed using existing research, which included a numerical comparison performed using the number of annual US lightning fatality cases from CDC WONDER versus the number of annual fatalities available on two different National Weather Service websites (National Weather Service 2025a; 2025d). The National Weather Service website data is consistent with the reporting by Jensenius (2025) and CDC (2025a), as they use the National Weather Service (2025a) storm events database, *Storm Data* (National Centers for Environmental Information 2025a), as their source for lightning fatality data. Unlike CDC WONDER which uses death certificate data, *Storm Data* utilizes reports from the media, public safety agencies, private companies, individuals, and others to individually describe and aggregately quantify deaths, injuries, property/crop damage by location, date and time (National Centers for Environmental Information 2025b). For comparing the complete data (2006–2023) on the National Weather Service websites (2025a, 2025d) and CDC WONDER fatality data, scatterplots, linear regression analyses, and paired t-tests were used.

3 Results

The frequency of lightning fatalities in the US significantly declined in the period of study (1979–2023). In 1979, there were 87 deaths; whereas, in recent years, there were 17 deaths in 2020, 11 in 2021, 19 in 2022, and 18 in 2023. The National Weather Service (2025a, b) reports 13 deaths in 2024. Lightning fatalities are remarkably lower now than early in the observation period, such as when there were 100 deaths in 1982, which represented a lightning-specific mortality rate of 4.32 deaths per 10 million persons. For comparison, the 2022 and 2023 mortality rates from lightning were 0.69 and 0.53 deaths per 10 million, respectively.

The mean number of lightning deaths (Table 1) and lightning-specific mortality rates (Table 2) are appreciably lower in the 1999–2023 period relative to the 1979–1998 period. Across US Census regions, the US South has had the highest frequency of lightning deaths. From 1979 to 2023, the mean number of deaths by year for the US South has been slightly above half of the total US. In recent years, the lowest frequency of lightning mortality for the US South has been five deaths. By comparison, the lowest frequency of deaths in 1979–1998 was 23.

Table 1 Summary statistics for the frequency of lightning deaths in the United States (US) and the US South Census Region by time period

Time period	Region	n (years)	Mean	Median	Min	Max
1979–2023	Entire US	45	54.3	50	15	100
	US South	45	29.3	29	5	58
1979–1998	Entire US	20	79.8	83	53	100
	US South	20	41.5	40	23	58
1999–2023	Entire US	25	34.2	29	15	66
	US South	25	19.6	17	5	40

Table 2 Summary statistics for the lightning-specific mortality rates in the United States (US) and the US South census region by time period

Time period	Region	Mean mortality rate per 10 Million	S.E. of mean mortality rate	*p*
1979–2023	Entire USA	2.07	0.18	0.0020
	US South	3.17	0.29	
1979–1998	Entire USA	3.24	0.16	< 0.0001
	US South	4.94	0.31	
1999–2023	Entire USA	1.13	0.11	0.0061
	US South	1.76	0.19	

Relative to the entire USA, mean lightning mortality rates in the US South Census region were significantly higher ($p < 0.0001$) according to three separate paired t-tests over the 1979–2023, 1979–1998, and 1999–2023 periods (Table 2). Upon performing f-tests associated with six linear regression analyses, all tests demonstrate significant ($p < 0.0001$) declines in the annual lightning mortality rates for the US and US South Census region (Fig. 1) across the 1979–2023 period, and over the 1979–1998 and 1999–2023 periods (Figs. 2, 3).

The scatterplots demonstrate that prior to 1990, the US was experiencing lightning mortality rates near three to four deaths per 10 million; however, by 2008, the rate dropped to below or near one death per 10 million (Fig. 1). A similar pattern existed for the US South Census region, however, the rates were approximately double the US rate (Fig. 1). As the US and South region are now approaching lightning fatality rates near zero per 10 million, the regression lines for the lightning fatality rates by year have somewhat flattened in the 1999–2023 period relative to the steep declines observed from 1979 to 1998 (Figs. 2, 3).

