Characteristics of Winter-Precipitation-Related Transportation Fatalities in the United States

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ABSTRACT

Winter precipitation can be very disruptive to travel by aircraft and by motor vehicles. Vehicle fatalities due to winter precipitation are considered ''indirect'' and are not counted in *Storm Data*, the publication commonly used to evaluate losses from meteorological hazards. The goal of this study is to examine the spatial and temporal characteristics of these indirect transportation fatalities that involve winter precipitation for the period 1975–2011. Motor vehicle fatalities were gathered from the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) database, while aviation fatalities were collected from the National Transportation Safety Board's (NTSB) Aviation Accident database. Statistical analysis and geographic information systems (GIS) were used to assess the spatial and temporal characteristics of these deaths. Most winter-precipitation-related motor vehicle fatalities occur during the daylight hours. Fatal motor vehicle accident rates are higher than expected in the Northeast and Great Lakes regions, while winter-precipitation-related aviation fatalities are most common in the western United States. Vehicle fatality counts due to winter weather are compared to fatality counts for various hazards from *Storm Data* to highlight the differences between the datasets. Because of the exclusion of vehicle fatalities, *Storm Data* underestimates by an order of magnitude the number of fatalities that involve winter weather each year. It is hoped that a better understanding of winter precipitation mortality can be applied in order to reduce fatalities in the future.

1. Introduction

Winter precipitation such as snow, sleet, and freezing rain is a hazard that can have a disruptive effect on human lives. One of the greatest impacts of these storms is on travel by both vehicles and aircraft. Poor road conditions and reduced visibility during winter precipitation can lead to motor vehicle collisions, while reduced visibility or flight through winter precipitation can lead to aircraft crashes. Previous research has estimated that 30–40 (Changnon 2007) or as many as 70 (Borden and Cutter 2008) fatalities a year can be attributed to winter storms in the United States. However, these studies have only considered what are termed as ''direct'' fatalities, where the storm is a direct agent in the death (NOAA 2007). An example of a direct fatality would be someone slipping on a snowy sidewalk and sustaining a fatal head injury. However, a much larger number of winter precipitation fatalities are ''indirect,'' where the weather created a situation that led to the death (NOAA 2007). This distinction is important as *Storm Data*, the publication of the National Weather Service (NWS) that records weather injuries and fatalities, only includes direct fatalities (NOAA 2007). As a result, many previous studies of winter precipitation mortality in the meteorological literature do not address indirect fatalities and therefore exclude a significant number of fatalities, which results in an incomplete picture of the threat posed by winter weather.

The goal of this study is to examine the spatial and temporal characteristics of fatal vehicle crashes—one type of indirect fatality—that involve winter precipitation for the period 1975–2011, similar to recent studies of direct fatalities due to other meteorological hazards such as tornadoes (Ashley 2007), lightning (Ashley and Gilson 2009), nonconvective wind (Ashley and Black 2008), or thunderstorm wind (Black and Ashley 2010). After sections on background (section 2) and methodology used (section 3), this study examines

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two types of transportation accidents that commonly occur during winter precipitation—motor vehicle (section 4a) and aircraft crashes (section 4b). In addition, this study highlights differences between mortality datasets by comparing fatalities due to motor vehicle and aviation crashes to mortality information from *Storm Data*, most notably the dissimilarity of fatality counts between the two datasets (section 4c). Reduction of mortality due to winter precipitation requires an understanding of both direct and indirect fatalities. The results of this study provide a more complete picture of the hazard posed by winter precipitation to motorists across the United States, which can then be used to guide efforts to reduce these fatalities in the future.

2. Background

While winter precipitation is one of many factors that could lead to a crash, the risk of motor vehicle crashes increases greatly when snow or ice is present despite reduced traffic volumes and reduced vehicle speed (Andrey et al. 2003). Snowfall across the United States leads to an additional 45 000 vehicle collision injuries and 150 000 property damage vehicle collisions per year as compared to dry days (Eisenberg and Warner 2005). In addition, Andrey (2010) notes that the relative risk of collision during any type of precipitation is similar to the risk of being responsible for a collision while under the influence of alcohol with a blood alcohol content of 0.08 relative to no influence of alcohol. A more modest increase in vehicle collision *fatalities* can be attributed to snowfall, with an additional 30 fatal vehicle crashes per year, occurring primarily during the first snowfall of the year (Eisenberg and Warner 2005). Subsequent snow days had fewer fatal crashes, but more overall crashes, and more injuries than days with no precipitation (Eisenberg and Warner 2005). The vulnerability of motorists to winter precipitation was not uniformly distributed, with elderly drivers having the highest risk for a fatal crash during the first snow of the year, while subsequent snowfalls increased the risk of fatal crashes for drivers aged 30–50 yr (Eisenberg and Warner 2005). After comparing six cities across Canada, Andrey et al. (2003) found that precipitation is associated with a 75% increase in traffic collisions and a 45% increase in injuries. Further, snow-related collisions have different characteristics than those that do not involve precipitation (Andrey et al. 2003). Snowfall-related collisions are more likely to occur at night, on gradients or curved sections of roadway, and tend to be less serious than crashes occurring under normal driving conditions (Andrey et al. 2003). Additionally, snow-related collisions are more likely to involve only one vehicle, occur on rural roads, and on roads with speed limits of 60 km h^{-1} or higher (Andrey et al. 2003). Collisions involving snow are less likely to occur at intersections or during a turning maneuver than collisions during normal driving (Andrey et al. 2003).

Aviation is also vulnerable to the effects of winter precipitation in several ways. During takeoff and landing, aircraft can slide off of runways that are wet or have accumulated slush, snow, or ice. A study of European aviation found that operating in these runway conditions leads to a fourfold increase in the accident risk (van Es et al. 1998). Another hazard is loss of control in flight due to winter precipitation. Analysis of commercial aviation loss of control accidents from 1979 to 2009 revealed two chains of events related to winter weather (Belcastro and Foster 2010). One chain involved snowfall-reducing visibility, while the second chain involved accumulation of ice or snow on aircraft control systems (Belcastro and Foster 2010). Belcastro and Foster (2010) found that both chains led to an eventual loss of control of the aircraft through some combination of mechanical failure, inappropriate crew response, or aircraft upset (unintentionally exceeding parameters experienced during normal operations). This study will build on existing research to determine the spatial and temporal characteristics of winter-weather-related transportation fatalities. Fatalities from these accidents are considered to be indirect and are traditionally omitted from analysis by the meteorological community. It is hoped that this research will reveal patterns of vulnerability, which can then be used to develop more effective intervention strategies to reduce fatalities due to winter weather.

