Fatal Weather-Related Carbon Monoxide Poisonings in the United States

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ABSTRACT: Carbon monoxide (CO) is a colorless, odorless gas that can cause injury or death if inhaled. CO is a frequent secondary hazard induced by the aftereffects of natural hazards as individuals, families, and communities often seek alternative power sources for heating, cooking, lighting, and cleanup during the emergency and recovery phases of a disaster. These alternative power sources—such as portable generators, petroleum-based heaters, and vehicles—exhaust CO that can ultimately build to toxic levels in enclosed areas. Ever-increasing environmental and societal changes combined with an aging infrastructure are growing the odds of power failures during hazardous weather events, which, in turn, are increasing the likelihood of CO exposure, illness, and death. This study analyzed weather-related CO fatalities from 2000 to 2019 in the United States using death-certificate data, providing one of the longest assessments of this mortality. Results reveal that over 8300 CO fatalities occurred in the United States during the 20-yr study period, with 17% of those deaths affiliated with weather perils. Cool-season perils such as ice storms, snowstorms, and extreme cold were the leading hazards that led to situations causing CO fatalities. States in the Southeast and Northeast had the highest CO fatality rates, with winter having the greatest seasonal mortality. In general, these preventable CO poisoning influxes are related to a deficiency of knowledge on generator safety and the absence of working detectors and alarms in the enclosed locations where poisonings occur. Education and prevention programs that target the most vulnerable populations will help prevent future weather-related CO fatalities.

SIGNIFICANCE STATEMENT: Carbon monoxide exposure is common after weather disasters when individuals, families, and communities seek alternative power sources—such as portable generators, petroleum-based heaters, and vehicles—that exhaust this deadly, colorless, and odorless gas. Initially, we catalog carbon monoxide fatalities associated with weather events in the United States over two decades; thereafter, we illustrate the characteristics and patterns affiliated with these deaths. Results will assist public officials, first responders, and individuals in their decision-making and response before, during, and after weather events so that these deaths may be prevented in the future.

KEYWORDS: Seasonal effects; Severe storms; Societal impacts; Tropical cyclones; Winter/cool season

1. Introduction

Carbon monoxide (CO) is a colorless, odorless gas caused by the incomplete burning of fossil fuels used by tools and equipment such as portable generators, heaters, and vehicles [U.S. Consumer Product Safety Commission (CPSC; CPSC 2019)]. CO can cause injury or death if inhaled and is a frequent secondary, or indirect, hazard induced by the aftereffects of disasters that cause power outages as individuals, families, and communities often seek alternative CO-emitting power sources to heat residences and power lights and appliances (Rappaport and Blanchard 2016). These alternative power sources, when not properly ventilated, can produce surges in CO poisoning and affiliated death or injury during and after disasters (Henretig et al. 2018). These unintentional, nonfire CO poisonings stem from a deficiency in safety education and understanding of the CO hazard, availability and correct operation of detector and alarm devices, and, ultimately, the improper use of petrol-powered engines or heaters, often in confined spaces (Hampson and Stock 2006).

CO exposure is increasing as power outages are growing in frequency and magnitude (Campbell 2012; Casey et al. 2020). The increasing number of power outages may be attributed, at least in part, to the aging U.S. electrical infrastructure. Indeed, 70% of the United States' power transmission lines and transformers are over 25 years old and power plants average over 30 years old (DOE 2014; Reidmiller et al. 2018). This aging infrastructure is particularly vulnerable to extreme weather conditions such as high winds, thunderstorm perils, tropical cyclones, heat waves, intense cold periods, snow events, ice storms, and extreme rainfall (DOE 2017; NCEI 2018; Reidmiller et al. 2018). As an illustration of the U.S. power infrastructure vulnerability, 69 electric facilities in the Southeast are prone to failure under storm surge of a category-1 hurricane, while 291 facilities in the Southeast are susceptible to storm surge from a category-5 event (Maloney and Preston 2014; Reidmiller et al. 2018). The United States' aging and vulnerable energy system is commingling with rising demand and the increasing likelihood of weather and climate impacts, which will create longer and more frequent power interruptions in the future (ASCE 2017; Reidmiller et al. 2018). Any such interruptions will increase the odds of future CO exposure and poisoning unless mitigation measures—such as education about the CO hazard, use of reduced-emission generators, wider dissemination of CO detectors, alarms, and automatic shutoff switches—are improved.

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TABLE 1. Contemporary (1996–2020) weather-related CO case studies and/or analyses.

Date	No. of fatalities	Storm type	Citation
Jan 1996	0	Blizzard	CDC (1996)
1991		Ice storm	Wrenn and Conners (1997)
1991		Ice storm	Wrenn and Conners (1997)
1994		Ice storm	Daley et al. (2000)
2002		Ice storm	Broder et al. (2005)
Aug–Sep 2004	6	Hurricane	CDC (2005a)
Aug–Sep 2005	5	Hurricane	CDC (2005b)
Sep 2005		Hurricane	Audin (2006)
Jan 1993	0	Windstorm	Hampson and Stock (2006)
Jan 1996	2	Blizzard	Hampson and Stock (2006)
Jan 1998	1	Ice storm	Hampson and Stock (2006)
Dec 2002	1	Ice storm	Hampson and Stock (2006)
Jan 2003	0	Ice storm	Hampson and Stock (2006)
Sep 2003	8	Hurricane	Hampson and Stock (2006)
Aug–Sep 2004	6	Hurricane	Hampson and Stock (2006)
Aug–Oct 2005	10	Hurricane	CDC (2006)
Aug–Sep 2005	5	Hurricane	Hampson and Stock (2006)
Sep 2005	5	Hurricane	Cukor and Restuccia (2007)
Sep 2008	7	Hurricane	CDC (2009)
1999–2009	186	All	Hnatov (2010)
Sep–Oct 2008	8	Hurricane	Zane et al. (2010)
Jan–Feb 2009	10	Ice storm	Lutterloh et al. (2011)
1991–2009	75	Hurricanes, winter storms, and floods	Iqbal et al. (2012)
Oct–Nov 2012	4	Hurricane	CDC (2013a)
Oct–Nov 2012	0	Hurricane	Chen et al. (2013)
2004–2013	206	All	Hnatov (2014)
1984–2004	226	Winter weather	Black (2015)
Oct–Nov 2011	3	Snowstorm	Styles et al. (2015)
Oct–Nov 2012	0	Hurricane	Styles et al. (2015)
2005–2016	220	All	Hnatov (2017)
Oct–Nov 2012	4	Hurricane	Schnall et al. (2017)
Sep–Oct 2017	16	Hurricane	Issa et al. (2018)
Sep 2017	0	Hurricane	Falise et al. (2019)