Lightning fatality rates by age were examined using the sets of available underlying cause of death in CDC WONDER (1979–1998, 1999–2017, and 2018–2023). The declines in the fatality rates over time are apparent for all age groups (Fig. 4). For two age groups, there have been less than 10 fatalities (suppressed data) in the 2018–2023 observation period, specifically the groups aged 5–14 years and 75–84 years. In 1979–1998, the mean annual fatality rate was highest among the 15- to 24-year-old age group, and this group has had the greatest improvement marked by the most substantial reduction in the mean annual fatality rate since 1999. In the most recent period (2018–2023), the 25- to 34-year-old and 35- to 44-year-old age groups exceeded the 15- to 24-year-old age group with higher average annual lightning fatality rates (Fig. 4).

Using a similar time period-based analysis of average annual lightning mortality rates by sex rather than age group, considerable declines have been observed for both males and

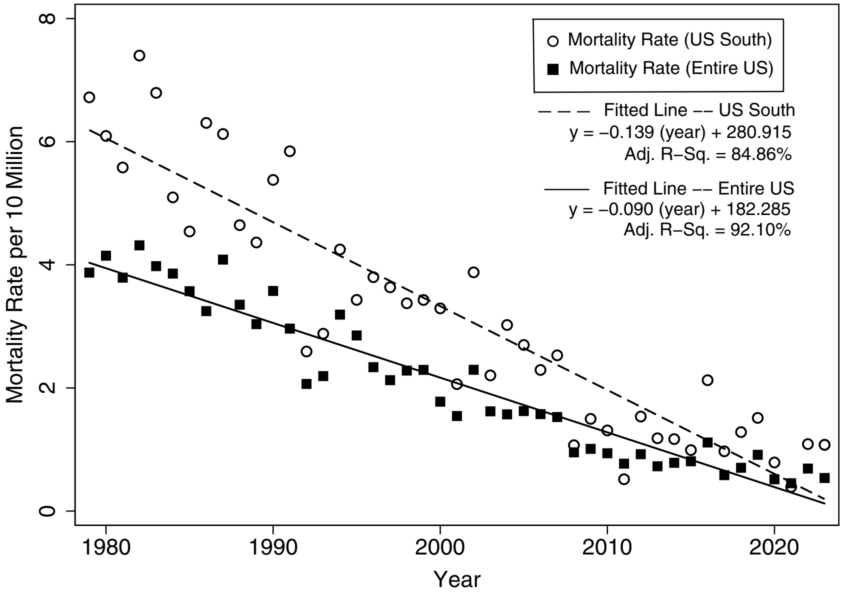

Fig. 1 Scatterplot depicting the change in the lightning mortality rate per 10 million persons for the entire US and the US South from 1979 to 2023 accompanied with a linear regression line-of-best fit for the entire US and the US South

females. While the absolute decline in the number of fatalities and fatality rates has been much greater among males (Fig. 5), the relative decline has been similar for both sexes (~80%). Specifically, the mean annual fatality rate per 10 million women was 0.913 in the 1979–1998 period, which improved to 0.199 in the 2018–2023 period marking a 78.2% decline. Similarly, an 80.7% decline in the average annual mortality rate for 10 million men improved from 5.610 to 1.081 for the respective time periods.

Upon assessing the fatality data used in this study from CDC WONDER versus National Weather Service (2025a, 2025d) data, scatterplots were developed (Fig. 6).

Figure 6 shows very strong correlations ($R^2 > 90\%$) between the annual lightning fatality statistics in CDC WONDER (used for the rates in this study) versus the data presented on the two National Weather Service (2025a, 2025d) websites informed by *Storm Data*. While not the focus of Fig. 6, upon comparing the data from the two National Weather Service websites, there is near-perfect correlation ($R^2 = 99.6\%$), which is expected since they use the same underlying data source. Upon comparing the annual fatality totals from CDC WONDER versus the National Weather Service (2025a, 2025d) fatalities website and lightning safety website, no significant difference was observed ($p = 0.434$; $p = 0.121$; respectively) upon performing paired t-tests between the CDC WONDER dataset and the two National Weather Service datasets (available in Table S1 [Online Resource 1]).