3. Methodology

Information on fatal vehicle crashes in the conterminous United States was gathered from the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) for the years 1975–2011. Created in 1975, the FARS database catalogs information on any motor vehicle crash that results in the death of any person (vehicle occupant and nonoccupant) within 30 days of the crash (NHTSA 2013a). Data on the crashes are gathered from various sources, including police reports, death certificates, vehicle registrations, and vital statistics, among others (NHTSA 2013a). These documents are analyzed and coded into the data elements within the FARS. To isolate the fatalities that were related to active winter precipitation, each annual FARS file was searched for coded weather variables that indicate the weather at the time of the crash. Fatalities that involved winter precipitation were coded as sleet (code 3) or snow (code 4), and these were extracted from the FARS data for further analysis. Since the focus of this study is on collisions that occur during winter precipitation rather than crashes that are related to winter weather as a whole, this approach intentionally limits the results to crashes where winter precipitation was occurring at the time of collision.

As expected, most fatalities occur during the winter season, roughly October through April, although winter precipitation can fall in high terrain as early as September or as late as May. Initial analysis of the number of fatalities by month revealed several winter-weather-related fatalities in the summer months of June–August. Fatalities occurring within the months of May through September were further analyzed to determine if they were truly a result of winter precipitation or if the weather conditions were possibly coded in error. To make this determination, daily cooperative weather data for each station within a county that saw a fatality during the May through September period were examined to determine if snowfall occurred or if below-freezing temperatures were observed in conjunction with precipitation. If snowfall or precipitation with below freezing temperatures were not observed, then the event was excluded from the database. Overall, this led to the exclusion of 132 events, or 0.5% of the original data.

Data on fatal aircraft accidents in the conterminous United States were gathered from the National Transportation Safety Board's (NTSB) Aviation Accident database for the years 1975–2011 (NTSB 2013). The NTSB database contains information about aviation accidents from 1962 to present and lists the circumstances and cause of the each accident. These data were gathered by searching the database for events with one or more fatalities where the accident narrative contained keywords associated with winter precipitation, such as "snow," "sleet," "freezing rain," "slid off runway," or "icing." For each event, the accompanying narrative was read to determine if winter precipitation was involved in the accident, and if so, the event was included for further analysis. Initial analysis found two main causes of these accidents. The first cause was an encounter with winter precipitation during some phase of flight, while the other cause was ice accumulation on aircraft control surfaces. Because icing can occur anytime an aircraft encounters supercooled water droplets (Rasmussen et al. 1992) and is not necessarily related to winter precipitation, the accident narrative for each crash was read to ensure only those caused by winter precipitation were included in the study.

Fatalities for both motor vehicle and aviation events were aggregated by county due to a lack of more precise location data within the motor vehicle crash data; for 1975–2003, only 30% of fatal motor vehicle crashes had geographic data beyond state and county. A geographic information system (GIS) was used to display the spatial patterns of these events and fatalities. All maps were projected using the Lambert conformal conic projection to preserve shape.

Mortality rates were calculated to explore the effect of population on the spatial pattern of fatalities and to compare the expected number of deaths that involve winter precipitation to the actual number of deaths that were observed. Age-adjusted death rates were calculated using direct standardization techniques based on winter-precipitation-related motor vehicle fatalities and the population by age group within each state (Wilson and Buescher 2002). Using the calculated age-adjusted death rates, the expected number of winter-precipitation-related motor vehicle fatalities for each county was determined (Wilson and Buescher 2002). The standardized mortality ratio (SMR) was then calculated for each county by dividing the observed number of fatalities by the expected number of fatalities. The SMR is a commonly used measure of mortality in spatial epidemiology research (Borden and Cutter 2008; Wilson and Buescher 2002). SMR values greater than one indicate that the death rate in a particular area was higher than that of the standard population, while values less than one indicate the rate in the particular area was lower than that of the standard population (Wilson and Buescher 2002). The SMR is sensitive to population size, with large variance of the SMR found in areas with small population and small variance in areas with large population (Meza 2003). In the extreme, when the expected fatalities are close to zero, the SMR will be very large for any positive count of actual fatalities (Lawson 2001). Counties with small populations see larger-than-expected variations in mortality rates for each death and tend to show high mortality rates despite small numbers of overall deaths, in what is commonly termed the "small number problem" (Borden and Cutter 2008; Meza 2003; Lawson 2001). To adjust for this, an empirical Bayes transformation using the gamma model with the method of moments estimation was used (Meza 2003; Marshall 1991). The transformation requires the calculated SMR for each county, along with information on the observed and expected fatalities. The gamma model is commonly used, as it has a direct solution (Meza 2003) and yields similar results as other more computationally intensive methods (Marshall 1991). Overall, the empirical Bayes method produces a nonzero estimate of SMR that is smoothed toward the mean in counties with a small expected fatality count, while it produces a value very close to the SMR in counties with a large expected fatality count. Subsequent