A recent example of the juxtaposition of the nation's power infrastructure vulnerabilities with extreme weather events was the February 2021 Texas power crisis. This event, which occurred after back-to-back winter storms, left 4.5 million homes and businesses in the state without power (Sullivan and Malik 2021; Doan 2021; Wright 2021; Douglas 2021). These power disruptions, some lasting for days, led many to seek alternative power and heating sources, which caused at least 1400 reported cases of CO poisoning, and at least 11 documented deaths (Trevizo et al. 2021). In one county alone, fire departments responded to 475 CO-related calls (Carter 2021). The 2021 Texas power crisis is a singular example of a long-lived, but incremental, story of CO as an important and often lethal aftereffect of extreme weather events. Weather perils of all types can promote situations that lead to CO-poisoning and death—for example, 10 CO-related deaths occurred in 2005's Hurricanes Katrina and Rita [Centers for Disease Control and Prevention (CDC 2006)], 4 occurred in 2012's Superstorm Sandy (CDC 2013a), and 8 occurred in 2020's Hurricane Laura (Treisman 2020), 2 teenage boys died of CO poisoning after a major tornado outbreak in 2019 (Associated Press 2019), and 10 CO-related fatalities occurred when a major ice storm impacted Kentucky in 2009 (Lutterloh et al. 2011). Despite public officials' efforts to prevent CO poisoning in the wake of disasters, CO-related poisonings and death continue to occur with alarming frequency (Treisman 2020).

Prior research into weather-related CO poisoning is often ad hoc and generally relegated to singular reports after major events (Table 1; e.g., CDC 2006, 2013a). This study examines the long-term spatiotemporal trends in CO poisoning in the United States by providing a multidecadal synthesis of deaths linked to weather peril-related CO poisoning. The study analyzed weather-related CO fatalities in the United States using data gathered from the CDC, the CPSC, the National Vital Statistics System (NVSS), and other official public and governmental sources. This research identifies the storm perils that pose the greatest risk for CO exposures, determines the demographics most vulnerable to poisoning, and assesses the spatiotemporal characteristics of weather-related CO deaths. Combining these new results with those uncovered in the case studies and reports generated in recent decades (Table 1) will help policy makers, emergency managers, forecasters, and the multiple, and diverse, publics prevent CO-related poisonings and deaths as we move into a future characterized by rapid environmental and societal change.

2. Background

a. CO as a hazard

CO is a colorless, odorless gas that can cause sudden illness and death and is produced by the incomplete combustion of carbon-based compounds (CDC 2019; Wu and Juurlink 2014). Common sources of CO emissions include vehicles, portable generators, grills, ovens/stoves, fireplaces, and household utilities such as heating systems [National Notifiable Diseases Surveillance System (NNDSS) 2019; Wu and Juurlink 2014]. When high concentrations of CO are inhaled by humans, flulike symptoms can occur, including headaches, dizziness, weakness, nausea, vomiting, chest pain, and confusion. These acute symptoms are problematic for early detection and remedy since these symptoms can be often misattributed to other illnesses (CDC 2019, 2005c).

CO poisoning often results from the misuse or improper placement of common emission sources, which is generally due to an incomplete understanding of CO as a hazard (Damon et al. 2015). For instance, improper use and placement of portable generators is a familiar cause of CO poisoning after extreme weather events that induce power failures. While in use, all portable generators should be placed at least 6 m (20 ft) away from any indoor structure (CDC 2020); however, many people continue to use them in or near their residences simply due to a deficiency in understanding that CO is a poisonous gas emission associated with alternative power sources (Damon et al. 2015). Seventy-one percent of all unintentional, nonfire CO fatalities (2005–17) occurred when the generator was placed in rooms, basements, or closets of a residential structure; this statistic does not include attached garages, which is another common location in which portable generators are mistakenly operated (Hnatov 2017).

b. Relationship between power generation and unintentional, nonfire CO poisonings

Power outages pose a public health and safety concern for the United States, as they affect transit systems, elevators, water-pumping equipment, food refrigeration, medical devices and facilities, and temperature regulation (Dominianni et al. 2018; CDC 2013b; Lee et al. 2016). As discussed, power outages can also spur CO poisoning as people turn to alternative energy sources such as portable generators. Weather events are a significant cause of power outages due to felled trees, debris, or floods that can compromise transformer and power transmission line systems of all scales. From 2003 to 2012, 679 power outages that affected at least 50 000 customers were caused by weather events (Wang et al. 2016). From 1992 to 2010, 78% of power outages were caused by natural hazards, including weather-related perils (Campbell 2012). Around 43% of power outages are over five minutes long and collectively cost, on average, \$20 billion–\$55 billion annually (Campbell 2012). Broadly, energy system repairs are becoming more costly and extensive because of aging infrastructure and changing environmental factors (Yao and Sun 2019).

CO poisoning risk is rising because of the escalating frequency, duration, and impact of power outages (Campbell 2012; Wang et al. 2016; Reidmiller et al. 2018; Yao and Sun 2019), a changing and increasingly variable weather peril landscape (Vose et al. 2014; Reidmiller et al. 2018) and increasing generator stock and usage among the populace. Indeed, portable generators and other alternative power sources have become more accessible, easier to operate, and more affordable, which has led to a large increase in their sales since 2000 (CDC 2005a). Simple safety measures—such as running a generator outdoors and operating CO-emitting sources at least 6 m from any indoor structure and installing CO detectors and alarms—can prevent CO poisoning (CDC 2005a; Lutterloh et al. 2011; Wu and Juurlink 2014; Damon et al. 2015). Yet, despite these mitigation measures, unintentional, nonfire CO poisonings continue to remain high during and after weather events, especially those that cause power failures.

Petroleum-based generators are a frequent source of unintentional, nonfire CO poisonings during and after extreme weather events, but another concern for CO exposure often involves vehicles, especially during snow events. For instance, during the Northeast U.S. blizzard of 2–8 January 1996, 25 poisoning victims occupied their cars while running the engines for warmth. In these cases, the snow accumulated over the vehicle tail pipes, obstructing the exhaust system and trapping CO within the vehicle (Hampson and Stock 2006). Ice storms—such as the 1998 New England ice storm (Daley et al. 2000; Hampson and Stock 2006) and 2009 Kentucky ice storm (Lutterloh et al. 2011)—and their affiliated power failures are common sources of CO poisoning as victims use portable generators, space heaters, and even charcoal to remain warm and/or facilitate cooking.

c. Prior CO poisoning research

CO poisoning—including both weather and nonweather related—is the leading cause of all unintentional poisoning fatalities in the United States, and hospitals report an average of 430 deaths and 21,000 emergency room visits each year due to non-fire-related accidental CO poisoning (NNDSS 2019; CDC 2019). On average, 170 CO fatalities are caused by nonautomotive and petrol-driven tools such as portable generators, fireplaces, water heaters, and furnaces (CPSC 2020a). Demographic groups most vulnerable to these unintentional, non-fire-related CO deaths include those who were ≥65 years of age, Caucasian, male, and residents of states at relatively higher latitudes (Hampson 2016; CDC 2017).