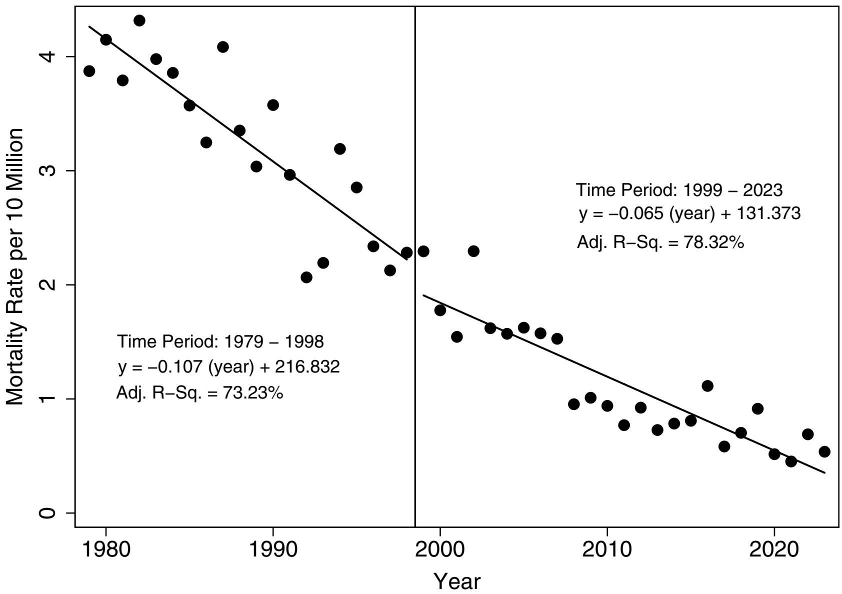

Fig. 2 Scatterplot for the US lightning mortality rate by year from 1979 to 2023 accompanied with linear regression lines specific to 1979–1998 (left) and 1999–2023 (right)

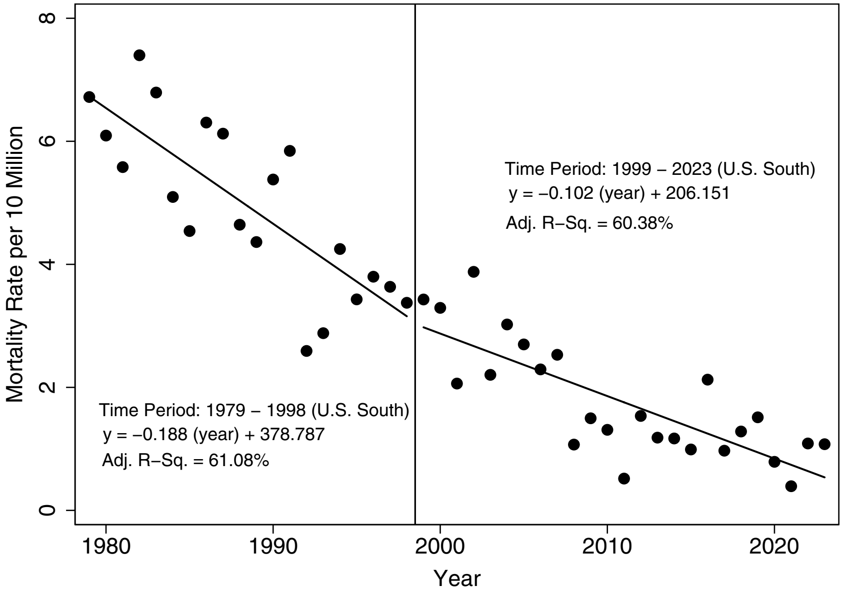

Fig. 3 Scatterplot for the lightning mortality rate by year for the US South Census region from 1979 to 2023 accompanied with linear regression lines specific to 1979–1998 (left) and 1999–2023 (right)

