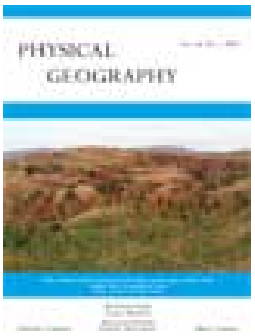

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ABSTRACT

General, or private and non-commercial, aviation accidents produce more fatalities than any other aviation category within the United States. Despite advances in scientific understanding and technology since the early 1900s, weather causes concern for aviation safety, and little is known about the characteristics of fatal weather-related general aviation accidents. We provide a comprehensive spatiotemporal analysis of fatal weather-related general aviation accidents from 1982 through 2013 using data culled from the United States National Transportation Safety Board (NTSB). Weather was a cause or contributing factor in 35% of fatal general aviation accidents, of which 60% occurred while instrument meteorological conditions were present. Fatal weather-related general aviation accidents occur most frequently between October and April, on weekends, in early morning and evening periods, and along the West Coast, Colorado Rockies, Appalachian Mountains, and the Northeast. There has been a long-term reduction in weather-related general aviation accidents and fatalities since the 1980s; nonetheless, these accidents are still responsible for nearly 100 fatalities/year in the United States. This study provides pilots, academics, the Federal Aviation Administration, the NTSB, and other aviation organizations with information to advance mitigation efforts aimed at reducing future aviation-related accidents in the United States.

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Introduction and background

Aviation accidents occurring within general aviation operations (as defined in Title 14 of the United States Code of Federal Regulations (CFR); Electronic Code of Federal Regulations, 2014, Part 91) result in an average of 765 fatalities each year (Grabowski, Curriero, Baker, & Li, 2002), making it the deadliest form of aviation transportation, with a rate of 6.51 fatalities per 100,000 flight hours (National Transportation Safety Board [NTSB], 2014). From 1990 through 2003, general aviation produced 83% of all aviation-related fatalities (Bazargan & Guzhva, 2011). The annual costs associated with general aviation accidents in the United States range from $1.64 billion to $4.64 billion (Sobieralski, 2013). Weather is often cited as a cause or contributing factor, accounting for roughly 25% of the accidents occurring in general aviation operations (Capobianco & Lee, 2001; Federal Aviation Administration

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[FAA], 2010). Despite a decreasing trend in general aviation operations since the 1970s, most of the United States national airspace and airport system is still utilized by general aviation operations (Shetty & Hansman, 2012).

Weather and aviation have a complex relationship that has plagued aviation for more than 100 years. Operating an aircraft safely within the atmosphere means that a pilot should have at least a basic knowledge of weather processes and how to recognize certain weather hazards. The idea that pilots should have a fundamental understanding of weather is not new. When the aviation industry became more influential for both mail and passenger transport in the early twentieth century, Humphreys (1930) noted that pilots should have at least some understanding of weather processes, the possible hazards associated with weather, and how to recognize those hazards while en route. The specific weather hazards commonly noted during this time were “fog” and “sleet” (Henry, 1930), where “fog” referred to any time a pilot operated in clouds and “sleet” referred to ice formation on the airframe, which is better known today as icing. Because weather is an integral part in aviation operations, it is alarming that a student pilot can incorrectly answer all weather-related questions on the pilot exam and still obtain his/her license (NTSB, 2005).

General aviation operations fall under Part 91 rules of Title 14 of the United States Code of Federal Regulations (14 CFR 91) and include a variety of aircraft – from hot air balloons, helicopters, a small single-engine Cessna aircraft, to even a large Boeing 747 – provided that the aircraft are privately owned and not offering seats for sale to the public, as opposed to Part 121 (commercial) operations (Jarboe, 2005). General aviation activities/services include emergency medical services, sightseeing, flight training, traffic reporting, aerial surveys, recreation, and personal or business use (Li & Baker, 2007). A pilot operating a single-engine aircraft under Part 91 rules for both day and night conditions must complete both a written and practical exam to obtain at least a private pilot’s license in accordance with 14 CFR 61.109.