Previous research into *weather-related*, unintentional, nonfire CO poisonings is often case-specific or for a relatively limited period of record [Table 1; e.g., CDC's *Morbidity and Mortality Weekly Report* (*MMWR*; CDC 2006, 2013a,b)]. These postevent assessments and reports are helpful in exemplifying CO as a hazard, and have illustrated some of the underlying peril attributes, demographic characteristics, and spatiotemporal patterns of many noteworthy fatal weather-related CO events. Along with this study, other extensive reports on CO fatalities were provided by the CPSC; this agency periodically releases long-term assessments on unintentional, nonfire CO fatalities that include analyses of those associated with weather hazards, such as winter storms, tropical cyclones, windstorms, thunderstorm perils, tornadoes, and rainstorms. These CPSC reports revealed that winter storms and tropical systems are the top two storm perils most frequently associated with CO deaths, and that most nonfire CO fatalities occurred in the cool-season months.

Other research reveals that fatal CO cases disproportionately impact non-Hispanic White individuals after weather perils (Black 2015)—for example, 73% of CO fatalities linked to Hurricane Irma (Issa et al. 2018), as well as all CO deaths connected to the four major hurricanes of 2004 (Charley, Frances, Ivan, and Jeanne), were non-Hispanic White (CDC 2005a; Hampson and Stock 2006; Issa et al. 2018). Other case studies, however, report that the Hispanic ethnicity is most vulnerable to CO exposure after weather events (Black 2015)—for example, five of the seven CO fatal victims associated with Hurricane Ike were Hispanic (CDC 2009). *MMWR* postevent reports suggest that women make up the most CO exposures, while men make constitute most of the fatalities (CDC 2009).

These postevent reports are helpful in illustrating the CO hazard, but a long-term assessment of weather-related CO deaths is needed to understand any trends and improve our understanding the characteristics of these fatal events. Empowered with this information, emergency managers, forecasters, policy makers, and the public may mitigate future poisonings and death from CO exposure.

3. Method

a. Data

The CO fatality dataset was compiled with death-certificate data from the NVSS of the National Center for Health Statistics (NCHS). Death-certificate data were assembled into yearly mortality-multiple-cause files, each consisting of all fatalities that took place within the United States between the years 1968 and 2019 (CDC 2020). CO deaths were sorted from the other deaths using the International Classification of Diseases (ICD) variable attribute. The ICD code is the underlying cause of death for each fatality, which was then categorized as "accidental poisoning" for this study. The ICD is revised every few years to accommodate changes in diagnoses and expanded understanding of disease etiologies to the changing medical field (CDC 2020). The NVSS mortality data provide demographic, geographic, and temporal variables; however, geographic data are not available after 2004.

A Freedom of Information Act (FOIA) request, which is a written or digital petition from anyone seeking to obtain data kept by federal agencies, was submitted and sought information on all weather-related CO fatalities, with demographic, temporal, and spatial data between 2000 and 2020. The agency assigned to the FOIA was the CPSC. Once the application was submitted, it was reviewed by the respective agency and then fulfilled when the request was determined not to violate any one of the nine FOIA exemptions (CPSC 2020b). This request provided the state in which each CO fatality took place between 2000 and 2019 as well as the weather phenomenon (ice storm, flooding, high winds, tropical cyclone, etc.) attributed to each death. Additionally, the source (e.g., fixed-generator, furnace, grill, camp stove, portable heater) of CO was included along with its relative location, or proximity, to the victim. Narratives are available for each CO fatality in the FOIA dataset, and they were critical for filling in information missing in the attribute tables and verifying that each death was related to a weather event.

The CPSC also provides bulk-sized data through its Clearinghouse datasets that contain incident reports associated with consumer products (2011–19). This dataset provides demographic data as well as the state in which each incident occurred. The Clearinghouse data were obtained from death certificates, medical-examiner reports, healthcare professionals, state agencies, federal agencies, local agencies, and public safety officials (CPSC 2011). For additional verification, the CPSC also offers consumer-product-related emergency room data through the National Electronic Injury Surveillance System (NEISS). The NEISS provides temporal, demographic, and narrative data for all CO poisoning reported by hospitals each year (CPSC 2019).

To ensure consistency for the final CO fatalities dataset, news aggregators, such as Google News, were used in combination with keyword or case-specific searches to provide additional contextual information. For further verification, the NCEI Storm Events Database, or *Storm Data*, was used to confirm the weather perils associated with each CO fatality. This resource contains information and observations from reported storm events that cause damage, injuries, and fatalities in the United States. Since CO poisoning is an indirect circumstance of weather events,[1] the indirect fatalities in this data resource were specifically analyzed and investigated for this study's final CO dataset.

b. Methods

The period of record for the study is 2000–2019 for the United States, including Alaska and Hawaii. As of this writing, CO fatality data are available for the year 2020; however, they are not included in the study, as the data are not officially published and are still under review. A 20-yr period of record permits adequate spatial, temporal, and demographic data for analyzing contemporary trends in the characteristics of weather-related CO deaths. After all information was

[1] The NWS categorizes weather-related fatalities into two types: direct and indirect (NWS 2021a). The NWS directive acknowledges that the determination of direct versus indirect causes of weather-related fatalities is extremely difficult. Direct deaths are defined as a fatality "directly attributable to [a] hydrometeorological event itself, or impact by airborne/falling/moving debris" in which the weather event was an active agent in creating the debris. Conversely, the NWS directive describes indirect fatalities as those that occur "in the vicinity of the hydrometeorological event, or after it has ended, but not directly caused by impact or debris from the event"; i.e., the weather event was a "passive entity." Indeed, a "generalized example" of an indirect fatality in the NWS directive includes people who "suffer carbon monoxide poisoning due to improper or inadequate venting of heating systems, portable heaters, generators, etc."

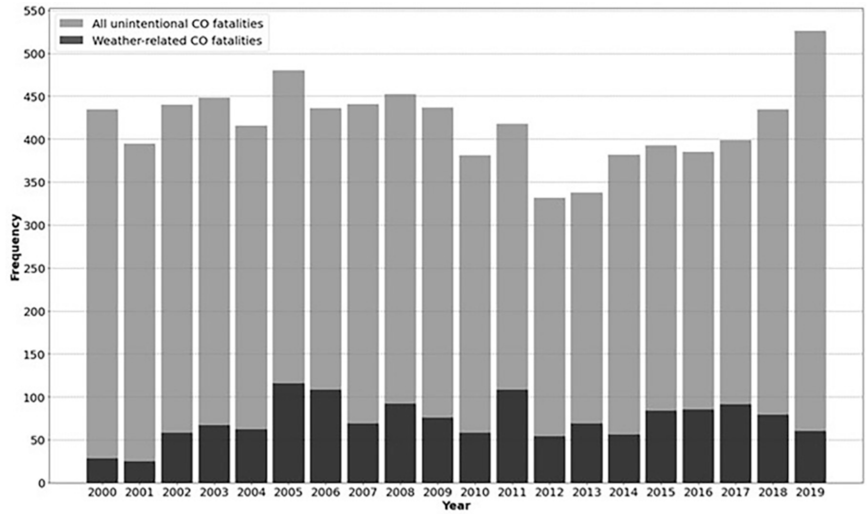

FIG. 1. The frequency of all reported unintentional CO fatalities (CDC's WONDER–NCHS; https://wonder.cdc.gov/) and weather-related CO fatalities by year. The light-gray bars represent all reported unintentional CO fatalities, and the black bars represent all unintentional weather-related CO fatalities.

compiled and verified, the final dataset contained 1) demographic information, such as age, race, and gender of the person who succumbed to CO; 2) the state of the fatality; 3) the time and date of the fatality; and 4) the type of weather event that indirectly caused the CO fatality.