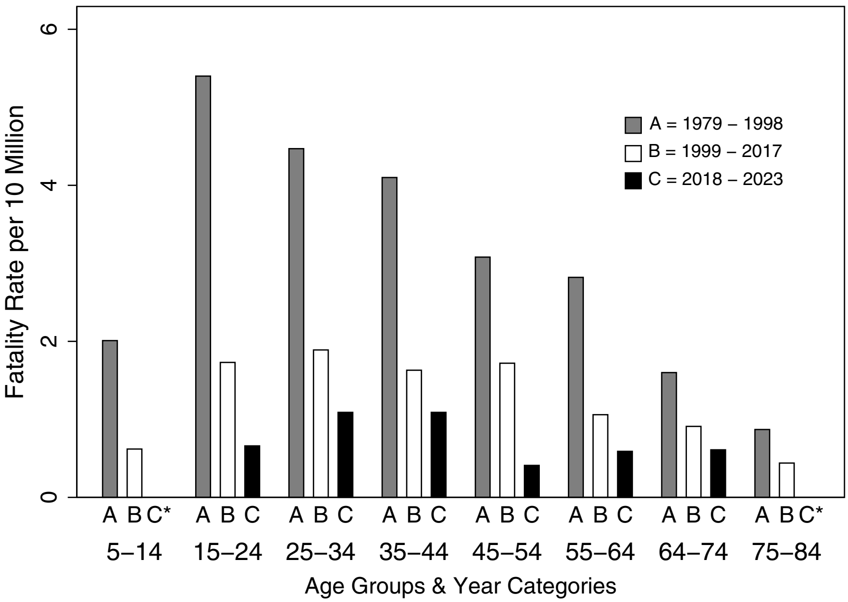

Fig. 4 Barchart for the mean annual lightning mortality rates in the US organized by 10-year age groups across three time periods: **A** 1979–1998, **B** 1999–2017, and **C** 2018–2023

4 Discussion

Consistent with prior research, the frequency of lightning-related deaths has continued to decline across the US overall and US South over time (Duclos and Sanderson 1990; Curran et al. 2000; Adekoya and Nolte 2005; Holle et al. 2005; Jensenius and Franklin 2014; Jensen 2023). The declines in lightning deaths by year are particularly notable given increases in the US and Southern US populations, which are reflected by the decreases in the mortality rates. Furthermore, these decreases are potentially more notable if there has been a true increase in the frequency of cloud-to-ground lightning (Williams et al. 2005; Price 2008; Romps et al. 2014; Yair 2018; Price and Rind 1994). While there may have been fewer lightning fatalities during the COVID-19 pandemic in 2020 and 2021, which speculatively could be attributable to different outdoor- and work-related human behaviors, the trend towards a lower mortality rate was already apparent prior to 2020. Furthermore, as of September 2024, the reduced frequency of lightning mortality through 2024 for the entire US population was sustained with 13 deaths, respectively (National Weather Service 2025a, 2025b).

The findings related to lightning fatalities may demonstrate significant public health achievements associated with the ongoing and historical activities of the National Oceanic and Atmospheric Administration (NOAA) and National Weather Service, Lightning Safety Alliance, US National Lightning Safety Council, emergency medical care providers, the individuals who are part of these organizations, among others. Future studies examining trends in lightning-related injuries and annual ratios of fatalities-to-injuries may be informative in understanding the relative importance of emergency medical care, human behaviors,