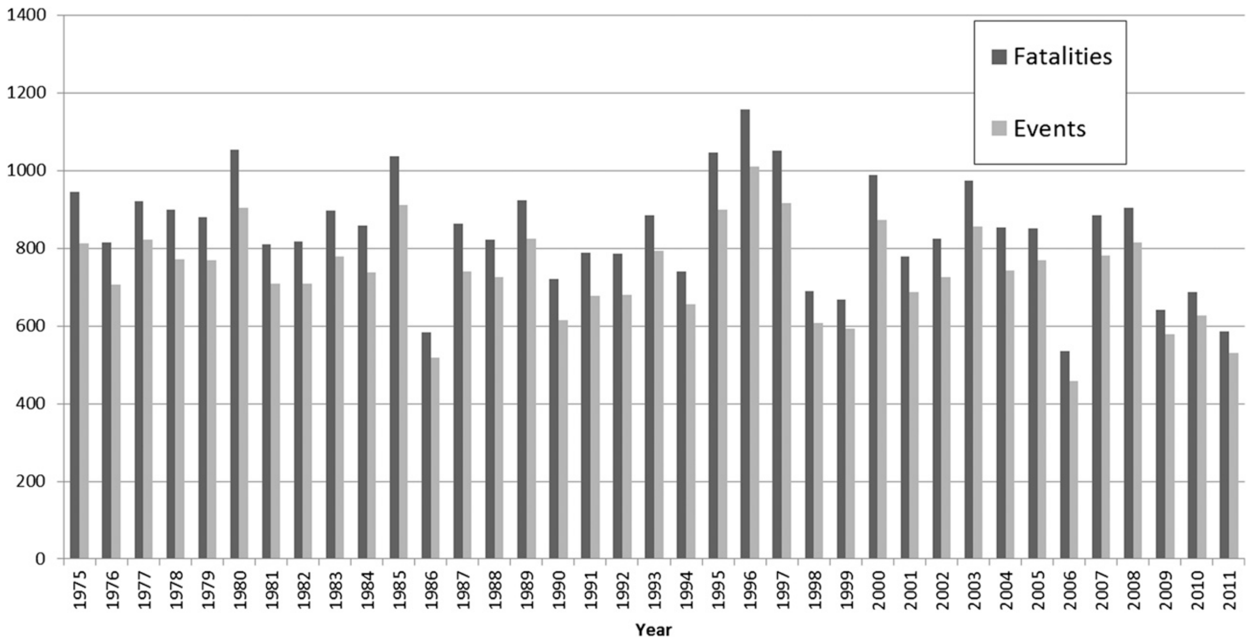

FIG. 1. Number of winter-precipitation-related motor vehicle fatalities (dark gray) and fatal vehicle accidents (light gray) by year, 1975–2011.

mentions of the SMR in this manuscript are referring to the empirical Bayes-transformed SMR rather than the raw SMR.

To compare the indirect fatalities from winter-precipitation-related motor vehicle and aviation crashes to direct fatalities from other meteorological causes, fatality counts from 1996 to 2011 were gathered for a number of weather hazards from *Storm Data*. While using the entire 1975–2011 period would be preferable, the online version of *Storm Data* only contains information on tornadoes, thunderstorm wind, and hail prior to 1996, making collection of data on fatalities from other sources such as winter weather very difficult. As there can be significant variability in the number of fatalities on an annual basis, the average number of fatalities per year due to winter-precipitation-related automobile and aviation crashes and several direct meteorological causes during the 1996–2011 period were used for this comparison. Results of this analysis are important in order to understand the relative contribution of direct and indirect fatalities to the overall losses produced by winter weather, and how these losses compare to losses from other meteorological hazards.

4. Results and discussion

a. Characteristics of motor vehicle fatalities

Winter precipitation was a factor in a total of 31 159 fatalities and 27 326 fatal crashes during the 36-yr period of record. In terms of precipitation type, 84% of crashes were attributed to snowfall, with the remaining 16% attributed to sleet or freezing rain. This may be due to several factors. Previous studies (Changnon et al. 2006; Changnon 2008; Changnon and Karl 2003) have found that sleet and freezing rain occur less frequently than snowfall. Another possible factor is that the public may perceive sleet and freezing rain as being more hazardous than snowfall and may choose not to drive or may drive more slowly than they would drive during snow or when the pavement is dry (Eisenberg and Warner 2005). Future work will address these possibilities and determine how crash rates respond to changing winter precipitation type.

Temporal trends in winter-precipitation-related motor vehicle fatalities were explored on multiple time scales in order to understand the annual, monthly, and daily trends of mortality and for comparison to other meteorological hazards. The number of fatalities ranged from a low of 535 in 2006 to a high of 1158 in 1996, while the number of crashes ranged from 458 in 2006 to 1011 in 1996 (Fig. 1). Fatalities did show a declining trend through the period. However, the percentage of motor vehicle fatalities related to winter precipitation showed little trend, indicating that the reduction in fatalities is related to improvements in vehicle safety and roadway improvements, which have led to a decline in all motor vehicle fatalities, including those that are related to winter weather (Table 1). Perhaps not surprisingly, 68% of fatalities and 70% of fatal crashes occurred during meteorological winter (December–February). When

TABLE 1. Total motor vehicle fatalities, winter-precipitation-related motor vehicle fatalities, and percent of total motor vehicle fatalities attributable to winter weather, 1975–2011.

Year	Total motor vehicle fatalities	Winter-precipitation-related motor vehicle fatalities	Total motor vehicle fatalities attributed to winter weather (%)
1975	44 525	944	2.12
1976	45 523	814	1.79
1977	47 878	921	1.92
1978	50 331	900	1.79
1979	51 093	879	1.72
1980	51 091	1053	2.06
1981	49 301	810	1.64
1982	43 945	816	1.86
1983	42 589	897	2.11
1984	44 257	857	1.94
1985	43 825	1037	2.37
1986	46 087	583	1.26
1987	46 390	864	1.86
1988	47 087	821	1.74
1989	45 582	923	2.02
1990	44 599	721	1.62
1991	41 508	788	1.90
1992	39 250	786	2.00
1993	40 150	885	2.20
1994	40 716	741	1.82
1995	41 817	1046	2.50
1996	42 065	1158	2.75
1997	42 013	1051	2.50
1998	41 501	689	1.66
1999	41 717	667	1.60
2000	41 945	989	2.36
2001	42 196	779	1.85
2002	43 005	825	1.92
2003	42 884	973	2.27
2004	42 836	854	1.99
2005	43 510	850	1.95
2006	42 708	535	1.25
2007	41 259	885	2.14
2008	37 423	904	2.42
2009	33 883	642	1.89
2010	32 885	687	2.09
2011	32 367	585	1.81

examined by month, January had the most fatalities and collisions (7805 fatalities and 6912 crashes), and December had the second-most fatalities and crashes (7664 fatalities and 6748 crashes). Winter-related vehicle crashes and fatalities occurred in every month except July. The earliest fatal crash of the winter season occurred on 26 August 2006 in Larimer County, Colorado, while the latest occurred on 24 June 1976 in King County, Washington. Just 0.48% of fatalities and 0.44% of fatal collisions occurred between 1 May and 30 September. These occurred primarily in the mountainous regions of the western United States, where winter precipitation can persist well into late spring and early summer.

Fatal motor vehicle crashes involving winter precipitation were further examined by hour of occurrence. The percentage of collisions by hour was calculated for both winter- and nonwinter-related fatal crashes, with nonwinter fatal crashes defined as any fatal accident in which the weather was not coded as sleet (code 3) or snow (code 4). Because no winter-related fatal crashes occurred between 24 June and 26 August of any given year, those dates were also excluded from the counts of nonwinter fatal crashes. This was done so that the two datasets would compare the same range of dates and to remove the effect of increased summer driving, which may skew the distribution of nonwinter fatal crashes. From 2002 to 2011, the highest rates of fatal vehicle crashes occurred in the summer months (NHTSA 2013b).