While the weather peril category was included in the FOIA dataset, 65% of all weather-related CO fatalities were not assigned to an associated weather peril. A Python script and NCEI's *Storm Data* were used to complete this missing information. The script sorted through all weather reports and kept those with the same state, month, and year of each fatality. The day of the fatality was not necessarily matched to the day of the report, as CO fatalities can take place up to 4 days (and, in some cases, longer) after a weather event. After a list of matching weather reports was computed from the script, the reports were then manually analyzed to determine the associated weather peril for each fatality; fatalities that already had an assigned weather peril were also analyzed to ensure consistent classification and to provide a verification check. If multiple reports took place during a specific window of time, or if it was unclear which weather peril was associated with the death, then the CO fatality was classified as unknown. After this process, the percentage CO fatalities with an unknown weather peril decreased from 65% to 16% and the thunderstorm class was added. This method did not greatly change the quantities possessed by the other weather perils; however, there were slight changes since the thunderstorm peril was added.

Once the master CO fatality dataset was compiled and verified, a temporal analysis was conducted to find daily, monthly, and/or seasonal patterns. Weather-related CO deaths by state are represented and visualized on a variety of maps made with ArcGIS Pro (2021). A population normalization method was employed to help accurately represent the distribution of fatalities. The weather peril affiliated with each CO fatality was spatiotemporally assessed, as well. Demographic analyses—including assessments of age, race, and gender—reveal those persons and groups most vulnerable to weather-related CO poisoning during the past 20 years.

4. Results

a. Temporal characteristics

CDC's NCHS reported 8360 unintentional, non-fire-related CO fatalities between 2000 and 2019; 1444 (17.3%) of those unintentional CO deaths were associated with a weather event during the study period, which is a mean of 72 weather-related CO fatalities per annum (Fig. 1). The annual mean of weather-related CO fatalities is on par, if not greater, than those of direct fatalities affiliated with weather hazards reported by the National Weather Service (NWS), including lightning, hurricanes, tornadoes, and floods (NWS 2021b). Some years had more weather perils than others, which parallel the CO fatality results; for example, 2005 holds the highest percentage of weather-related CO fatalities (25%) and was a year of mass power outages from an active and destructive tropical cyclone season, including Hurricanes Katrina and Rita that affected the Gulf Coast (CDC 2005b). Conversely, only 6% of all unintentional, non-fire-related CO fatalities were reported to be weather related in 2001, which reveals the fluctuation of annual CO fatalities and the situational aspects of weather-related CO mortality. While there is a large amount of year-to-year variability, the overall trend of weather-related CO fatalities is persistent, which is further supported by prior results from Henretig et al. (2018). Short annual segments in the period of record—such as 2000–06 and 2012–17—illustrate an increasing trend; however, most of the other years did not deviate greatly from the mean.

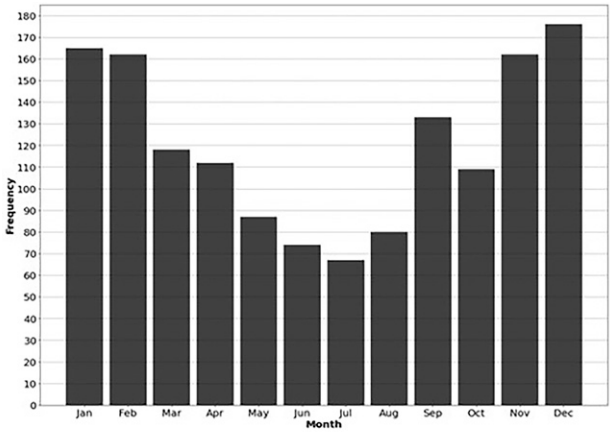

FIG. 2. Frequency of all weather-related CO fatalities by month from 2000 to 2019.

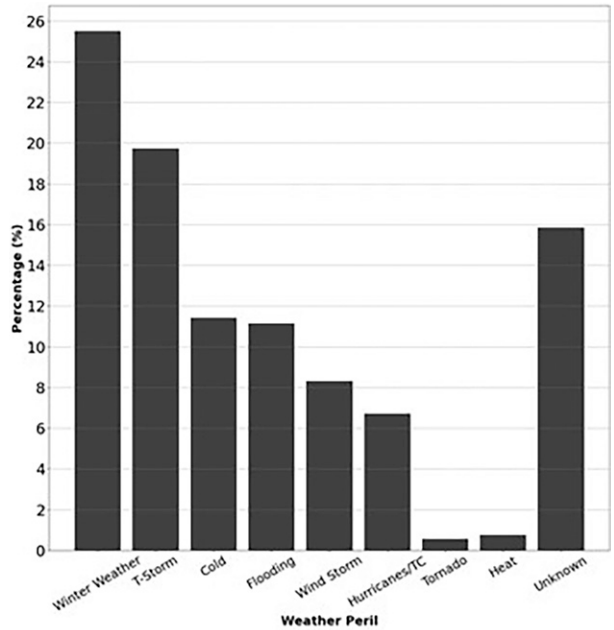

FIG. 3. Percent of weather-related CO fatalities by affiliated weather peril.

Nearly one-half (46%) of weather-related CO fatalities occurred in the cool-season months or, more specifically, November–February; this aligns with Hnatov's (2017) finding, as he reported 49.6% of CO deaths from November through February. Americans are most vulnerable to weather-related CO fatalities during the winter season (December, January, and February), with 34.8% of all weather-related fatalities recorded during this season (Fig. 2). Winter weather—such as snowstorms, ice storms, and extreme cold temperatures—was the leading weather peril that fostered CO fatalities during the winter. While the winter months hold the highest frequency of weather-related CO fatalities, large numbers of CO fatalities occurred in other seasons, as well. Around 21.9% of all weather-related CO fatalities were reported in the spring (March, April, and May); these deaths were generally a result of winter weather conditions or, in many instances, extreme cold. The summer months (June, July, and August) feature relatively infrequent weather-related CO deaths, with only 15.3% of total deaths reported during this season. These warm-season fatalities were related to the perils of flooding, high wind events, and excessive heat. CO fatalities that occurred in the autumn (September, October, and November) made up 28% of all weather-related CO fatalities and were largely associated with tropical cyclones.

