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How Many People Were Killed by Windblown Dust Events in the United States?

Daniel Tong, Irene Feng, Thomas E. Gill, Kerstin Schepanski, and Julian Wang

ABSTRACT: Windblown dust events, including dust storms and smaller blowing dust events, pose severe risks to public health and transportation safety. In the United States, the statistics of fatalities caused by dust events remains elusive. We developed a new dataset by merging dust fatality data from NOAA Storm Events Database and the Department of Transportation Fatality Analysis Reporting System (FARS). There was a total of 232 deaths from windblown dust events from 2007 to 2017. This number is much larger than that reported by the NOAA Natural Hazard Statistics, which assigns some dust fatalities to high winds and thunderstorms (~45%) and does not include many events in FARS. Dust fatalities are most frequent over the Southwest, consistent with the spatial distribution of dust storm occurrences. Other high-risk regions include the Colorado Plateau, Columbia Plateau in Washington and Oregon, the High Plains where the disastrous "Dust Bowl" occurred, and the Corn Belt where blowing dust from croplands presents a driving hazard. All six most deadly dust wrecks (three deaths or more) involved semi trucks and five of them were caused by dust storms along Interstate 10. There exist two "hotspots" for dust fatalities: 1) the "Deadliest 10 Miles" between Phoenix and Tucson, Arizona, and 2) Lordsburg Playa in New Mexico, where active dust mitigation projects have been managed by state transportation agencies. In most years, dust events caused comparable life losses to that from other weather hazards such as hurricanes, thunderstorms, lightning, and wildfires. This work presents new evidence that dust is an underappreciated weather hazard.

KEYWORDS: Atmosphere; Social Science; North America; Aerosols; Particulates; Visibility

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Windblown dust events, including both dust storms (visibility < 1 km) and smaller, localized events from deserts, fallow farmlands, and construction sites, pose severe risks to public health and transportation safety. Exposure to dust particles has been associated with a variety of adverse health effects, including respiratory disease (Gross et al. 2018), cardiovascular mortality (Crooks et al. 2016), and fungal infections (Williams et al. 1979; Tong et al. 2017). In addition, dust storms can remove topsoil, damage crops, delay transportation, disrupt commerce, and reduce the recreational value of landscapes (Shepherd 2016).

Another acute societal impact of windblown dust events is to cause injury and fatalities in highway transportation. Dust storms are the third largest cause of weather fatalities (after extreme heat and flooding) in Arizona, where 157 people were killed and 1,324 injured by dust storms on highways between 1955 and 2011 (Lader et al. 2016). On 29 November 1991, the largest single dust-related highway incident in U.S. history occurred on Interstate 5 in the San Joaquin Valley, California, where 164 vehicles collided, resulting in 151 people injured and 17 fatalities (Pauley et al. 1996). At least 41 dust-related fatalities have been recorded since 1967 where Interstate 10 (I-10) crosses Lordsburg Playa, a dry lakebed in New Mexico (Van Pelt et al. 2020). Although dust storms are often viewed as desert phenomena, windblown dust can occur anywhere in the world over cropland, construction sites, or other uncovered land surface. For example, Weber et al. (2014) reported that blowing dust associated with road construction caused collisions on Route 108 near Carlinville, Illinois. Windblown dust in eastern Arkansas led to at least two multivehicle crashes that injured 11 and killed 1 in April 2016 (Breslin 2016).

Windblown dust impacts highway safety in several ways. Dust clouds can drastically and suddenly obscure horizontal visibility for drivers, causing disorientation and compromised decision-making. In addition, the deposition of fine particles reduces traction on the road surface (Pan et al. 2021), requiring a longer stopping distance and reducing control. Dust events are often paired with high winds, adding more difficulty in controlling a vehicle under low visibility over a slippery road.

The health and safety burdens of windblown dust events are likely to be further amplified by climate change (Bell et al. 2016; Pu and Ginoux 2017). Climate models have consistently projected a drying trend in the southwestern United States (Cook et al. 2014; Prein et al. 2016), raising speculation of more frequent dust storms and potentially another megadrought-driven "Dust Bowl" in the coming decades (Romm 2011). The western United States has become dustier in recent decades, indicated by increased rainwater calcium (Ca^{2+}) (Brahney et al. 2013), more dust deposited on snow in the Rocky Mountains (Clow et al. 2016), and rapid intensification of locally originated dust storms (Tong et al. 2017). In the Great Plains, remote sensing, and particulate matter monitoring (PM) networks indicated a 5% yearly increase in dust loading from 2000 to 2018 (Lambert et al. 2020). It is projected that dust activity will increase in the southern Great Plains from spring to fall in the coming decades (Pu and Ginoux 2017).

Despite rising risks, the number of fatalities caused by windblown dust events in the United States remains largely uncertain. The U.S. Natural Hazard Statistics (NHS), a widely used information portal prepared by the NOAA National Centers for Environmental Information (NCEI) using the Storm Events Database (Storm Data), reports far fewer dust-related deaths than the media does, even for high-profile events. For instance, news outlets and transportation agencies reported three separate dust-related crashes resulting in 11 deaths at Lordsburg Playa, New Mexico, during 2017 (Hutchinson and Botkin 2018), but the NHS reported zero dust-associated deaths for the entire nation that year (National Weather Service 2023). The NHS data are derived from the Storm Data, which has been the source for prior studies of dust and wind events (e.g., Peterson and Zobeck 1996; Ashley and Black 2008; Crooks et al. 2016; Murley et al. 2021). The Storm Data is known to be incomplete and inconsistent for various applications (e.g., Ashley and Black 2008; Tong et al. 2022; Ardon-Dryer et al. 2023).

The objective of this study is to compare existing datasets of dust fatalities in order to understand and clarify the death toll of windblown dust events in the United States. We focus on dust fatality data from two major sources: the NOAA Storm Data and the Department of Transportation's Fatality Analysis Reporting System (FARS). We also utilize satellite observations of dust events and other sources, such as independent media reports, to validate these events when possible. This work extends prior investigations in several ways. First, we focus only on fatalities caused by windblown dust. Prior studies investigated all events impacted by low visibility or high winds (Ashley and Black 2008; Ashley et al. 2015), which are different hazards driven by different mechanisms and therefore require corresponding mitigation and warning measures. Second, we extend the work by Ashley et al. (2015) with updated data for recent years, examining the continuous impacts of the dust hazard. Finally, we compare two popular dust fatality datasets and attempt to clarify the actual number of dust fatalities for public awareness. This study only considers dust-related fatalities from traffic crashes (deaths on the site or immediately after the crashes); other dust fatalities, such as those associated with respiratory and cardiovascular diseases, are not accounted for here.

Methods and data

Fatality data sources. Two fatality datasets are examined in this study, the NOAA Storm Events Database (NCEI 2021) and the Department of Transportation (DOT) FARS database (Briggs et al. 2005). The Natural Hazard Statistics, which also reports yearly fatalities and injuries from various weather events, are derived from the Storm Data.