Winter-related and nonwinter-related fatal vehicle crashes have a very different hourly distribution (Fig. 2). A much larger percentage of nonwinter crashes occur during the evening and overnight hours (1900–0559 local

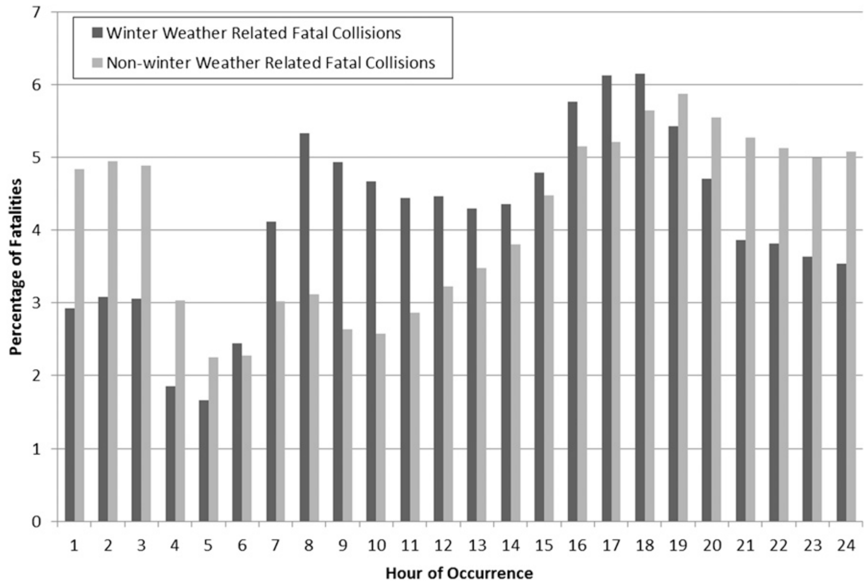

FIG. 2. Percentage of winter-precipitation-related fatal motor vehicle accidents by hour (dark gray) and nonwinter-related fatal motor vehicle accidents by hour (light gray), 1975–2011.

time), while a larger percentage of winter-related crashes occur during the morning and daytime hours (0600–1859 local time). Examination of lighting conditions during each crash revealed that only 45% of winter-related fatal accidents occur at night, with another 5% during dawn or dusk. This is surprising, as daylight hours are shortest in the winter months, so it would seem likely that a higher proportion of fatalities would occur at night. In comparison, 51% of nonwinter-related fatal crashes occur at night, with an additional 3% occurring during dawn or dusk. Fatal accidents involving rainfall are similar to nonwinter-related fatal accidents, with 54% occurring at night and 4% occurring during dawn or dusk. This indicates that the hourly distribution of winter-precipitation-related vehicle fatalities differs from not only fatal crashes as a whole but also crashes involving rainfall. Eisenberg and Warner (2005) found that people aged 30–50 yr had increased fatality rates due to snowfall-related motor vehicle accidents as compared to those under 18 or over 65 years of age, presumably because adults in the 30–50-yr age group had to travel to work regardless of the weather. This may in part explain the high number of daytime motor vehicle fatalities involving winter precipitation.

The empirical Bayes-transformed SMR for each county in the United States was log-transformed to obtain a normal distribution and was used to examine the spatial characteristics of winter-precipitation-related motor vehicle fatalities (Fig. 3). Positive (negative) values indicate areas where the SMR was higher (lower) than the mean and that saw mortality higher (lower) than expected. As would be expected, the majority of high SMR areas are located in the Northeast, the Great Lakes, and the western regions of the United States, regions where snowstorms are most common (Changnon et al. 2006). In particular, the western United States saw several areas with SMRs greater than 2.5 standard deviations from the mean. Areas of SMRs below the mean are evident primarily in the Southeast due to a lack of snowfall; however, many urban areas across the United States (e.g., Chicago, Illinois; Minneapolis–St. Paul, Minnesota; New York City, New York; Milwaukee, Wisconsin) also have lower-than-expected values of SMR and ultimately saw fewer fatalities than would be expected given the age and population size characteristics of the county. There are several potential explanations for the lower-than-expected fatalities in urban areas, including reduced travel speed during winter weather due to roadway congestion, road maintenance practices during winter weather, and use of mass transit as an alternative to driving during winter precipitation. Future research will explore these explanations and others to determine why these areas experience lower-than-expected mortality.

Previous studies have found that vehicle fatalities are often spatially clustered (Eckley and Curtin 2013). A global Moran's I test was used to determine if the empirical Bayes-transformed SMR data were significantly clustered. Neighbors were designated based on the spatial extent of the underlying process that produces the fatalities—winter precipitation. Since 84% of winter-precipitation-related motor vehicle fatalities