The weather-related CO mortality dataset contained a weather peril variable, which defined the weather event associated with each fatality. Fatalities were categorized into one of nine different classes, which included 1) winter weather, 2) cold, 3) tropical cyclone, 4) thunderstorm, 5) windstorm, 6) flooding, 7) tornado, 8) heat, and 9) unknown. For clarification, cold refers to instances in which the victims used alternative sources of power to solely heat their structure in response to excessively cool temperatures and not necessarily a weather peril; the same logic may be applied to heat, except the intention of the victim was to cool their structure in response to excessively warm temperatures. The CO fatalities associated with thunderstorms took place during or after a reported nontornadic thunderstorm with lightning, hail, and/or wind impacts. Unknown fatalities were those that took place in response to weather perils but the type of storm was not clear or was not specified in the data provided. Around 16% of all weather-related CO fatalities were classified as unknown, which accounts for the third largest portion of all the other classes behind winter weather (25%) and cold (19%).

Like the CPSC reports authored by Hnatov (2010, 2014, 2017), ice storms and snowstorms were the leading perils affiliated with weather-related CO fatalities in this study's more expansive period of record. Thunderstorms (19%) were affiliated with the second highest percentage of weather-related CO fatalities. This reflects the vulnerability of powerlines to the various short-lived elements of a thunderstorm, such as hail, heavy rain, lightning, and debris from high winds (Campbell 2012; Reidmiller et al. 2018). Tropical cyclones were associated with a relatively low percentage (8%) of weather-related CO fatalities, which differs from Hnatov's reports; however, this may be explained by the high percentages with flooding (11%) and windstorms (11%), which are two perils often embedded within tropical systems that may cause power outages (Fig. 3). The distinctions among the three weather perils were based on weather reports, news reports, and narratives of each fatality.

b. Demographic characteristics

The weather-related CO mortality dataset includes demographic information, such as age, race, and biological sex. Males are more vulnerable to CO poisoning during and after weather perils, making up 78.6% of weather-related CO fatalities during the period of record; this aligns with the demographic findings from research on other weather hazards—such as floods (Ashley and Ashley 2008), rip currents (Gensini and Ashley

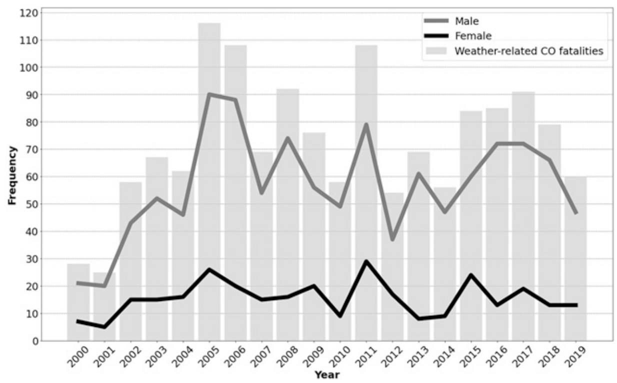

FIG. 4. Frequency of weather-related CO fatalities separated by sex. The gray line represents the frequency of males, and the black line represents the frequency of females per year. The light-gray bars represent all weather-related carbon monoxide fatalities per year.

2009), and lightning (Ashley and Gilson 2009). They consistently had higher frequencies of fatalities annually than females (Fig. 4), which aligns with prior results from the CDC (2009).

The middle-aged and elderly appear to be most vulnerable to weather-related CO deaths (Fig. 5). Those aged 35–69 years experienced the highest percentages that were the most disproportionate relative to their percentage of the overall U.S. population. More specifically, those between 40 and 54 years of age were the most vulnerable to weather-related CO deaths when compared with other age groups. Those under 25 years old experienced very low percentages of weather-related CO fatalities relative to that age group's proportion of the nation's population. The CDC (2005c) also found that those 65 years or older experience one of the highest CO poisoning death rates of all age classes; however, the high rates experienced by those 40–54 years old (between 2000 and 2019) suggest that the elders are not the most vulnerable to weather-related CO poisoning when using this study's more extensive period of record. The full range of ages impacted—from 19 months to 93 years old—during the study period illustrates that CO poisoning can affect every age group, from young children to the elderly (Henretig et al. 2018).

While all races and ethnicities have been victims of weather-related CO-deaths, White and Black populations were impacted at greater rates (Fig. 6). Relative to their percentage of U.S. population, the Black demographic experienced the greatest deviation between their percentage of weather-related CO fatalities (19%) and their percentage of the U.S. population (13.4%). The White demographic has the highest frequency of weather-related CO fatalities and is highly vulnerable, but the Black demographic appears to be most vulnerable to these events relative to the proportion of the overall population.

c. Spatial characteristics

The spatial resolution of the mortality data was limited because of privacy concerns. In general, state level was the finest resolution provided by the sources. Texas, Michigan, and Florida had the highest quantities of fatalities during the study period (Fig. 7). Florida, which ranked third in deaths, experienced 81 total CO fatalities predominantly related to tropical cyclone perils. Michigan, which ranked second, had 96 reported CO fatalities, with many of those resulting from extreme cold as people were more inclined to combat

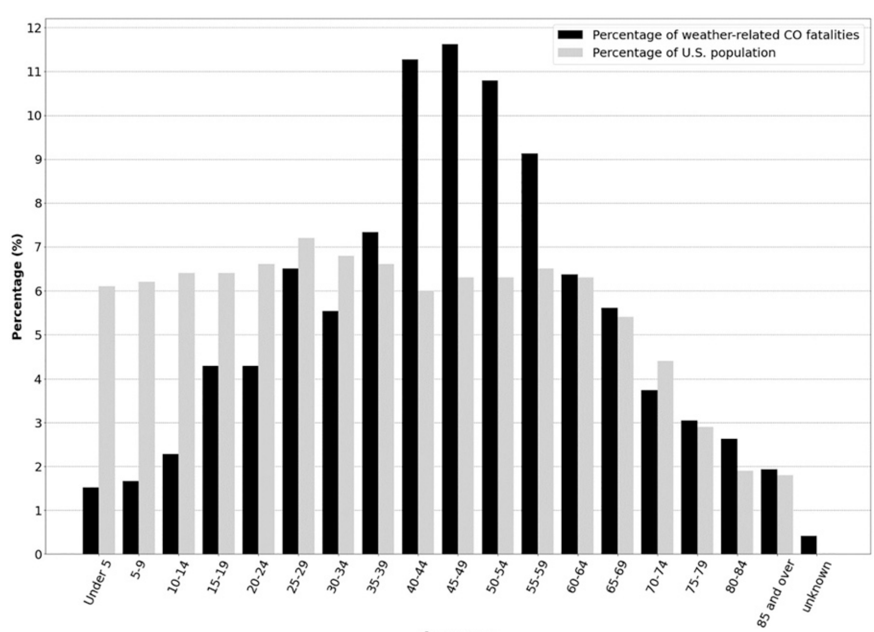

FIG. 5. Percent of weather-related CO fatalities (2000–19) and percent of population (U.S. Census Bureau 2019b) by age.