NOAA Storm Events Database and Natural Hazard Statistics. The NOAA Storm Data documents severe weather events from 1950 to the present, compiled monthly by the NCEI and is one of the most complete records of notable U.S. weather events. Storm Data events are reported through various sources, such as trained weather spotters, meteorological stations, law enforcement, media, and the public (Tong et al. 2022). In this study, a method was developed to filter the Storm Data to identify fatal crashes related to windblown dust events from the lower 48 states, Alaska, and Hawaii. We accounted for only the fatal crashes associated with airborne soil particles using keywords "dust" or "sand" that was explicitly described in the event narrative. We excluded the events with windborne nonsoil objects during strong winds. Finally, we included the fatalities caused by both large dust storms and smaller dust events (e.g., blowing dust of any scale). Dust storms are large windblown dust events reducing visibility to <1 km (WMO 2019). Small-scale dust events, such as these originated from fallowed fields or playas and local-scale winds, are often more dangerous due to little lead time for drivers to respond and no warnings from weather or public safety agencies.

The Storm Data was used by the National Weather Service (NWS) to create the NHS, which summarizes fatalities, injuries, and damages caused by severe weather. These summaries were published each year by the National Weather Service and may be considered official statistics of various weather hazards, including dust storms, although it is not considered as an official source of data on cause of death. In this study, only data for 2007–17 were extracted from both the NHS and Storm Data to match the time period of FARS.

DOT Fatality Analysis Reporting System dataset. FARS is a compilation of police reports on fatal motor vehicle collisions by the National Highway Traffic Safety Administration (National Center for Statistics and Analysis 2023). It reports critical information on these incidents, including number of fatalities, weather type, collision type, and vehicle types. While FARS has data starting from 1975, "blowing sand, soil, and dirt" was not given its own category until 2007 in most states. FARS data were filtered for "blowing sand, soil, and dirt" for the years 2007–17. We include all visibility-related (VR) fatal crashes from FARS, not distinguishing whether visibility is the major contributing factor or sole trigger in the crashes (Ashley et al. 2015). A limitation of the FARS dataset is that it is based on police accident reports (PARs), which vary from state to state and are subjective to a police officer's assessment of weather conditions. For instance, Mississippi (and Virginia until 2009 and Montana until 2013) does not have PARs in which blowing dust events are recorded in the weather conditions. Therefore, fatal crashes with blowing dust were not recorded from those states (Ashley et al. 2015). This is problematic as Mississippi, Montana, and Virginia have dust events reported within the Storm Data, indicating potential missing dust fatalities from these states. The FARS dataset also lacks a detailed description (narrative) of the accident in the PARs, making it difficult to confirm the presence of a dust event. Therefore, we conducted additional quality control of the FARS by cross-checking with Storm Data, satellite observations, and media reports. A more detailed description of the intercomparison is provided in the "Merging Storm Data and FARS" section.

Dust data. Records of local windblown dust events were obtained from the Interagency Monitoring of Protected Visual Environments (IMPROVE), a national aerosol monitoring network (Malm et al. 1994), for 2007–17. IMPROVE data were filtered using a satellite-aided dust identification algorithm (Tong et al. 2012), which detects dust events using five criteria: 1) high concentrations of PM_{10} and $PM_{2.5}$ (particulate matter with diameters smaller than 2.5 and 10 μm, respectively); 2) low ratio of $PM_{2.5}$ to PM_{10}, representing dominance of coarse particles, typically mineral dust; 3) high concentrations of crustal elements (Si, Ca, K, Fe, Ti); 4) low concentrations of anthropogenic components (As, Zn, Cu, Pb, sulfate, nitrate, organic carbon, elemental carbon); and 5) low enrichment factors of anthropogenic pollution elements (Cu, Zn, Pb). These criteria are based on distinct chemical and physical characteristics of aerosols during dust storms (for details, see Tong et al. 2012). This approach was applied to process ground-level aerosol observations collected by the IMPROVE network to develop a 2007–17 dust storm climatology matching the fatality dataset. The number of detected dust storms was calculated for each site during the study period. Due to the nature of the dust detection algorithm, the IMPROVE data only captured dust events with daily average PM_{10} concentrations > 40 μg m^{-3} (Tong et al. 2012, 2017).

Results

Comparisons of NHS, Storm Data, and FARS. The numbers of annual fatalities caused by windblown dust events reported by the NHS, Storm Data, and FARS are compared for the period 2007–17 (Fig. 1). The NHS typically reports zero dust-related fatalities each year, except in 2009, 2015, and 2016, during which 5, 2, and 3 deaths were recorded, correspondingly. FARS reports much higher numbers, from 13 deaths in 2010 and 2011 to 32 deaths in 2014. On average, the NHS reported 1 death per year and FARS reported 21 deaths per year during the study period. The Storm Data ranged from 0 to 12 annual deaths, averaging 3.5 deaths per year for 2007–17. These differences highlight the need to investigate the causes behind the discrepancies.

We conducted case studies to understand the strengths and weaknesses of each dataset by using independent data sources. First, we investigated media reports of dust-related wrecks in 2017, a year with several well-documented dust-associated highway crashes. We searched Google News using the time, location, and keywords related to sand, dust, soil, or dirt. We also conducted separate searches on social media, including Twitter, Instagram, YouTube, and Facebook. There were three fatal collisions caused by dust storms near Lordsburg Playa, resulting in 11 deaths and many injuries (Hutchinson and Botkin 2018). NHS reported zero deaths from dust storms for 2017, Storm Data recorded two fatal dust events, and only FARS contained all three events.

While the FARS appears to report more fatal dust crashes, it is incomplete too. For instance, several wrecks caused by blowing dust resulted in at least one fatality on 27 February 2011 in Andrews County, Texas (NCEI 2021). As both datasets have missing data, there is a need to compile a more comprehensive dataset of dust fatalities using both FARS and Storm Data.

Although NHS are based on Storm Data, there is a large difference in dust fatalities between the two datasets. First, the majority of dust events within Storm Data are not labeled "dust storm." Approximately 45% of the dust events were categorized as "high wind" or "thunderstorm wind" while "dust storm" and "dust devil" accounted for only 41%. The remaining events were classified as "wildfire," "strong wind," "hail," and other event types. Second, comparing NHS and Storm Data reveals that NHS appears to only account for "direct deaths" from the Storm Data events specifically labeled as "dust storm." In Storm Data, direct deaths caused by dust storms are defined as caused by asphyxiation, flying debris, or a pushed-over vehicle due to strong winds (National Weather Service 2018). These "direct deaths" are mainly due to strong winds rather than the presence of dust itself. Many dust-related fatalities are