Even with today’s advances in technology – such as in-cockpit radar availability via satellite – weather is consistently an obstacle for general aviation safety. This is largely due to both pilot error and aircraft performance. Aircraft operating within this category are more susceptible to weather hazards because they are lighter and smaller, and generally fly at lower altitudes than aircraft operating in other categories (Li & Baker, 2007). The most common weather citations for aviation accidents are wind, visibility, low ceiling, and high-density altitude, respectively (FAA, 2010). Instrument meteorological conditions (IMCs) – conditions in which operating and navigating an aircraft using visual references outside the aircraft are not feasible – account for only 6% of all general aviation accidents, yet they are responsible for 25% of all accident fatalities (Groff & Price, 2006). Spatially, mountainous locations, such as the Rockies and Appalachians, are considered to be the most hazardous locations for general aviation operations within the conterminous United States (CONUS) due to a combination of factors such as rapidly changing weather conditions, frequently changing terrain, and reduced aircraft performance at higher altitudes (Baker & Lamb, 1989; Black & Mote, 2015; Grabowski et al., 2002; Kearney & Li, 2000; Ungs, 1995). However, the spatial and temporal aspects of weather-related general aviation accidents in the CONUS are not well known.

While there is literature examining the human component of aviation events (e.g. Hunter, Martinussen, Wiggins, & O’Hare, 2011; Taneja, 2002; Wiggins, Hunter, O’Hare,

& Martinussen, 2012), there is little research regarding the spatial and temporal aspects of weather-related general aviation accidents. Some studies have contributed to weather-related aviation research by examining certain weather topics, such as nontornadic convective wind fatalities (Black & Ashley, 2010) and winter-precipitation (Black & Mote, 2015). Williamson, Stailey, and Welshinger (2009) examined weather-related events using eight weather categories and found that at least 50% of restricted visibility-related accidents end fatally. However, there has been no comprehensive evaluation of all weather-related general aviation accidents in the United States. Using a spatiotemporal framework, this study investigates fatal weather-related general aviation accidents in the CONUS from 1982 through 2013 to determine the relationship between fatal general aviation accidents and their associated weather factors.

This study is divided into three parts, providing an updated, comprehensive, and novel look at weather-related general aviation accidents. The initial analysis examines fatal weather-related accidents and their associated weather factors while subsequent analysis assesses the spatiotemporal aspect of all fatal weather-related general aviation accidents. A final section investigates further the most recent fatal weather-related accidents occurring in the United States from 1999 through 2013. Results suggest that mitigation efforts should focus on pilot education with regard to weather and safe operations, particularly within mountainous regions and locations in which restricted visibility is frequently reported.

Data and methods

This study examines general aviation (Part 91) accidents occurring over the CONUS from 1982 through 2013 using aviation accident data gathered from the National Transportation Safety Board's (NTSB's) aviation accident relational database via [http://www.ntsb.gov/_layouts/ntsb.aviation/index.aspx]. This database extends to the early 1960s, but this study focused on accidents occurring after 1982 because reports and data types differ in previous years. Accident data from the NTSB include descriptive data for both the pilot and aircraft, causal and/or contributing factors, as well as narratives discussing the sequence of events leading up to the accident. Upon final investigation of the accident, the NTSB determines and briefly describes the accident's probable cause for future mitigation practices and safety announcements. Prior to September 2008, the NTSB provided 57 weather factors that could be attributed to aviation accidents. After this time, the NTSB added, removed, or combined certain weather factors and changed its coding procedure in the database. This change resulted in 53 weather factors that could be attributed to aviation accidents along with their associated hazard categories provided by the NTSB (Table 1). These categories are (1) temperature, humidity, and pressure, (2) turbulence, (3) convective weather, (4) wind, and (5) ceiling, visibility, and precipitation.

As Capobianco and Lee (2001) noted, it is also important to state that weather-related aviation accidents can be multifactorial, meaning that more than one weather factor could be assigned as a contributing factor to a single accident. To reduce excessive over-counting in this study, accidents were counted only once for each of the associated hazard categories in which they were placed. For example, an accident involving snow, clouds, and gusts would be counted only once in the ceiling, visibility, and precipitation category and once in the

Table 1. Current NTSB codes, hazard categories, and weather factors attributable to aviation accidents.