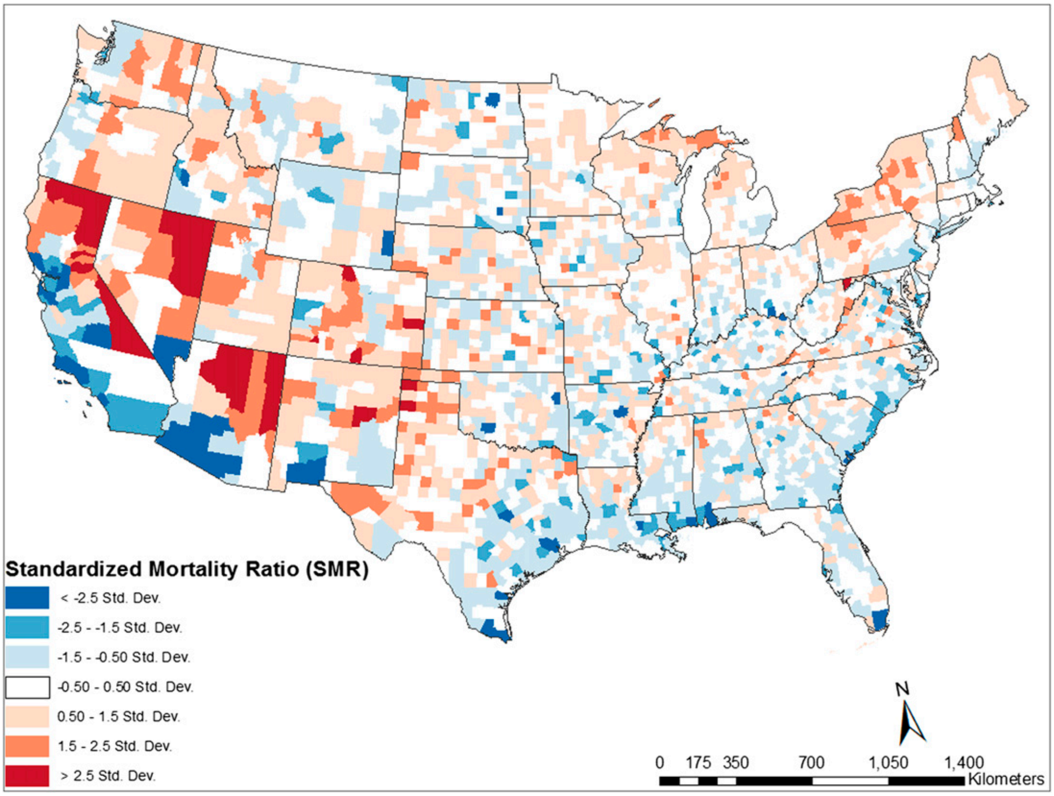

FIG. 3. County-level SMR due to winter-precipitation-related motor vehicle crashes, 1975–2011, after log-transformation to obtain a normal distribution. Positive (negative) values indicate areas where the SMR was higher (lower) than the mean and that saw mortality that was higher (lower) than expected.

involved snowfall, the spatial extent was based on the size of a typical snowstorm. Changnon and Changnon (2007) found that snowstorms in the eastern United States are often elliptically shaped with a major axis of 568 km and a minor axis of 171 km, and the average of these two distances (370 km) was then used to determine the neighborhood. The likelihood of positive spatial autocorrelation in the SMR dataset was confirmed, with a Moran's I coefficient of 0.06 ($p < 0.001$).

With the tendency for SMR values to cluster established, a local indicator of spatial association (Anselin 1995) was used to identify significant ($p < 0.05$) SMR cluster locations (Fig. 4). Clusters of high and low SMR values are found in many of the locations that saw SMR values 1.5–2.5 standard deviations above or below the mean. Clusters of high SMR are most prevalent in the western United States, the Upper Peninsula of Michigan, and across parts of New York and Pennsylvania, while low SMR clusters are found primarily across the Gulf Coast and across the Ohio River valley. Perhaps more interesting are the clusters of outliers. In the western United States, several low–high clusters exist, indicating areas with low SMR surrounded by areas with high SMR. Many of these clusters contain highly populated urban counties, such as Salt Lake City, Utah; San Francisco and the Central Valley of California; Las Vegas, Nevada; and the urbanized counties of the Front Range of Colorado. High–low outliers, indicating areas with high SMR surrounded by areas with low SMR, are found throughout the Southeast and particularly along the spine of the Appalachian Mountains from north Georgia through West Virginia. Examination of both the low–high and high–low outliers provides useful case studies to determine why mortality is different from neighboring clusters. The overall vulnerability of a place is a product of both the vulnerability to the physical hazard and the vulnerability due to societal factors (Cutter 1996). While it is likely that many factors, both physical and societal, are involved in the pattern of mortality found, future work to identify and mitigate these factors may lead to a reduction in winter-precipitation-related motor vehicle fatalities.

b. *Characteristics of aviation fatalities*

The same 1975–2011 period had 1316 fatalities and 559 aviation accidents related to winter precipitation (Fig. 5). The number of fatalities ranged from 139 in 1982 to 4 in 2010. Annual fatality counts are highly sensitive to large

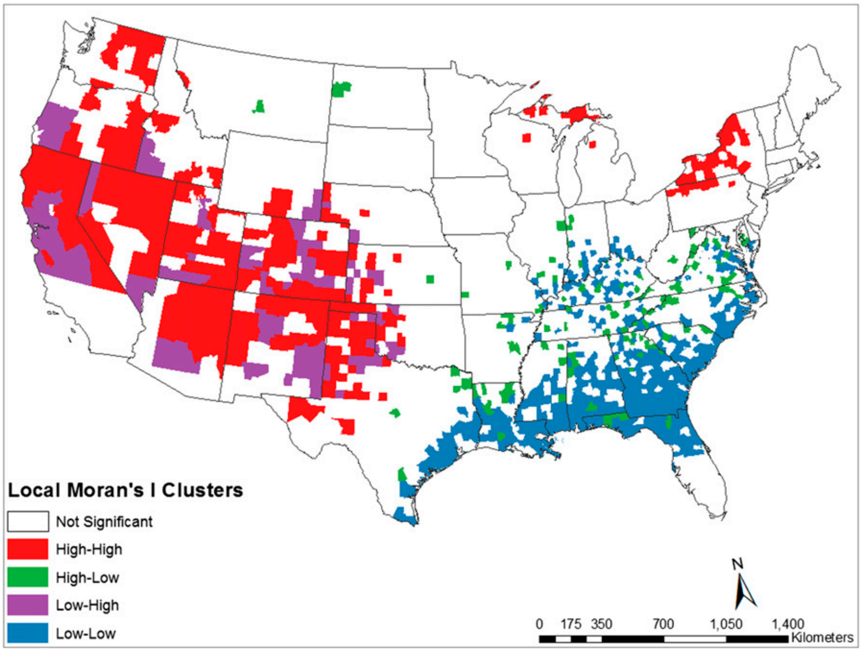

FIG. 4. County-level SMR clusters due to winter-precipitation-related motor vehicles crashes 1975–2011. All clusters significant at the $p = 0.05$ level.

events. For example, the 1982 crash of Air Florida flight 90 during takeoff in snow from Washington, D.C. was responsible for 56% of the fatalities found in 1982 and 6% of the total fatalities. However, most winter-precipitation-related crashes involved smaller aircraft, with an average of 2.35 deaths per crash. Unlike motor vehicle fatalities, there is a discernable downward trend in the number of winter-precipitation-related aviation fatalities. This reduction is likely partly due to improvements in deicing procedures and materials, along with improvements in cockpit communication and protocol between the aircraft captain and first officer following the Air Florida disaster (http://www.washingtonpost.com/local/30-years-after-air-florida-crash-skies-safer-than-ever/2012/01/05/gIQAW0GwtP_story.html).