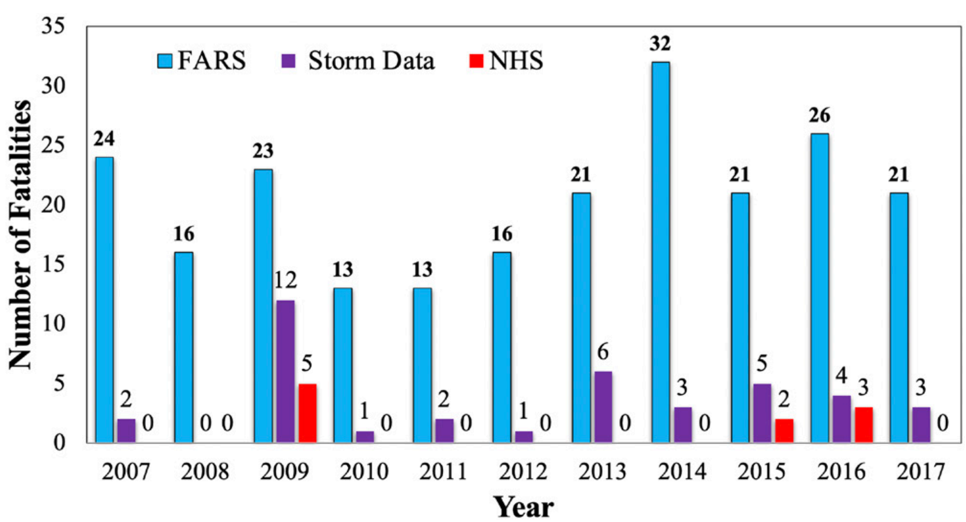

Fig. 1. Comparisons of annual roadway fatalities caused by windblown dust events from the Fatality Analysis Reporting System (FARS), the Storm Events Database (*Storm Data*), and the Natural Hazard Statistics (NHS) between 2007 and 2017 in the United States.

designated as "indirect deaths" because they are primarily caused by decreased visibility or debris left on the road after the event (National Weather Service 2018). This means if dust storms cause motor vehicle fatalities, it will not be counted in the NHS under the Dust Storm category. For these reasons, the NHS are not expected to capture dust fatalities well. In summary, the NHS, Storm Data, and FARS do not capture all dust-related fatalities. The Storm Events Database (and consequently the NHS) is shown to be missing a substantial number of fatal dust events, consistent with earlier findings by dos Santos (2016).

Merging Storm Data and FARS. A new dataset merging Storm Data and FARS was generated to obtain a more complete picture of dust fatalities in the United States. Although these datasets measure different aspects of dust fatality, a common parameter is the number of fatalities. Each fatal event in Storm Data was compared with that in FARS to remove duplicate data records. Events with the same time and location were considered the same. For quality control, a record was considered valid if both FARS data and Storm Data listed the same event(s). For records only listed by one of these datasets, additional validation methods were applied. For events in Storm Data, the narratives and report source were examined closely. If the narrative confirmed the presence of dust from a verifiable report source (e.g., media outlets, agency news release, traceable social media reports), it was considered valid. Because FARS did not have these narratives, we relied on satellite observations of dust storms, land-use conditions, and media reports.

Satellite observations have long been used to detect dust storms from space (e.g., Kaufman et al. 2001). For example, a regional dust storm in eastern Washington was captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's *Terra* satellite on 3 October 2009 (Fig. 2). Although this area is not a desert, it is prone to wind erosion during the dry season when cropland is bare (Claiborn et al. 2000). From 2009 to 2015, there were five fatal crashes caused by windblown dust events in the Columbia Plateau of Washington.

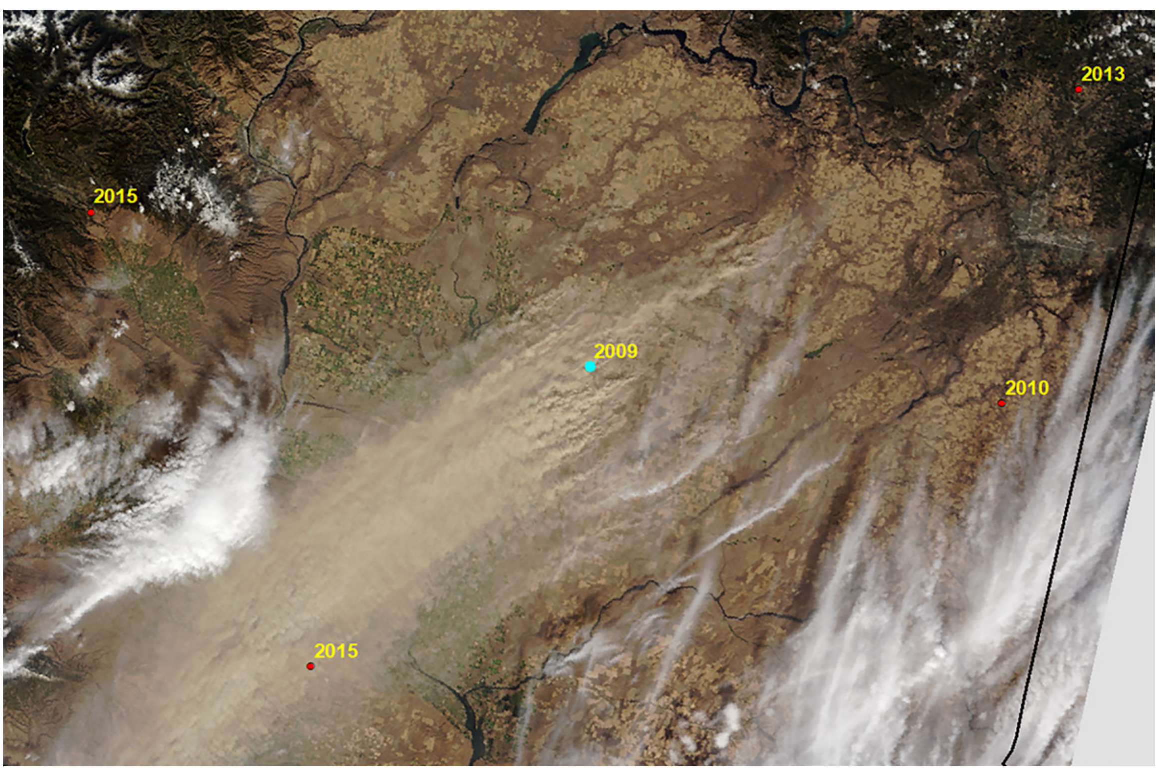

Fig. 2. Overlay of NASA MODIS true color observations of a 3 Oct 2009 dust storm in Washington that caused one death on Highway I-90. The dots in cyan and red indicate the locations of the 2009 wreck and four others in the same region, respectively.

While there were no direct satellite observations for the other four cases, these events were regarded as valid based on existing dust sources and historic records. The same rationale was applied to validate fatality records in other known dust regions, such as the Southwest and the Colorado Plateau (Gillette and Hanson 1989).

For events without detailed narratives or satellite observations, we examined media report or land-use data using Google Maps and the time-lapse function of Google Earth Engine. In most cases, the crash was situated near farmland, a major dust source across the United States (Gillette and Hanson 1989; Lambert et al. 2020). Another method of verification was cross-checking these events with media reports, including social media (mostly YouTube and Twitter). One example is the exclusion of the 26 October 2013 event in Arizona where FARS reported three deaths. Examining media outlets found zero reports on this case, while the other triple-death crash on 29 October 2013 at the same location was widely reported. Given the similarity of these two events and the lack of supporting evidence of the first event, a major crash that is unlikely to be ignored by mainstream news or social media, we determined it is not a valid record and hence be excluded from subsequent analyses.