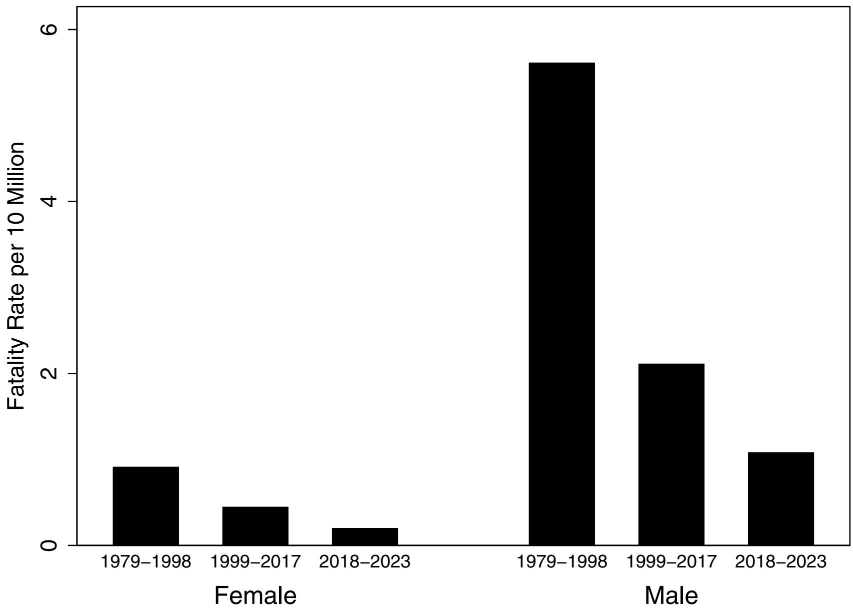

Fig. 5 Barchart for the mean annual lightning mortality rates in the US organized by sex across three time periods: **A** 1979–1998, **B** 1999–2017, and **C** 2018–2023

and urbanization regarding lightning risk mitigation and the overall reduction in lightning fatalities. For example, lightning deaths are highly correlated to the percentage of the population living in rural areas in the US as well as countries experiencing urbanization (Cooper et al. 2019) with the majority of deaths worldwide occurring in rural regions (Holle 2016).

Globally, the high-income countries have had annual lightning mortality rates below 0.3 victims per million (Ströhle et al. 2018; Holle 2016); whereas rates in lower income countries on the African continent, such as Malawi (2007–10), Swaziland (2000–07), and Zimbabwe have ranged between 14 and 84 fatalities per million (Holle 2016). The US results illustrate a mean mortality rate of 0.113 per million from 1999 through 2023 (Table 2). The lower rates in high-income countries, including the US, are not only attributable to lower percent rurality, improved emergency medicine and better warning systems, but also having buildings which provide shelter during storms that are lightning-safe due to their construction (Cooper et al. 2019). While these improvements have been notable, the hazard remains and warrants continued vigilance with respect to monitoring and active preventive measures. Targeted and ongoing education for the general public, and males in particular (Fig. 5), remains warranted. Furthermore, education for younger populations and families ought to continue for maintaining awareness of the danger presented by outdoor activities proximal to thunder.

In a recent case series analysis of fatal lightning victims from 2006 through 2022, Jensen (2023) noted that males represented 80% of all the victims, and 90% of the lightning victims when stratifying for those who were engaged in fishing, work, and sports, during the period. Among all the victims, 63% were engaged in leisure or recreational activities at the time of