While nearly 70% of winter-precipitation-related motor vehicle fatalities occurred during meteorological winter, the distribution of aviation fatalities and accidents is slightly different. Overall, 49% of winter-precipitation-related aircraft fatalities and 33% of crashes occurred during meteorological winter, but fatal crashes occurred in every month except July and August. The fatal accident occurring latest in the season was on 26 June 1989 in Granite, Oregon, while the earliest fatal crash in the winter season occurred on 4 September 1992 in Steamboat Springs, Colorado. Aviation-related fatalities and crashes occurred at higher rates than motor vehicle fatalities and crashes during the 1 May–30 September period; 5.5% of aviation fatalities and 5.3% of aviation crashes occurred during this period, while only 0.48% of motor vehicle fatalities and 0.44% of fatal auto accidents occurred during the period. Of the aircraft crashes occurring between 1 May and 30 September, the vast majority (96%) occurred in the western United States.

The spatial patterns of winter-weather-related aviation fatalities are very different from those of motor vehicle fatalities (Fig. 6). Aviation fatalities are concentrated in the western United States, with relatively few fatalities east of the Rocky Mountains, while the number of motor vehicle fatalities was high in the western United States, in the Northeast, and in the Great Lakes region. The large number of aviation-related fatalities in the western United States is not necessarily surprising. Most areas in the Intermountain West see at least one snowstorm of 15.2 cm (6 in.) or more per year, with some areas in the highest terrain having 10 or more of these events per year (Changnon et al. 2006). Falling snow can greatly reduce visibility, which can lead to a loss of situational awareness by the pilots. More than one-third of the winter-related aviation fatalities and accidents involved controlled flight into terrain, most commonly when mountain tops were obscured by precipitation and pilots crashed into the rising terrain. In addition, accumulation of snow on the aircraft control surfaces can alter the aerodynamic properties of the aircraft and potentially lead to an eventual loss of control of the aircraft through

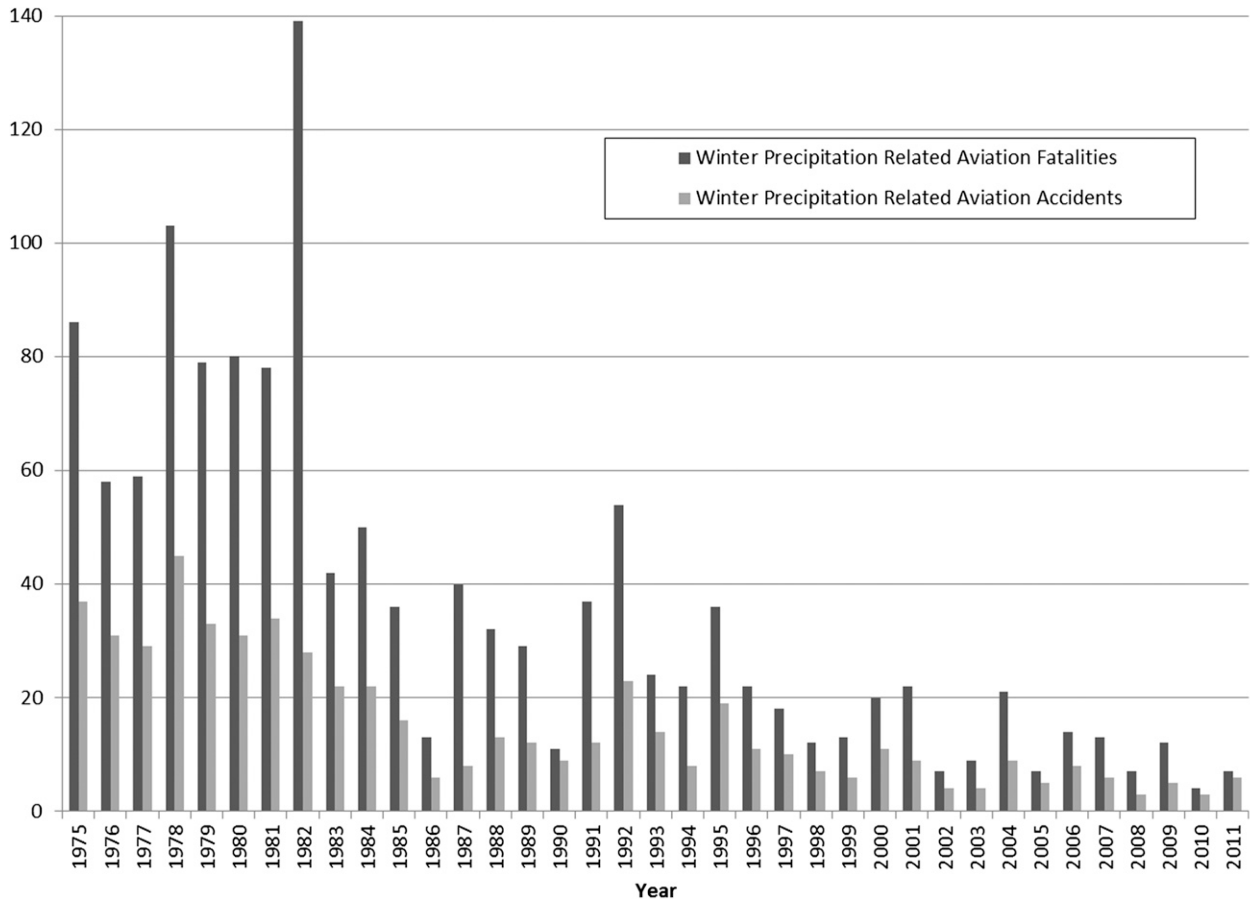

FIG. 5. Number of winter-precipitation-related aircraft fatalities (dark gray) and fatal aviation accidents (light gray) by year, 1975–2011.

some combination of mechanical failure, inappropriate crew response, or aircraft upset (Belcastro and Foster 2010). These factors, coupled with the proximity of the ground in high terrain areas, leave pilots with little room for error when winter precipitation is encountered.

c. *Comparison with* Storm Data *and other hazards*

Unlike hazards such as tornadoes (Ashley 2007) and thunderstorm wind (Black and Ashley 2010) where most fatalities are a direct consequence of the environmental hazard, this research has shown that there are large numbers of indirect fatalities that involve winter precipitation. While *Storm Data* is not intended to capture indirect fatalities from motor vehicle and aviation accidents, it is important to compare these datasets to better understand the limitations of using *Storm Data* (or any specific dataset) when examining hazard losses from winter precipitation (Gall et al. 2009).