After validation, all events were classified into three categories: verified, likely, and false. The "verified" records are those reported by both FARS and Storm Data. The "likely" category includes the records reported by one of the two datasets and cannot be excluded after checking with media report, satellite observations of dust storms, or land-use types. Events in the last category were excluded from this study. The combined dataset includes both "verified" and "likely" records. Compared to Ashley et al. (2015), which reported a total of 89 fatalities from blowing dust, soil, and dirt, the number of dust fatalities (93) was comparable for the overlapping years of 2007–11, providing additional confidence in the method and the statistics presented in this study. While Mississippi data are absent from the FARS, Storm Data only noted two dust events in Mississippi from 1996 to 2018, suggesting that Mississippi is not a major dust region, and the possibly missing data are not expected to have a large impact on the overall data. It is also the case for Virginia and Montana in which a separate dust category in PARs was adopted late.

The combination of these datasets after cross validation provides the most comprehensive information of dust fatalities in the United States. The merged dataset showed a total of 232 deaths from dust events for the years 2007–17 (Table 1). The number of deaths ranged from 14 to 32 per year with a yearly average of 21 fatalities. This is a much higher number than that reported by NHS, as well as Storm Data. The NHS reports a yearly average of one dust death for the same time period, demonstrating that fatalities caused by windblown dust events have been consistently and drastically underreported.

Spatial distribution of dust fatalities. Dust fatalities occurred across the entire United States, not only in the arid Southwest. The spatial distribution of dust fatalities shows that the majority involved one or two deaths, but some events claimed three lives or more (Fig. 3).

The map revealed a few high-risk regions prone to fatal dust wrecks: the Southwest, the Colorado Plateau, the Columbia Plateau, the Great Plains, and the Corn Belt. The Southwest, extending from California to western Texas, is an active dust source region (Gillette and Hanson 1989; Tong et al. 2012) and has the highest frequency of dust storm activity in the past two decades (Tong et al. 2017). Four deserts, the Mojave, Great Basin, Sonoran, and Chihuahuan, contribute large amounts of dust that often decrease visibility on major highways, such as I-10. The Colorado Plateau is another traditional dust source region with wind erosion increased by land degradation and strong spring winds (Gillette and Hanson 1989; Lambert et al. 2020). The Great Plains, site of the 1930s Dust Bowl extending from the Texas Panhandle northward, are subject to dust emissions during the cold, dry, windy season (Lee et al. 1993) as well as from agricultural practices (Lambert et al. 2020). Compared to these traditional dusty

Table 1. Dust fatalities by state and year from 2007 to 2017 in the 48 contiguous states and Alaska. There were no dust fatalities reported during this period in Hawaii or the District of Columbia.

	Year											
State	07	08	09	10	11	12	13	14	15	16	17	State total
Alaska	0	0	0	0	0	0	0	0	0	1	0	1
Arizona	4	1	7	2	3	1	3	4	0	2	1	28
Arkansas	1	0	1	0	0	0	0	0	0	1	0	3
California	8	6	3	0	2	0	5	1	2	2	0	29
Colorado	1	0	2	0	0	0	0	0	2	0	0	5
Idaho	0	1	0	0	0	0	0	0	0	1	0	2
Illinois	0	0	0	0	0	0	0	0	0	0	2	2
Indiana	0	0	1	0	1	3	2	0	2	3	3	15
Iowa	0	2	2	1	0	0	0	0	0	5	0	10
Kansas	1	0	0	1	0	0	0	4	0	0	0	6
Kentucky	0	0	1	1	0	3	0	1	2	2	0	10
Louisiana	1	0	0	0	0	1	0	0	0	1	0	3
Maryland	0	1	0	0	0	0	0	0	0	0	0	1
Massachusetts	0	0	1	0	0	0	0	0	0	0	0	1
Michigan	0	0	0	0	0	0	0	0	1	0	0	1
Minnesota	0	1	1	2	0	0	2	0	0	5	0	11
Montana	0	0	0	0	0	0	1	0	1	0	0	2
Nebraska	0	2	0	1	1	1	1	8	2	0	0	16
Nevada	0	0	1	2	0	1	2	0	1	0	2	9
New Mexico	0	1	0	0	0	1	1	7	0	1	11	22
North Carolina	0	0	0	0	1	1	0	0	0	0	0	2
Ohio	0	0	0	2	0	0	0	0	3	1	0	6
Oregon	0	0	0	0	0	0	0	0	1	0	0	1
South Dakota	0	0	0	1	0	0	0	0	0	0	0	1
Texas	3	1	3	0	4	4	4	2	1	1	2	25
Utah	2	0	0	0	0	0	0	0	1	0	0	3
Virginia	0	0	0	0	1	0	0	0	0	0	0	1
Washington	0	0	1	1	1	0	0	1	2	0	0	6
Wisconsin	3	0	1	0	0	0	2	0	0	0	0	6
Wyoming	0	0	0	0	0	0	0	4	0	0	0	4
Yearly total	24	16	25	14	14	16	23	32	21	26	21	232

areas, the Columbia Plateau and the Corn Belt, the corn producing region extending from the Dakotas to the Ohio Valley, are seasonal sources that emit soil dust when the cropland is dry and not covered by vegetation (Claiborn et al. 2000) or caused by agricultural operations (Hill et al. 2019). The silty soils of the Columbia Plateau are very emissive, and much of the area is only cropped once per 2-yr cycle. Thus, on average, half the cropland is in the fallow phase of the rotation (S. Van Pelt 2021, U.S. Department of Agriculture, personal communication). With wind erosion a long-standing challenge for agricultural research and management, the risk of dust-related fatal crashes adds additional urgency to address cropland wind erosion.

Dust from near-road sources caused many vehicle crashes (Lader et al. 2016; Li et al. 2018). Several hotspots were identified inside these high-risk regions, such as the Lordsburg Playa in New Mexico, the “Deadliest 10 Miles” in south-central Arizona, I-40 in the Mojave Desert, the San Joaquin Valley of California, I-80 along playas in the Great Basin, the High Plains Dust Bowl in northwestern Texas and surrounding states, and the I-80 corridor between