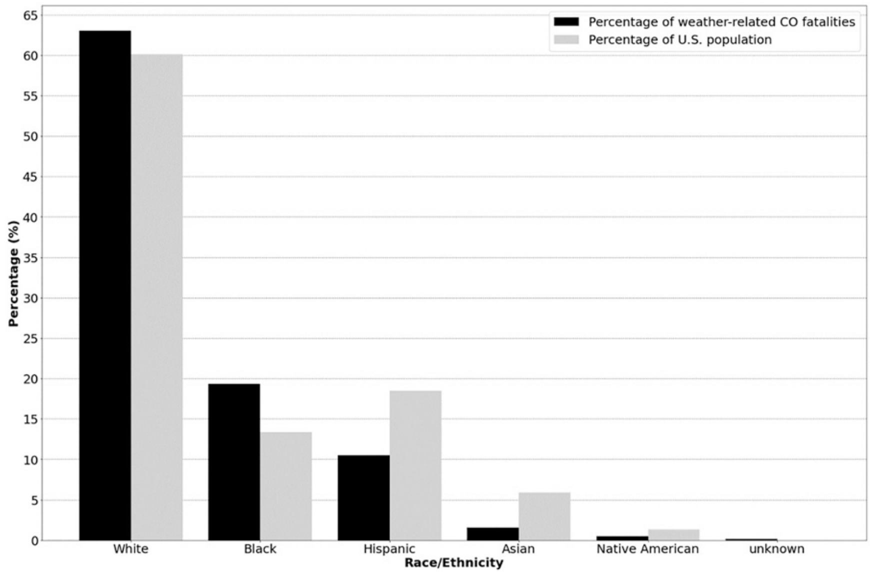

FIG. 6. Percentages of weather-related CO fatalities (2000–19) and percent of population (U.S. Census Bureau 2019b) by race or ethnicity.

plummeting temperatures with a petrol-driven tool such as a generator or portable heater. Texas, which ranked first in weather-related CO mortality, had 98 total deaths largely affiliated with tropical cyclones. Regionally, the Midwest and Southeast had the highest counts of weather-related CO deaths. Western states of Washington and California and Northeast states, such as New York and Pennsylvania, also had relatively high mortality. The Great Plains and most of the West had the lowest frequencies, and Idaho did not report any weather-related CO fatalities during the study period.

State-level data were subsequently normalized to visualize states and regions experiencing the most weather-related CO fatalities per capita (per 100 000 people; Fig. 8). The states most impacted by weather-related CO fatalities when normalized by population included Alaska, Maine, Mississippi, and Louisiana. Mississippi and Louisiana had very high weather-related CO mortality that was due to a particularly active hurricane season in 2005 during which 30 reported CO fatalities occurred after several tropical cyclones affected the central Gulf Coast.

Large portions of the Great Plains and Midwest had high counts of weather-related CO fatalities when normalized by population (per 100 000 people) that were not linked to any major weather events. The northern portion of the United States experienced higher counts of CO fatalities, which is reflective of the cooler temperatures and increased winter weather perils these regions experience. These results align with the CDC (2017), which found states at higher latitudes were more vulnerable to CO poisoning; however, because of increased landfalling of tropical cyclones over the last two decades, Southern states have become more vulnerable to weather-related CO fatalities.

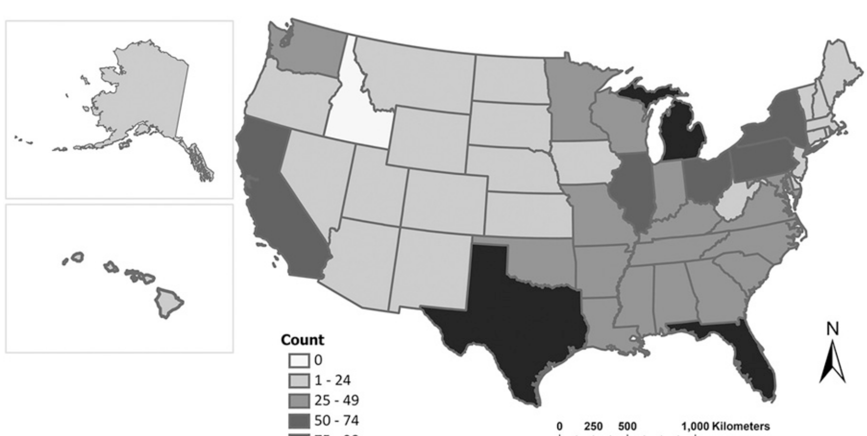

FIG. 7. Frequency of weather-related CO fatalities by state, 2000–19.

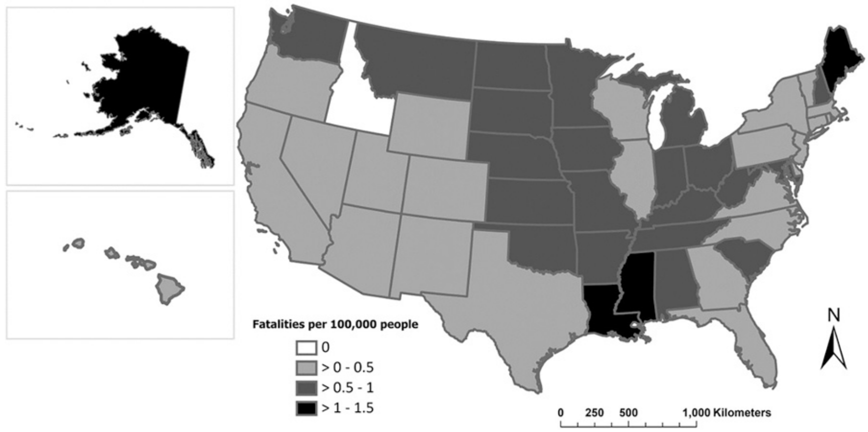

FIG. 8. Weather-related CO fatalities by state normalized by population (per 100 000 people) (U.S. Census Bureau 2019b), 2000–19.

Zones provided by the Federal Emergency Management Agency (FEMA) were referenced in a regional analysis for all weather-related CO fatalities and their associated weather perils (Table 2). Of the 10 regions, 8 were primarily impacted by weather-related CO fatalities associated with winter weather. Thunderstorm perils were reported to be dominant in 2 regions: region IV (Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee) and region VI (Arkansas, Louisiana, New Mexico, Oklahoma, and Texas). These regions also have high counts of tropical cyclone–associated CO fatalities (9.8% and 14%, respectively). States in region IX (Arizona, California, Hawaii, and Nevada) were mostly impacted by winter weather–related CO fatalities; however, wind events made up another large portion (23.9%) of CO fatalities in the same area.