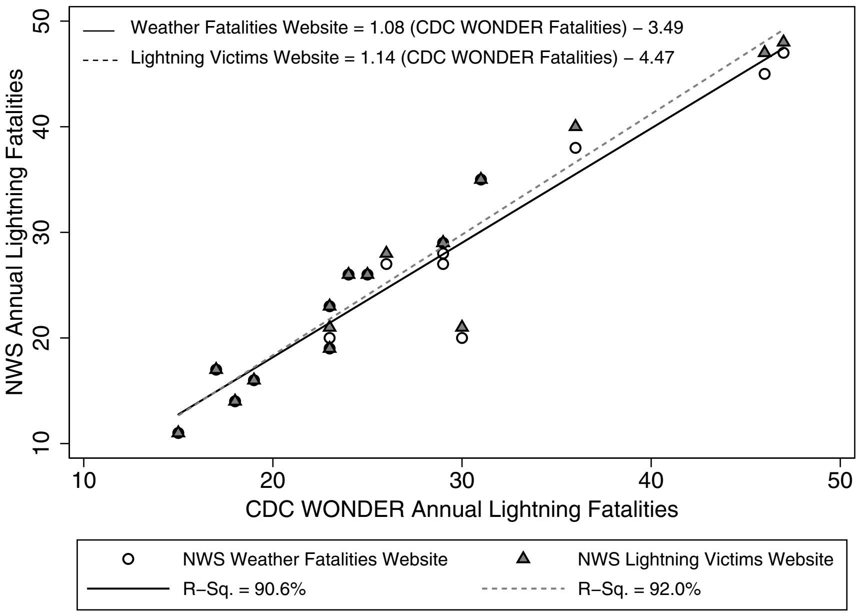

Fig. 6 Scatterplot with two lines of best fit comparing the number of annual lightning fatalities in the US as presented in CDC WONDER versus annual fatalities contained within two National Weather Service websites covering the 2006–2023 time period

death, including water-related activities (fishing, beach, boating, and swimming), outdoor sports, and camping. In addition to leisure activities, work-related fatalities have consistently represented about 18.5–25% of the lightning mortality in the US since the 1980 s (Duclos and Sanderson 1990; Adekoya and Nolte 2005). From 2006 through 2022, 19% of the lightning deaths were work-related with farming/ranching, roofing, and construction being the highest risk groups (Jensen 2023). The results of this case series remain useful for informing ongoing education and outreach.

While emergency medical care for victims has been considerable and has reduced lightning mortality (Zimmermann et al. 2002), the Wilderness Medical Society emphasizes prevention in their practice guidelines for preventing and treating lightning injuries (Davis et al. 2014). The guidelines embrace the National Weather Service maxim, “When the thunder roars, go indoors.” The guidance also clarifies that estimating a safe distance from the time between hearing thunder and seeing a lightning flash has contributed to false presumptions of safety. Accordingly, the prevailing guidance is as follows, “Individuals should wait a minimum of 30 min after hearing the last thunderclap before resuming outdoor activity. Waiting 30 min should allow for the trailing edge of the thunderstorm to move the estimated 10 miles needed to establish an appropriate buffer zone.” (Davis et al. 2014). Furthermore, the time necessary to evacuate at-risk locations should be incorporated into lightning action plans, with adults (teachers, lifeguards, sporting officials/coaches, etc.) assuming responsibility for the safety of any children (Zimmermann et al. 2002).

Two notable limitations of this study relate to the use of death certificate data in CDC WONDER and a focus on mortality versus injury. CDC WONDER uses "place of residence" from the death certificate data (CDC 2025c), rather than the actual location of the lightning event. While this may not significantly impact the national-level mortality statistics, it is plausible that a few cases may be missed or not coded to the geographic region where the death occurred, which could include fatalities among vacationers or workers away from their residence. This limitation could result in underreporting lightning deaths in the US South Census Region if relying upon CDC WONDER. Another concern was examined regarding non-residents of the US with CDC WONDER. Death certificates are issued for resident immigrants, undocumented individuals, and non-citizens (Metchnikoff et al. 2018) and would presumably be included in CDC WONDER, whereby WONDER documents the place of residence, which "refers to the usual place of residence (that is, the place where one usually lives and sleeps)" (CDC 2024).

Unlike CDC WONDER, the underlying data (*Storm Data*) used by the National Weather Service (2025a, 2025d) and Jensenius (2014) describes the location of the fatality (or injury), often at the state, county, and community level. A few limitations of *Storm Data* are the potential for regions with less surveillance to experience underreporting and inclusion of data from potentially unverified sources (National Centers for Environmental Information 2025b), whereas CDC WONDER obtains national-level data using vital statistics linked to state health departments. While *Storm Data* has several advantages in geocoding the site of a lightning fatality (and lightning injury), there may be more limitations with *Storm Data* for estimating the mortality rate due to the denominator in the rate calculation (the total population at risk) for each event being difficult to obtain or more dynamic than the Census-based population estimates used in CDC WONDER.