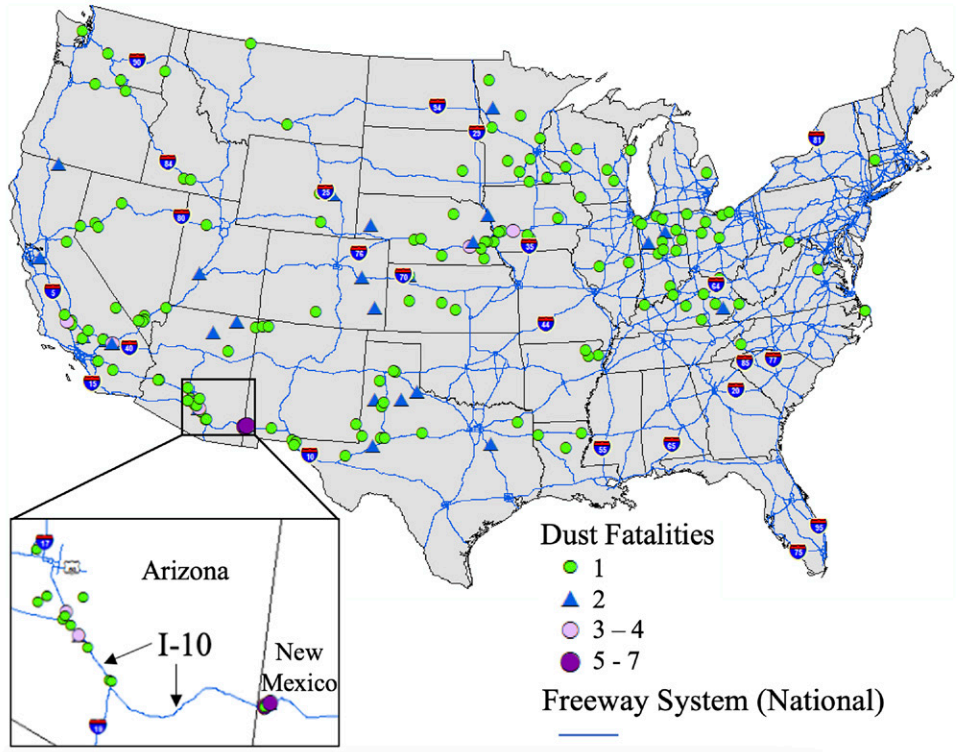

Fig. 3. Spatial distributions of dust-related roadway fatalities (circles and triangles) from 2007 to 2017 in the United States. The fatality data are from the merged FARS and Storm Events databases.

Iowa and Nebraska (Fig. 3). Of these, two sites stand out as the deadliest stretches of road for dust-related crashes in the United States. The largest single location of fatal crashes was a segment of Interstate 10 in southwestern New Mexico, near the border to Arizona (Fig. 3). In this hotspot, Interstate 10 crosses the Lordsburg Playa, where dust plumes caused fatal pileups with increasing frequency in the last decade (Li et al. 2018; Van Pelt et al. 2020). The "Deadliest 10 Miles" on I-10 near Picacho Peak between Phoenix and Tucson, Arizona (Hyers and Marcus 1981), has been ranked as one of the most dangerous highway stretches in the nation. Between 2010 and 2015, 85 dust-related crashes were reported in this area with more than 50% within 1 mile of milepost 214 near Picacho Peak (Patrick 2018). Note the number of nonfatal crashes is much larger than that of fatal crashes covered in this study.

Figure 4 compares spatial distributions of dust storms and dust-related fatalities from 2007 to 2017. Both dust storms and dust fatalities are most frequent over the Southwest, from California to Texas. Among these states, Texas has a high number of dust fatalities (25) but fewer reported dust storms by our calculations. This is because the state has only two IMPROVE sites, Big Bend National Park (BIBE1) and Guadalupe Mountains National Park (GUMO1). Both sites report a very high dust frequency. At many locations where dust crashes occur, there are no monitors, an issue that limit our knowledge of the dust events in this region. In addition, the absence of dust monitoring in the agricultural heartland of the southern Great Plains points to a need to strengthen dust observations in a region with frequent fatal dust wrecks (Fig. 3).

There are many fatalities outside the southwestern United States, despite having a much lower frequency of large dust storms. For instance, each of Indiana, Minnesota, Iowa, Kentucky, and Washington has less than 1% of the dust storms in the dataset. However, there are a disproportionally larger number of dust fatalities in these states. Cropland dust storms are usually small in size, form quickly, and are more difficult for drivers to navigate through. Due to a shorter response time available for motorcyclists, these storms often lead to disproportionately higher life and property losses. Because of their smaller sizes and shorter durations,

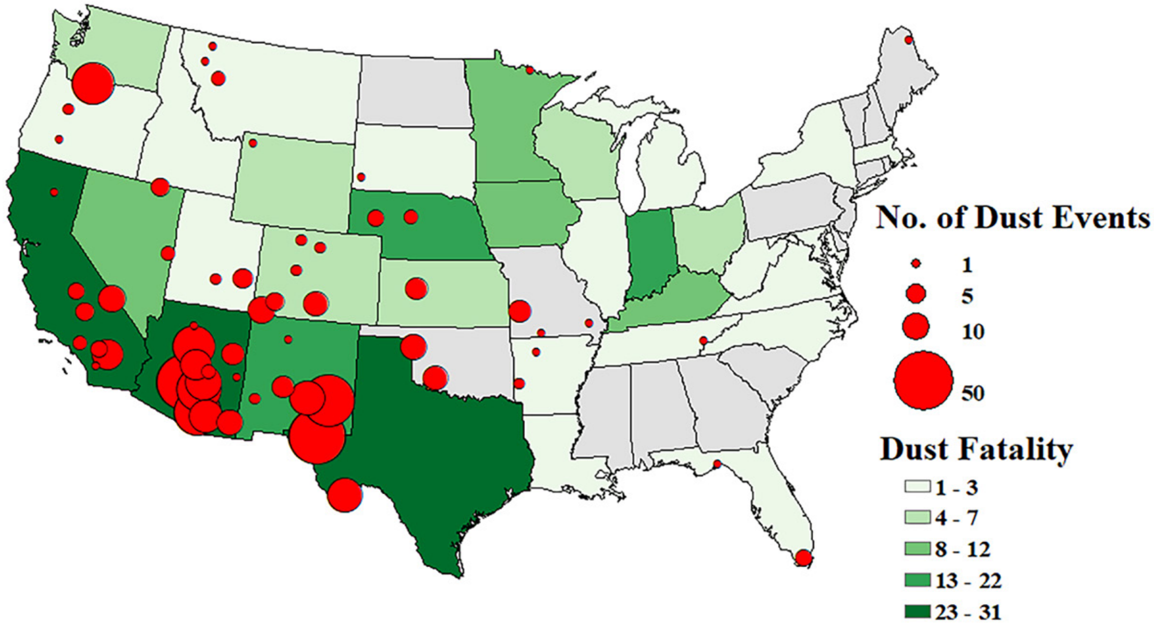

Fig. 4. Spatial distribution of dust storms (red circles) and dust fatalities (background shading) from 2007 to 2017 in the United States. The dust storm data are obtained from the IMPROVE network following Tong et al. (2017) and fatality data are the state totals from the fused FARS and *Storm Data*.

such dust events are difficult to detect by ground-based aerosol monitoring networks, meteorological stations, or satellite sensors. It is also unlikely to be warned about by weather agencies, due to the challenge in predicting such local events with computer models. This would explain the inconsistency between low dust storm frequencies from IMPROVE and the high number of fatalities in agricultural states.