Weather-related CO vulnerability exemplified seasonal shifts, as some seasons are more favorable for weather perils, such as the autumn for tropical cyclones and winter for snowstorms and ice storms. Residents of Montana, Maine, and many states in Southeast are most at risk for weather-related CO fatalities during the winter months, as they possess the highest mortality per capita (Fig. 9). As temperatures become milder in the spring, most states experience low rates, except for Oklahoma, Wyoming, North Dakota, and Alaska. Spatial trends are not apparent in the summer, as the overall frequency is minimal, and the CO fatality-prone weather perils do not occur as often as they do in winter and autumn. Because of decreasing temperatures and increased tropical cyclone activity, CO fatalities rise in the autumn for many states. Florida has the highest frequency of weather-related CO fatalities in the autumn, but other Southern states such as Alabama and Louisiana experience higher normalized fatality rates stemming from the seasonal maximum in tropical cyclone activity. States in the northern half of the United States experienced higher rates of weather-related CO poisoning during the cool season because of extreme cold, snowstorms, and ice storms. Washington also experienced high CO fatality rates in the autumn from extreme cold.

Since the CPSC did not provide county- or city-level data, spatial analysis at a finer resolution is unavailable; however, the dataset did offer the rurality of each fatality by describing the size of the city or town in which the victim was residing at the time of death. Rurality was provided by the CPSC, which was based on measures of population density, urbanization, and daily commuting; these codes are constructed from the most recent set of U.S. Census data closest to the time of each weather-related CO fatality and were provided by the

TABLE 2. Frequency of weather-related CO fatalities and affiliated weather peril by FEMA zone.

Zone	Total	Winter weather	Thunderstorm	Cold	Flooding	Wind	Hurricane/tropical cyclone	Tornado	Heat	Unknown
I	57	19	7	4	3	5	3	0	0	16
II	73	31	8	5	9	8	0	0	0	12
III	148	49	19	18	23	12	6	0	2	19
IV	337	57	92	40	26	6	56	4	4	52
V	317	81	69	39	40	31	0	2	1	54
VI	214	31	57	13	32	18	30	2	2	29
VII	86	23	15	17	11	5	2	0	0	13
VIII	58	28	11	4	3	6	0	0	0	6
IX	86	25	4	14	9	21	0	0	2	11
X	63	22	4	11	5	8	0	0	0	13

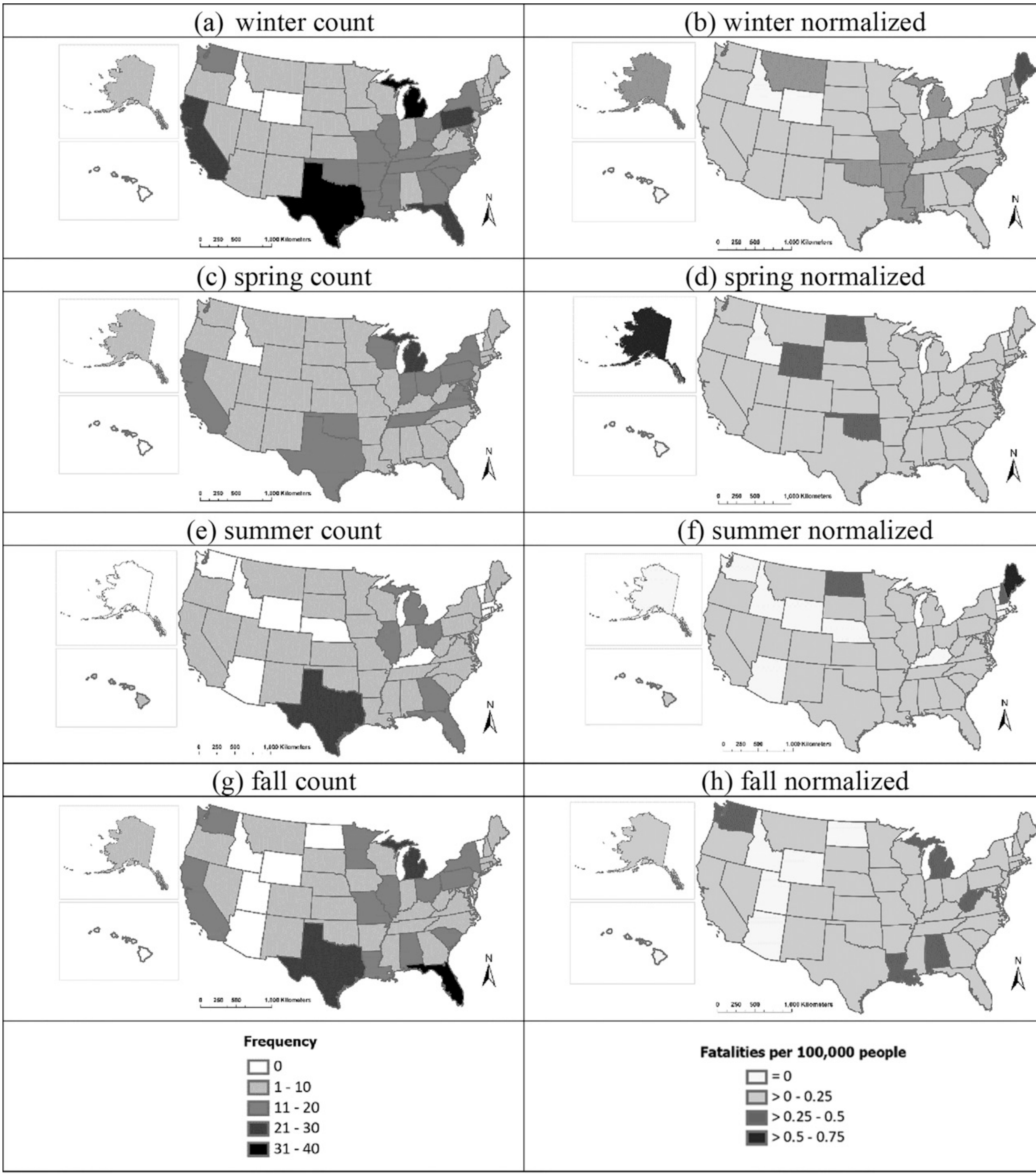

FIG. 9. (left) Seasonal frequency of weather-related CO fatalities by state, and (right) the same normalized by state population (per 100 000 people) (U.S. Census Bureau 2019b), 2000–19 for (a),(b) winter (December–February); (c),(d) spring (March–May); (e),(f) summer (June–August); and (g),(h) autumn (September–November).