Overall, 571 direct fatalities attributed to winter precipitation were found via the *Storm Data* dataset from 1996 to 2011, an average of 36 fatalities per year. For comparison, winter-precipitation-related motor vehicle crashes were responsible for an average of 817 fatalities per year during the period, while aviation accidents resulted in 13 fatalities per year (Fig. 7). Winter-precipitation-related motor vehicle crashes resulted in far more fatalities per year than any other hazard during the 1996–2011 period. Results of this work found 13 073 motor vehicle fatalities and 208 aviation fatalities, while *Storm Data* contained only 571 winter precipitation fatalities from any cause during the period of record. Combined, these datasets represent 13 852 total winter weather fatalities during the period, of which *Storm Data* contributed only 4%. It is not surprising that there is such a large difference in fatalities between *Storm Data* and the sources used for this study, as winter-precipitation-related motor vehicle and aviation fatalities are considered indirect and should not appear in official *Storm Data* loss tallies (NOAA 2007). However, *Storm Data* can include information about indirect fatalities within the narrative that provides additional details about the event (NOAA 2007). To determine if

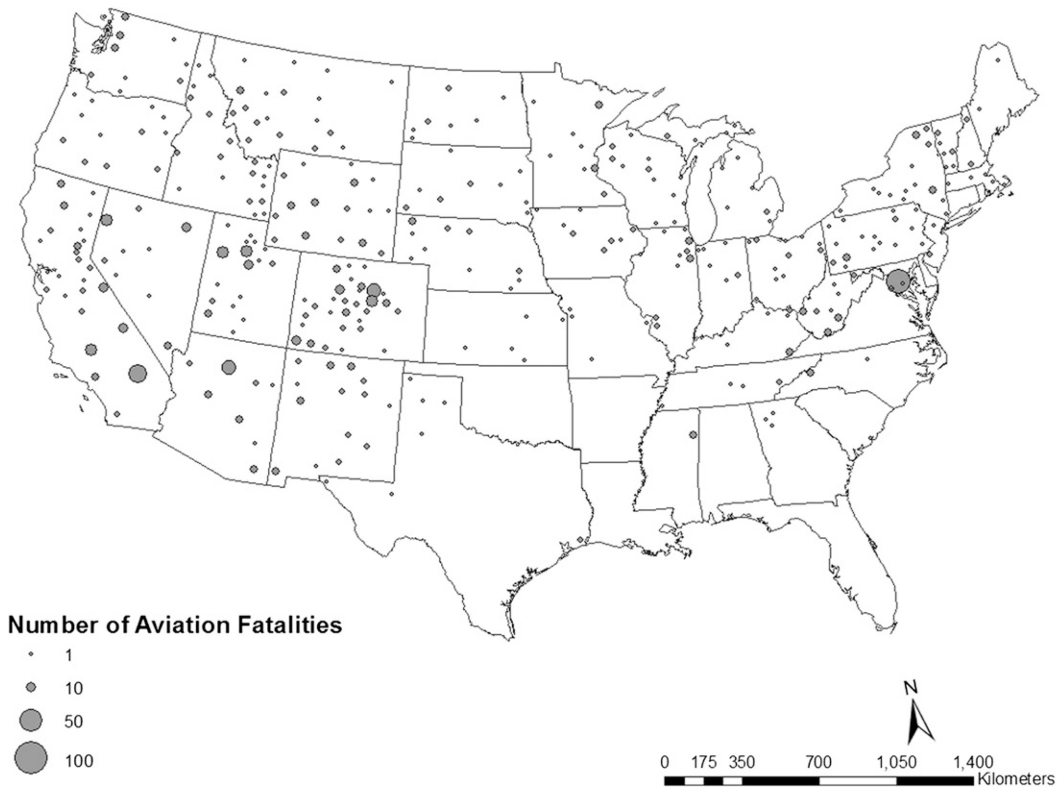

FIG. 6. Number of winter-precipitation-related aviation fatalities by county, 1975–2011.

Storm Data did account for some indirect fatalities in the narrative, winter-precipitation-related motor vehicle crashes that resulted in five or more fatalities were compared to information about the same event from *Storm Data*. Previous research has found that *Storm Data* tends to undercount fatalities when a weather event only causes a small number of fatalities (Ashley and Gilson 2009), and the threshold of five fatalities represented the deadliest 1% of winter-precipitation-related collisions, making it more likely that *Storm Data* would have information about the crash.

Only 46 out of 27 326 fatal motor vehicle crashes caused five or more deaths, and only six out of the 46 had any details or information listed in *Storm Data.* In one of the six cases, the motor vehicle crash fatalities were actually incorrectly categorized as direct fatalities and appeared in official tallies. That particular year saw 17 winter-precipitation-related fatalities, including the six that were incorrectly categorized, meaning that fully 35% of the direct winter fatalities were actually indirect. It is reasonable to assume that other years in *Storm Data* have similar issues with the distinction between direct and indirect winter fatalities, adding further uncertainty regarding the reliability of the data. In terms of fatal aviation accidents, there were 35 events that caused five or more fatalities (accounting for 23% of winter-precipitation-related aviation fatalities), of which *Storm Data* only had information on two. Based on the analysis of these indirect winter precipitation fatalities, it appears that relying on the narratives provided in *Storm Data* would result in a significant undercounting of indirect fatalities. In addition, caution should be used when examining direct fatality counts from winter weather due to issues encountered when making the distinction between direct and indirect fatalities.

It is important to reiterate that *Storm Data* is not intended to be a comprehensive database of all losses but rather of direct losses only; however, it is one of the most commonly used data sources used when examining hazard losses. As such, it is important that users of *Storm Data* understand that for hazards such as winter weather, which result in a large number of indirect fatalities, that *Storm Data* is far from comprehensive and may only represent a small percentage of the actual number of fatalities caused by the hazard.