Temporal distribution of dust fatalities. Temporal variations of dust-related fatalities are illustrated in Fig. 5, including yearly, monthly, weekly, and diurnal patterns. The annual number of dust fatalities varied considerably (Fig. 5a), with a peak of 32 dust fatalities in 2014 and minimum number of fatalities 14 in 2010. The average deaths per year (21) are comparable to the 24 fatalities from nonconvective high winds during 1980–2005 reported by Ashley and Black (2008). The winter months had the greatest number of fatalities, total 84 for December–February. Ashley and Black (2008), using Storm Data, also found that high wind deaths occurred the most frequently in November, December, and March. This implies that dust storms occurring in the winter months could be more dangerous than those in other months. These months (November–April) are the season of synoptic-scale dust events driven by fronts and gradient winds across the western United States, which cover a much larger spatial area than the more convective (and thus mesoscale) summer events. Also, lower vegetation cover and soil moisture and fallowed cropland during November–April compared to summer make the land more prone to wind erosion.

The highest number of fatalities occurred on Saturdays (50 deaths) (Fig. 5c), with the fewest dust-related deaths on Fridays (19). Dust fatalities increase toward the middle of the week, and dip on Wednesday. Many fatal dust crashes, in particular those with multiple deaths in the southwestern United States, involve commercial trucks, as reported by FARS. Given the United States' size and regionally distributed production, trucking is a main mode of transporting agricultural and industrial goods between the coasts and inland regions. To avoid commuter traffic, trucks are often operated during nontypical hours, including nighttime and weekends.

The number of fatalities starts to increase from 0700 local time and peaks at 1700 local time (Fig. 5d). In the United States, dust storms take place more often in the afternoon due to enhanced daytime planetary boundary layer dynamics (Huang et al. 2015; Lei et al. 2016)

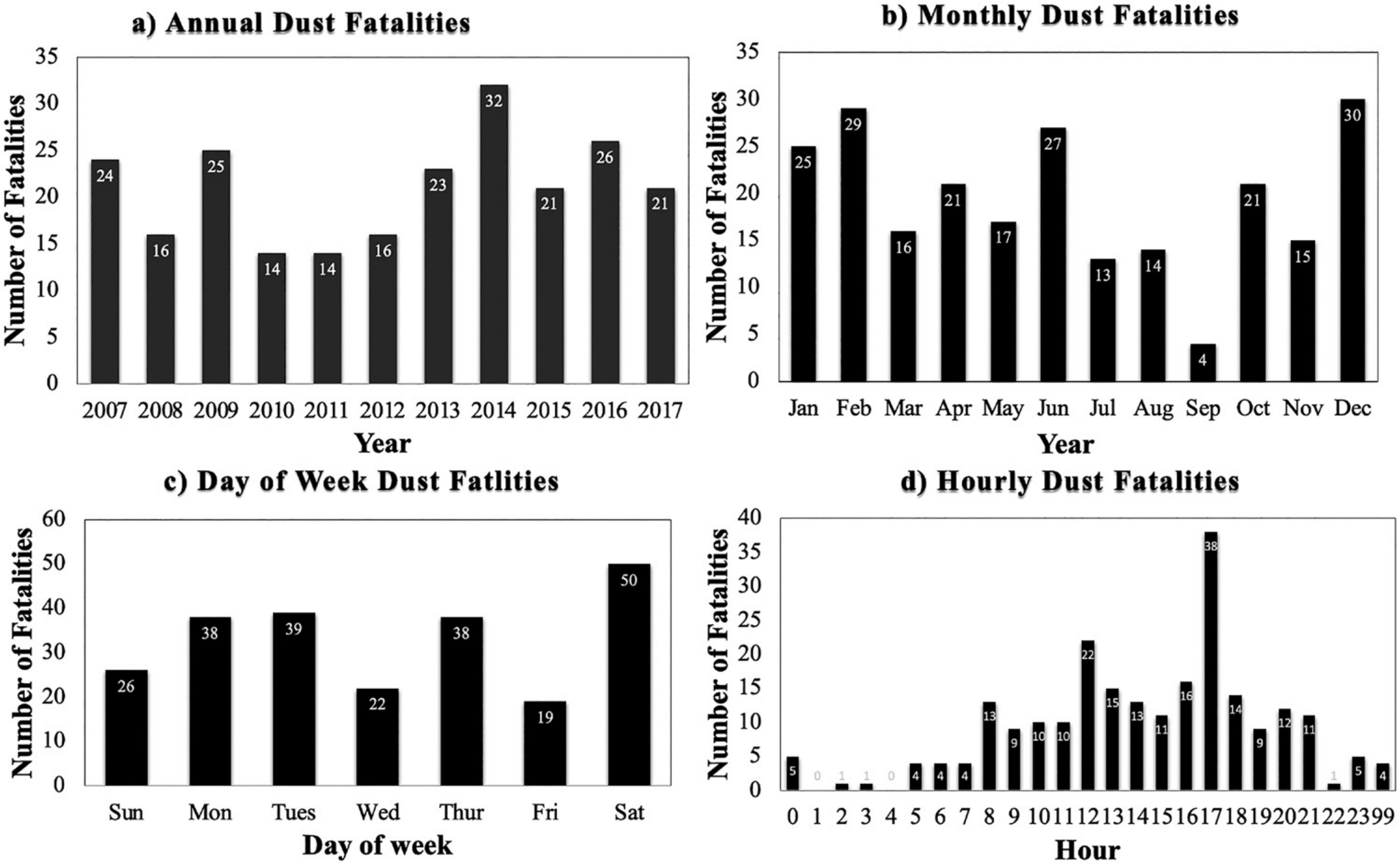

Fig. 5. **Temporal variations of dust-related fatalities between 2007 and 2017 in the United States: (a) yearly variations, (b) monthly variations, (c) day-of-week variations, and (d) diurnal variations (0 = 0000, 23 = 2300, and 99 represents an unknown time; all times are in local time).**

and sand saltation enhanced by surface heating and drying (Stout 2010), especially in the spring windy season in the Plains and parts of the Southwest (Stout 2015). Highway traffic is also more active during the working hours. The number of fatalities at 1700 local time is 72% greater than that at noon due to higher traffic volume, higher dust frequency, and possibly sun glare during times of the year when days are shorter (Sun et al. 2018). Our results agree with Crooks et al. (2016), which found that in 1993–2005 the amount of dust storms increased starting from 0600 local time and peaked around 1800 local time.

Top-ranked fatal events. Table 2 lists the deadliest dust events during the study period, six wrecks with two each occurring in Arizona, California, and New Mexico. The deadliest pileup resulted in seven deaths and numerous injuries on 22 May 2014 along Interstate 10 at Lordsburg Playa. A chain reaction of crashes occurred due to the leading driver slowing down in response to reduced visibility caused by windblown dust. Several trucks and passenger cars were involved in crashes and a tractor trailer burned into an unrecognizable husk (Daily Mail 2014; Associated Press 2014). The second deadliest crash also occurred on I-10 near Lordsburg Playa, on 19 June 2017. This wreck involved 25 vehicles, including 18 commercial trucks (Morganroth 2017) and caused six deaths, including a 9-month-old infant (Associated Press 2017). Approximately 100 km of I-10 was closed for several hours in both New Mexico and Arizona (Allen 2017), causing economic losses not only via increased travel time and other logistical delays, but also by damaging pavement and bridges on the structurally weaker detour routes (Van Pelt et al. 2020).