Economic Research Service (ERS; Hnatov 2020). Rurality provides some limited insight on the socioeconomic status of the victim and the conditions of the community's infrastructure and its ability to withstand intense weather conditions. Of the three possible categories, urban areas experienced the most weather-related CO fatalities (884, or 61.2%) (Fig. 10), which echoes the increased accessibility of petroleum-based generators in populated areas and the increased health risk to the residents of these cities as power outages are becoming longer and more complex to repair (Casey et al. 2020,

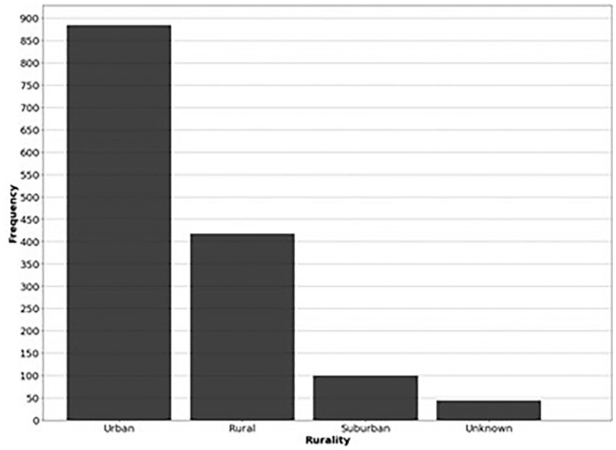

FIG. 10. Weather-related CO fatalities by rurality of the town or city of the victims.

Campbell 2012). Rural areas, on the other hand, rely heavily on comparatively old transmission and distribution systems (including extensive power line arrays) that are extremely vulnerable to weather perils and often take longer to repair and restore power (Campbell 2012), which may help explain the relatively high frequency of CO fatalities (417, or 28.9%) in rural areas. Percentages of rural population and urban population are difficult to obtain, as these classes can be defined in numerous ways. The U.S. Census Bureau (2019a, p. 2) referred to the American Community Survey report that claimed 19% of the U.S. population resided in a rural area as of 2016, which suggests that rural communities are vulnerable to weather-related CO fatalities relative to their percentage of population.

People are most vulnerable to CO exposure in their homes after a major storm; 72.2% of weather-related CO fatalities occurred in a home, with an additional 9.3% in a temporary structure such as a motor home or travel trailer, 9% in a detached garage or other external structure, and the remaining deaths in automobiles, camp sites, and other locations. Portable generators were reported as the primary CO source for 81.7% of all weather-related CO fatalities, revealing the extreme risk of these temporary power sources. An additional 16.4% of weather-related CO deaths were from other petrol-driven tools such as propane and kerosene heaters. The sources for the rest of the fatalities included grills, ranges or ovens, and wood stoves. Data reveal that engine-driven tools affiliated with deadly CO poisoning were primarily operating in unattached garages, basements, or within the living areas, which suggests that many people do not know how to properly locate these CO-emitting devices in a place that ensures proper ventilation and distancing from any inhabited structure.

5. Conclusions

Extreme weather—such as high winds, tornadoes, tropical cyclones, and intense snow and ice events—is increasingly affecting an aging, growing, and stretched energy system and, consequently, causing power outages that can have wide-ranging effects (Reidmiller et al. 2018). One of those effects is CO poisoning, which is often the result of persons using alternative and improperly located CO-exhausting power supplies for heating, cooking, lighting, and cleanup during and after an extreme weather event. CO is the leading cause of unintentional, non-fire-related poisoning deaths in the United States (Casey et al. 2020; CDC 2019), with portable generators being the number one source of nonfire CO poisoning (CDC 2019). After extreme events, emergency medical services, hospitals, and community health centers experience influxes in CO poisoning due to the improper use of portable generators, vehicles, and appliances, revealing a deficiency in safety education on the proper use of petroleum-driven utilities (Hampson and Dunn 2015) and/or potential behavioral barriers to their safe use.

Results from this study reveal that people are most vulnerable to weather-related CO poisoning in the winter months. The year-to-year frequencies from 2000 to 2019 varied, as years with more weather extremes and disasters tended to have higher cases relative to somewhat quieter years. Winter weather perils such as ice storms and snowstorms were the leading peril-inducing situations that resulted in fatal weather-related, unintentional, nonfire CO poisonings. Thunderstorms were another leading weather peril, which were mainly linked to the power outages that are caused by thunderstorm hazards such as lightning, strong winds, and heavy rain. Extreme cold was another leading contributor to situations that can cause CO mortality; in these instances, people seek out alternative sources of power to heat their residences, which can lead to death or injury when sources are not properly ventilated.

A demographic analysis on weather-related CO fatalities revealed that males were most vulnerable to CO fatal poisonings, and people between 40 and 54 years old were the most vulnerable age group relative to their percentage of U.S. population. The White demographic experienced the highest count of weather-related CO fatalities, but the Black demographic was more affected than other races/ethnicities when normalized by U.S. population.

Last, Texas, Michigan, and Florida were the leading states affiliated with weather-related CO fatalities. However, when normalized by state population, the leading states per capita were Alaska, Louisiana, Maine, and Mississippi. The vulnerability shifted by season, as parts of the South and Midwest had highest death rates during the winter, the Northeast was highest in the summer, and parts of the South and Midwest were highest in the autumn. Since the available data resolution was at the state level, a spatial analysis of county or city data was limited; however, the FOIA dataset offered the rurality of the victim's location. Those in urban and rural areas appeared to be most vulnerable to weather-related CO fatalities; suburban communities were the least vulnerable.

Ultimately, the results of this study show that anyone in proximity to a CO-emitting source is vulnerable to poisoning and, potentially, death. Because of the growing odds of power disruptions, individuals, families, and communities are increasingly seeking and using alternative power sources for heating, cooking, lighting, and cleanup during the emergency and recovery phases of a disaster. These alternative power sources exhaust CO that can ultimately buildup to toxic levels in enclosed areas. An aging and continually growing energy system vulnerable to environmental shocks is boosting the odds of power failures during hazardous weather events, which is increasing the likelihood of CO exposure, illness, and death. Indeed, the lack of decline in this weather-related mortality over the period of study reveals that people remain largely unaware of this phenomenon and/or that the risk is outpacing mitigation measures.

Findings from this study and parallel research efforts (Table 1) should be used by policy makers, emergency managers, and other public officials to prevent future occurrences of weather-related CO deaths. As a weather peril approaches, the most vulnerable groups should be further targeted by first responders and educated about the risk, especially for those who employ alternative power generation utilities. Education about proper generator use is limited, which can be fixed at the time of purchase; this could entail an improved user's manual, a more effective hazard tag, and the inclusion and/or improvement of CO detectors and auto-shutoff switches on generators. First responders patrolling and performing community education in the most vulnerable areas is another possible solution to mitigating CO poisoning in households that already own portable generators, as improper use can be identifiable from outside of the houses with portable generators running in attached garages, detached garages, porches, or nearby to a structure. Through education and simple, yet effective, mitigation measures, CO-emitting tools may be used safely to provide necessary power and support during times of need.

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Data availability statement. Data that support the findings of this study are available from the corresponding author upon reasonable request.

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