5. Conclusions

Between 1975 and 2011, winter precipitation was a factor in nearly 28 000 aviation and motor vehicle accidents that resulted in over 32 000 fatalities, an average of nearly 900 fatalities per year. Fatality totals from

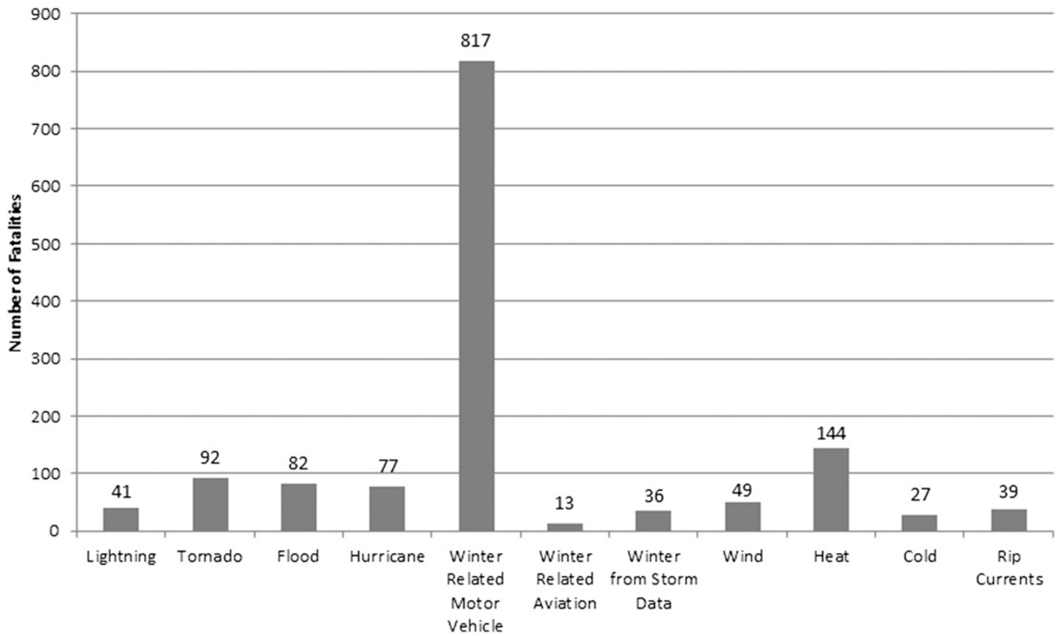

FIG. 7. Average number of fatalities per year from various meteorological hazards for the period 1996–2011. Totals for all hazards except winter-related motor vehicle and winter-related aviation fatalities are from *Storm Data*.

winter-precipitation-related vehicle accidents far eclipse fatality totals from other, more prominent weather hazards, such as tornadoes, flooding, and hurricanes. Despite this, these fatalities receive far less attention from the meteorological community, as they are ''indirect'' and occur when the weather creates a situation that leads to a death, while fatalities from events such as tornadoes are ''direct'' and occur when the storm is a direct agent in the death. Indirect fatalities are not included in counts of weather-related mortality in *Storm Data*, resulting in an underestimation of the true impacts of weather events such as winter precipitation, which can cause a large number of indirect fatalities. While there are many factors that can lead to a fatal winter-precipitation-related vehicle crash, the meteorological community plays an important role through forecasting winter precipitation and through communication of the risk of winter precipitation to the public. This work is important, as it is among the first to explore the temporal trends, spatial distribution, and excess mortality due to winter-related vehicle crashes.

The number of motor vehicle fatalities involving winter precipitation showed a decreasing trend during the period; however, the annual percentage of motor vehicle fatalities attributable to winter weather has remained nearly constant through the study period. The decrease in motor vehicle fatalities related to winter precipitation is proportional to the overall decrease in all motor vehicle fatalities, and it is likely that the decrease in winter-precipitation-related deaths is the result of improvements in vehicle and roadway safety, which have led to a decline in all motor vehicle fatalities, including those that are related to winter weather. This is consistent with Andrey (2010), whose analysis of 10 Canadian cities found that while the relative risk of crash during rainfall decreased in each city, the risk of crash during snowfall remained constant or increased. Andrey (2010) speculates that the risk from snowfall remained relatively constant due to increased driving speeds in snow as a result of better road engineering or winter maintenance. Another possibility is that reduced winter maintenance due to shrinking budgets may be responsible for the trend (Andrey 2010). Improved vehicle safety equipment, such as airbags or antilock brakes, could also give drivers a false sense of security and lead to riskier driving behavior. Future work will further examine these trends and determine how crash rates may change in response to snow versus other frozen precipitation and if factors such as precipitation intensity and timing affect the rate of fatal crashes.

Most fatal motor vehicle crashes involving winter precipitation occur during the daylight hours, while fatal crashes involving other weather conditions are more prevalent at night. Age-adjusted standardized mortality ratios reveal significant clusters of increased mortality in the western United States and areas of New York and Pennsylvania, while several urban and Gulf Coast locations had clusters of lower-than-expected mortality. More interesting are the high–low (indicating areas with high SMR surrounded by areas with low SMR) clusters located mostly in the eastern United States and Ohio River valley, and low–high (indicating areas with low SMR surrounded by areas with high SMR) clusters found in the western United States. Identification of these clusters is an important first step in determining factors that influence crash risk and collision rates during winter weather. Future work to examine both the high–low and low–high clusters will attempt to identify the factors that influence mortality and result in different outcomes as compared to neighboring clusters. It is hoped that once identified, these factors can be used to reduce mortality from winter-precipitation-related automobile crashes across the entire United States.

Aviation fatalities also followed a declining trend, most likely due to improvement in deicing procedures and cockpit communications after the Air Florida disaster in 1982. The spatial distribution of fatal winter-precipitation-related aviation crashes was very different from that of vehicle collisions. Fatal aviation crashes were most common in the western United States, where winter precipitation can obscure mountaintops or rising terrain and where high terrain can make it difficult for pilots to recover from a loss of situational awareness when precipitation is encountered.

While this study found over 13 000 transportation fatalities that involved winter precipitation during the 1996–2011 period, *Storm Data* only contained 571 winter-precipitation-related fatalities from any cause, as vehicle fatalities are considered to be indirect and therefore not officially counted in *Storm Data*. *Storm Data* is not intended to capture indirect fatalities, but users of *Storm Data* (or any dataset) must understand the limitations of the data. Users of *Storm Data* must understand that omitting indirect fatalities results in a significant underestimation of the number of deaths caused by winter weather. Reduction of mortality due to winter precipitation (or any hazard) requires an understanding of all fatalities, both direct and indirect. The authors echo the call of Gall et al. (2009) for an open, comprehensive dataset of hazard losses that focuses on accurate counts of losses, both direct and indirect, from all hazards.

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