The third deadliest wreck was a collision on 9 November 2008 on Interstate 40 (I-40) in the Mojave Desert of California, when gusty winds up to 80 km h^{-1} were recorded at the

Table 2. List of the deadliest highway crashes caused by windblown dust during 2007–17 in the United States. All major crashes involve semi trucks.

State	Date	Local time (HHMM)	No. of deaths	Location (lat, lon)	Truck involved	Short description
New Mexico	22 May 2014	1717	7	32.3°, –108.9°	Yes	Chain reaction wreck involving 8 vehicles caused by a dust storm that brought visibility near zero on I-10 at Lordsburg Playa near the Arizona border (Associated Press 2014).
New Mexico	19 Jun 2017	1716	6	32.28°, –108.87°	Yes	25-vehicle pileup that caused 6 fatalities and caused I-10 to be shut down for several hours. This was caused by a sudden appearance of blowing dust on Lordsburg Playa (Morganroth 2017; Allen 2017).
California	9 Nov 2008	0844	4	34.81°, –116.59°	Yes	Blowing dust reduced visibility to cause a 13-vehicle pileup on I-40, resulting in 4 fatalities (NCEI 2021).
California	13 Oct 2009	1710	3	35.27°, –119.23°	Yes	Blowing dust as a result of a storm system caused 3 people to die from vehicle crashes on I-5 (NCEI 2021).
Arizona	22 Dec 2009	—	3	32.92°, –111.69°	Yes	Eighty acres of freshly plowed farmland led to a dust storm that would not have occurred under normal circumstances. Thirty to forty vehicles were involved in this wreck on I-10 that resulted in 3 deaths (Beal 2011; Rentas and Pratley 2009).
Arizona	29 Oct 2013	1200	3	32.7°, –111.5°	Yes	Another multivehicle wreck caused by blowing dust on I-10 resulted in 3 fatalities. At least 19 vehicles were involved, including at least 6 commercial trucks (Fox News 2013; Duarte 2013).

nearby Barstow–Daggett Airport. A total of 13 vehicles, including 7 tractor trailers, were involved, with 4 deaths and 4 more injured (Rossetti 2008). Another triple-fatality crash occurred on 13 October 2009 along Interstate 5 (I-5), near Bakersfield, California, in the San Joaquin Valley.

Two triple-fatality events took place in Arizona. On 29 October 2013, a 19-vehicle pileup killed three people on I-10 between Tucson and Phoenix (Fox News 2013) due to a 15-min-long dust storm (Duarte 2013). The highway was shut down for more than 5 h (Associated Press 2013) and traffic was also backed up for 10 km from the afternoon until the night (Duarte 2013). The crashes involved six trucks with several passenger vehicles sandwiched between them (Nicosia and Otarola 2013). Crashes on this segment (near Milepost 214) of I-10 constitute a large portion of the total fatalities, making it "the deadliest 10 miles" in the United States. Highly erodible abandoned agricultural lands in this area have increased dust hazard risk when strong winds blow through this region (Raman et al. 2014). The other triple-fatality crash in Arizona also took place on I-10 on 22 December 2009. While wind speeds were lower than typical for dust storms (Rentas and Pratley 2009), approximately 30 ha of land near the highway was freshly plowed and primed for wind erosion (Beal 2011). The thick, blinding dust set off a series of crashes, causing 30–40 vehicles to be dragged into the incident (Rentas and Pratley 2009), starting fires that caused burn injuries and three deaths. This particular event highlights how land management adjacent to transportation corridors is crucial in mitigating blowing dust (Li et al. 2018).

In response to dust-related crash risks, the Arizona Department of Transportation (ADOT) and New Mexico Department of Transportation (NMDOT) have actively worked to mitigate these hazards (ADOT 2019a; and also the appendix). In addition to static roadside signs alerting drivers as they enter dust hotspots, both states deploy dynamic message boards above the freeway (Fig. 6) to flash warnings when dusty conditions occur. ADOT's "Pull Aside, Stay Alive" campaign launched in 2012 encompasses signs and billboards, public service announcements on television and radio, social media posts, a website, and other forms of publicity including a poetry contest to educate the public on dust storm driving safety (Reid et al. 2015). Detailed description of these efforts can be found in the appendix.

Fig. 6. Dust storm as a driving hazard over Lordsburg Playa: (top) dust plumes crossing Interstate 10 on Lordsburg Playa with traffic moving at ~120 km h^{-1} (~75 mph), 22 March 2016; (bottom) dynamic message board indicating dust hazard on Interstate 10 in Arizona.

Comparisons to other weather hazards. To assess the significance of windblown dust as a life-threatening weather hazard, we compare the amount of dust fatalities with those caused by other weather hazards in the United States. Figure 7 shows the number of fatalities caused by different hazards from NHS. It suggests that windblown dust events are not insignificant threats to human life. With the revised data, dust events cause a comparable life loss to many other weather hazards. The total number of dust fatalities is higher than that directly attributed to fire weather, hurricanes, and winter storms during 2007–17. Note winter storm–related indirect fatalities are much higher (Black and Mote 2015) and fatalities from fire weather increased sharply in 2018 and 2020, and from hurricanes in 2019, outside the bounds of this study. Dust-related fatalities are comparable to those from high winds, lightning, thunderstorms, and cold weather. Dust fatalities amount to 20% or more of those from the four top weather/ocean hazards in the United States, namely, tornadoes, heat, flood, and rip current. Dust events cause more fatalities than fire weather during half of the time during 2007–17 and pose a more constant risk and greater source of weather-related deaths than hurricanes in most years. Though some years see a large number of hurricane fatalities, there are typically 15 or fewer annual deaths from hurricanes in the United States. In comparison, dust events caused more than 15 deaths yearly except for 2010. Dust accounts for 0.07% of all-cause vehicle crashes in the United States.

Discussion and conclusions

It remains unclear how many people were killed by traffic crashes associated with windblown dust, although it is often pointed out that dust is an underestimated weather hazard.

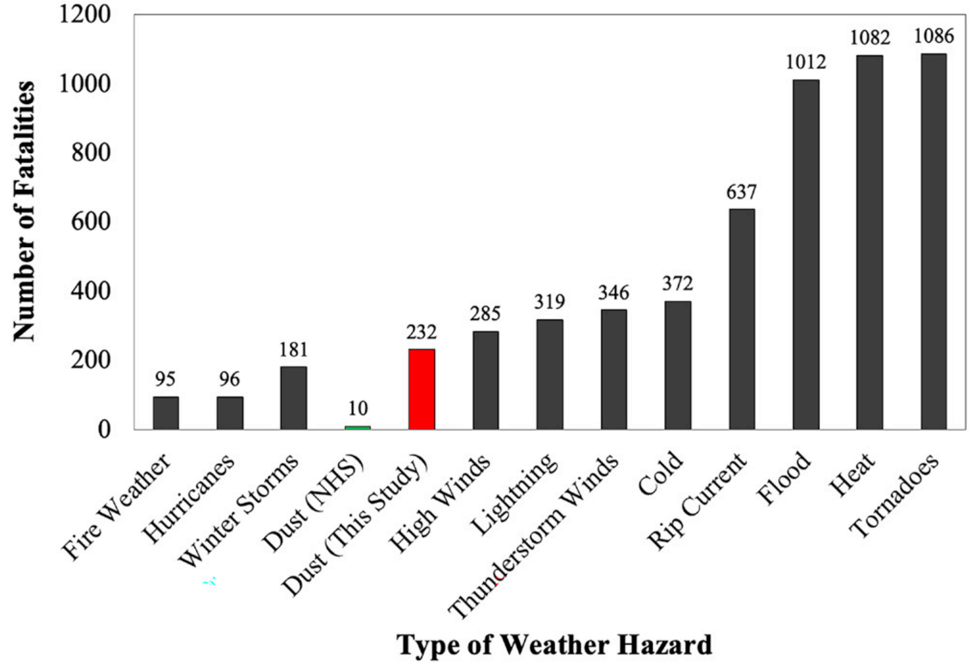

Fig. 7. Comparisons of total fatalities of major weather hazards from 2007 to 2017 in the United States. Dust fatality data are taken from this study while those from other disasters are from the Natural Hazard Statistics.