Building from the study limitations, additional research is warranted to explore the extent of the decline in fatality rates which may be attributable to emergency medical care versus potentially fewer exposures to lightning or changing mechanisms (e.g. direct strikes, contact voltage, flashover, etc.) for exposure. For example, in Canada, the frequency of lightning-related fatalities has declined in recent years, but the number of lightning-related injuries has slightly increased in recent years (2002–2017) relative to the 1994–2003 period (Mills 2020). While Jensen (2023) provides an estimate of 400 lightning injuries in the US annually caveated with a claim of potential underestimation, it is possible for researchers to explore modern trends in lightning injuries using *Storm Data* (National Centers for Environmental Information 2025a) which has been done historically (Curran et al. 2000; Holle et al. 2005) to determine if the reduction in the lightning fatality rate has been due to a reduction in the frequency of harmful lightning exposures.

As a means for estimating injuries from lightning, previous research estimates 70–90% of victims from lightning will survive; however, many (76%) of the survivors will endure long-term sequelae (Ritenour et al. 2008). The lightning victim survival rates in high-income countries are estimated to be near 90% (Holle et al. 2021), and if that estimate remains reliable, then approximately 230 and 180 persons were struck by lightning in 2022 and 2023, respectively, based upon an extrapolation from the 23 and 18 deaths observed in 2022 and 2023, respectively (CDC 2025a). Additionally, if 180–230 persons in each of those years experienced long-term sequelae in 76% of those events, then it is plausible that in the last two years there have also been approximately 137–175 persons in these recent two years have had, or continue to have, long-term adverse health effects from those events.

The sequalae likely include disorders with their central nervous system, vision/eyes, skin, muscles, and more (Ritenour et al. 2008). For comparison, using averages from 2008 to 2018 data, the National Weather Service estimated 243 injuries from 27 lightning deaths in 2019 (National Weather Service 2025c). The reports within *Storm Data* documented 20 fatalities and 100 injuries in 2019 (National Centers for Environmental Information 2025a), thereby representing five injuries per death versus the nine injuries per death estimate used by Holle et al. (2021) and the National Weather Service (2025c). Future research is warranted for determining if the severity of lightning incidents is increasing (e.g., more direct strikes versus side flashes) or if there is some other explanation, such as a change in the ratio of underreporting injuries in *Storm Data* relative to reported deaths.

Another limitation of our data analysis focusing on annual US mortality is that it could lead to an underestimation of the lifetime risk of being struck by lightning or dying from a lightning strike. While the annual and lifetime rates are considerably higher for males, in 2008, the risk for the average US person being struck in a lifetime was one in 3000, and the risk of death was one in 35,000 (Ritenour et al. 2008). Using data through 2018, the National Weather Service (2025c) estimated the lifetime risk (80 years) of being struck at one in 15,300. Using similar extrapolations, if 27 deaths were linked to a lifetime risk of 1:15,300 being struck in 2018, then if the 18 deaths in 2023 remained constant from into the future, the updated lifetime risk in the US would be approximately one lighting strike per 22,950 persons, in which nearly 10% or 2295 of those persons would succumb to the lightning. These risks are considerably higher for males and persons in the US South. Modern lifetime lightning strike risk estimates are reliant on the assumption that the incidence of lightning strikes will remain at all-time lows and strike mechanisms (e.g. ground current, side flash, direct strike, etc.) will maintain their historical frequency.

Potential barriers for sustaining these all-time low lightning mortality rates in the US or preventing the further reduction in lightning injuries and mortality in the US include: (1) changes in the climate and other atmospheric conditions that promote more lightning (Romps et al. 2014; Banerjee et al. 2014) or different types of lightning strike mechanisms, (2) complacency or overconfidence by the most at-risk citizenry regarding the hazard (Casteel 2023), (3) increases in the number of unsheltered or poorly sheltered citizens (Settembrino 2017; Bezgrebelna et al. 2021; Richards and Kuhn (2023), and (4) changing population demographics that could impact public alerts, warning messages, and educational campaigns (Sadiq et al. 2023).