We investigated the discrepancies between dust fatalities reported by the Natural Hazard Statistics, and two large datasets of dust-related traffic wrecks: the NOAA Storm Events Database and the Department of Transportation's Fatality Analysis Reporting System. We found that there are significantly more dust-related fatalities than previously reported by any single data source. Merging FARS and Storm Data showed 232 deaths from dust-related crashes in 2007–17. Deaths ranged from 14 to 32 per year with a yearly average of 21 fatalities, much higher than that reported by NHS.

Both dust storms and dust fatalities occur most frequently over the Southwest, including California, Arizona, New Mexico, and Texas. Five of the six deadliest dust crashes occurred along Interstate 10, making it the most dangerous highway to travel on during a dust storm in the United States. I-10 contains the United States' two greatest dust fatality zones, the "Deadliest 10 Miles" in Arizona and Lordsburg Playa, New Mexico. Winter months generally saw a higher number of fatalities than in the summer. The day with the highest number of fatalities is Saturday (50 deaths), likely influenced by dust occurrences and social and transportation network factors. The peak dust fatality time is between 1200 and 1700 local time.

The Natural Hazard Statistics, a widely used summary released to the public, should consider including data from additional sources such as the FARS, separating dust events from high wind events in the Storm Data, allowing multiple classifications of a single weather event, and redefining "direct deaths" for dust events. Dust events differ from high wind events by creating a sudden loss of visibility and altering traction of the road surface with deposited sediment. The finding that 45% of dust-related events are labeled as high winds or thunderstorms indicates that there are inconsistencies in how NWS Weather Forecast Offices (WFOs) were reporting windblown dust events during the 2007–17 period and still likely are today. Last, there is no standard police accident report form for all states; thus, state PAR forms are subject to inconsistency from state to state. The addition of a narrative or description of the event in the FARS would help verify and understand each individual event for the research community. Weather agencies and law enforcement should collaborate to 1) train law enforcement in identifying these weather events, 2) standardize police report forms across different states, and 3) collect dust fatality data with higher accuracy to better understand dust hazards. It is also important to coordinate among different agencies to reduce time lag in reporting dust fatalities, since the NHS is frequently used by various groups (such as media outlets) that need a quick summary of weather-related deaths.

We found that windblown dust causes a comparable direct life loss to other major weather hazards, such as hurricanes, thunderstorms, lightning, and wildfires, during the study period in the United States. This work adds evidence to the argument that dust storms are an underappreciated and underreported deadly weather hazard (Ashley et al. 2015; Middleton et al. 2019).

Safety and transportation agencies mitigate dust risks along highways and educate the public on proper driver behavior during dust storms, including 1) monitoring dust hazards near the roadway with remote automatic camera systems, dust monitors, and real-time forecasting; 2) implementing land rehabilitation, soil stabilization, and wind erosion control on lands judged to be significant dust sources; 3) installing static and dynamic roadside signs alerting drivers as they enter dust hotspots; and 4) educating and informing the public with signs and billboards, television and radio announcements, and social media campaigns. As the population continues to grow, road infrastructure ages and degrades, projections of future climate and land-use foresee increasing drought incidence and agricultural expansion, we currently see no likely reduction in dust-related risk in transportation safety. Therefore, efforts to increase public awareness and form an inclusive reporting system on dust events and fatalities are warranted.

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Data availability statement. The Natural Hazard Statistics is available at www.weather.gov/hazstat/. The Fatality Analysis Reporting System (FARS) was downloaded from ftp://ftp.nhtsa.dot.gov/fars. *Storm Data* are obtained from NOAA Storm Events Database available at www.ncdc.noaa.gov/stormevents. The dust data are extracted from the Interagency Monitoring of Protected Visual Environment (IMPROVE) at http://vista.cira.colostate.edu/Improve.

Appendix: Dust mitigation efforts in the United States

The "Deadliest 10 Miles" of I-10 near Casa Grande, Arizona has been extensively reengineered since 2016 to for dust hazard prevention and mitigation at a cost exceeding $72 million. The freeway was widened, dust and weather sensitive dynamic signs were added to issue warnings and change speed limits as a function of dust hazard level, and other techniques were implemented to change driver behavior during dust events (Larson 2020). Dust, wind, and visibility sensors, closed-circuit cameras, and an X-band radar were installed adjacent to the highway to monitor roadside conditions in real time, and vehicle sensors were embedded in the roadway to detect traffic response. The system began full operation in 2020 and performed successfully during the monsoon dust season (Larson 2020).

In New Mexico, the fatal crashes at Lordsburg Playa led the NMDOT to secure approximately $2 million in federal highway funding to detect dust hazards with remote automatic camera systems and dust monitors, and implement land rehabilitation, soil stabilization, and wind erosion control on the playa and surrounding dust-emissive lands (Botkin and Hutchinson 2020). ADOT recommended a project with costs exceeding $60 million to improve detours around Lordsburg Playa on the Arizona side of the state line to accommodate traffic when I-10 is closed (ADOT 2019b).

Both states actively intervened to perform emergency land management on improperly managed agricultural lands adjacent to highways. For example, dust from an abandoned, barren 120-ha field near Milan, New Mexico, caused two separate crashes on Interstate 40 involving more than 20 vehicles and 3 deaths within 7 days in April 2004. Within hours of the first crash, the state poured thousands of liters of water on the field and started installing more than 500 m of sand fencing, tilled the ground, and applied a chemical soil stabilizer. At San Simon, Arizona, multiple crashes on Interstate 10 in early 2016 were caused by dust from highway-adjacent land that had been cleared and tilled. ADOT, along with the Arizona Department of Environmental Quality, and the Arizona Department of Agriculture, applied chemical stabilizer and water, planted vegetation, and sanctioned the landowner (Broeder 2017). After the state spent $600,000 to mitigate the site, less than a year later the landowner retilled the site and plowed the soil, resulting in dust clouds that caused four crashes in 4 days on I-10 (Broeder 2017). These cases illustrate the difficulties encountered and efforts required to reactively stem the risk of deadly dust-related highway crashes in drylands and agricultural regions.

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