There was one documented lightning-related death in a homeless individual in the case series of lightning deaths for 2006 through 2022, which represented one (0.21%) case out of 466. Additionally, among work-related lightning victims, there has been overrepresentation of Hispanic workers in historical studies; whereby from 1995 to 2000, Hispanic workers represented nearly one-third of those work-related lightning deaths despite being 12% of the population at-risk (Adekoya and Nolte 2005).

The ongoing work by Vagasky et al. (2024) and others that map the distribution, including the frequency and intensity of lightning events impacting the ground, could be used for informing interventions and ascertaining if the hazard is intensifying across the entire US or within certain regions of the US. Overlaying these maps with population demographics could also inform educational campaigns aimed at preventing lightning-related injuries and deaths. Continued vigilance and active reporting of lightning hazards by the media and government sources remains warranted to prevent complacency from the public health successes related to lightning over the last several decades, all while the incidence and intensity of lightning has likely been increasing in growing US population centers.

Future research is needed for informing interventions aimed at protecting health and safety. Studies in the US that examine the ratio of lightning-related injuries to lightning-related fatalities could be informative for determining the relative impact of emergency care versus changes in human exposure to the hazard. These studies may be confounded by possible changes in the frequencies of various mechanisms of lightning injuries or fatalities. For example, among the seven mechanisms of lightning injury which can all be immediately dangerous to life, the most dangerous mechanism, direct strike, is far less common than incidents involving ground current, side flash, and upward current (van Ruler et al. 2022; Holle et al. 2021). Ground current and side flash mechanisms account for over 80% of all lightning injuries and in many countries account for nearly 100% (van Ruler et al. 2022).

For policy considerations, the impact of lightning-related mortality is not fully characterized in ICD coded data due to exclusions of deaths from lightning-related fires and tree falls. Since fatalities associated with lightning-ignited fires are indirectly related with the lightning, rather than directly related, they are excluded in the ICD code for victims of lightning, which Mills et al. (2008) described as a limitation if using ICD codes for studying the impacts of lightning. As an alternative, there are records in *Storm Data* (National Centers for Environmental Information 2025a) that record fatalities linked to events, including fire. There have been suggestions from scientific literature encouraging consideration of revisions to ICD codes for enabling better characterization of climate-related deaths (Wheat et al. 2023; McDermott et al. 2021). If lightning risks are increasing from climate factors, then future opportunities may exist for incorporating or expanding ICD codes linked to natural weather events, fires, or tree falls to better capture the extent of lightning-related public health hazards.

5 Conclusions

Lightning-related mortality has declined substantially over recent decades in the US. The reduction in the rate from 4.3 deaths per 10 million in 1982 to 0.53 deaths per 10 million in 2023 has occurred while lightning activity has increased. While there have been advances in emergency medical care, risk communication, education, urbanization, and increased access to lightning-safe buildings, future research needs exist. Expanded research on the ratio of injuries-to-fatalities and time-trend analyses specific to the number of US lightning-related injuries could improve intervention efforts and enhance understanding on which factors are most responsible for declines in US mortality rates directly attributable to lightning. As cloud-to-ground lightning is anticipated to continue increasing in the US, sustained education and outreach, particularly targeting the most at-risk populations, will remain essential for sustaining progress and minimizing future lightning-related fatalities and injuries.

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Declarations

Conflict of interest Dr. Marion and Eli Lanning have no relevant financial interests. Dr. Marion is the owner of Eastern Scientific, LLC, which focuses on water quality. Dr. Marion is also the inventor of a water quality testing product for fecal contamination. Dr. Brown has received travel support for speaking engagements within the past three years while serving as the President and Past-President of the National Environmental Health Association. Dr. Brown is President of JHB Environmental/Occupational Health Consultants, LLC which performs industrial hygiene and safety-related consulting and training services for industry, government, non-profit, and educational entities. Non-financial interests: Dr. Gary Brown has served on the Board of Directors for the National Environmental Health Association.

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