NTSB code	Weather factor	Hazard category
03030000	(general)	(general)
03031000	(general) – Temp/humidity/pressure	Temp/humidity/pressure
03031010	Low temperature	Temp/humidity/pressure
03031015	High temperature	Temp/humidity/pressure
03031020	High density altitude	Temp/humidity/pressure
03031025	Conducive to structural icing	Temp/humidity/pressure
03031030	Conducive to carburetor icing	Temp/humidity/pressure
03031035	Temperature inversion	Temp/humidity/pressure
03031040	Thermal lifting	Temp/humidity/pressure
03032000	(general) – Turbulence	Turbulence
03032010	Terrain induced turbulence	Turbulence
03032015	Clear air turbulence	Turbulence
03032020	Convective turbulence	Turbulence
03032025	Wake turbulence	Turbulence
03033000	(general) – Convective weather	Convective weather
03033010	Thunderstorm	Convective weather
03033015	Tornado	Convective weather
03033020	Hurricane	Convective weather
03033025	Lightning	Convective weather
03033030	Hail	Convective weather
03034000	(general) – Wind	Wind
03034010	Sudden wind shift	Wind
03034015	Tailwind	Wind
03034020	Windshear	Wind
03034025	Variable wind	Wind
03034030	Updraft	Wind
03034035	Downdraft	Wind
03034040	Crosswind	Wind
03034045	Gusts	Wind
03034050	Microburst	Wind
03034055	High wind	Wind
03034060	Dust devil/whirlwind	Wind
03035000	(general) – Ceiling/visibility/precip	Ceiling/visibility/precip
03035010	Low ceiling	Ceiling/visibility/precip
03035015	Low visibility	Ceiling/visibility/precip
03035020	Haze/smoke	Ceiling/visibility/precip
03035025	Clouds	Ceiling/visibility/precip
03035030	Obscuration	Ceiling/visibility/precip
03035035	Rain	Ceiling/visibility/precip
03035040	Freezing rain/sleet	Ceiling/visibility/precip
03035045	Snow	Ceiling/visibility/precip
03035050	Drizzle/mist	Ceiling/visibility/precip
03035055	Fog	Ceiling/visibility/precip
03035060	Whiteout	Ceiling/visibility/precip
03035065	Sand/dust storm	Ceiling/visibility/precip
03035070	Below approach minima	Ceiling/visibility/precip
03035075	Below VFR minima	Ceiling/visibility/precip

wind category. In total, there were 1,713 accidents, or 11.1%, out of 15,439 associated with at least two weather hazard categories.

This study focuses on the spatiotemporal characteristics of general aviation accidents and the weather factors/categories attributed to them based on previously established methods from past aviation accident (e.g. Williamson et al., 2009) and atmospheric hazard research (e.g. Ashley, Strader, Dziubla, & Haberlie, 2015). An accident was deemed "weather-related" if there was an associated NTSB weather-related code listed for the accident. In contrast to the eight weather hazard categories used by Williamson et al. (2009), we assigned weather factors associated with aviation accidents during this time period into the five weather hazard categories based on the current NTSB categorization method.

The NTSB provides an abundant amount of information regarding accidents; however, data for weather-related accidents are limited in that definitions for weather factors are not provided. For example, no threshold values are provided for wind speed or gusts in the case of wind-related accidents. Other issues include social issues such as not knowing the pilot's familiarity with the area when the accident occurred. Understanding an individual's typical flying location and how often they fly in that area would provide useful information regarding these accidents. For example, a pilot flying in a mountainous location for the first time will be much less familiar with the environment than an individual who has logged many more hours flying in mountainous regions. Although pilot/human factors are an important part of aviation, they were not the focus of this study.

This study also investigated fatal accidents based on general aviation activity data obtained from the Federal Aviation Agency (FAA). These data include estimated total hours flown per year and total active aircraft by state and are publicly available from the FAA for each year since 1999 [http://www.faa.gov/data_research/aviation_data_statistics/general_aviation/]. At the time of this study, data for the year 2011 were not available and were therefore estimated using the mean of 2009 through 2013 data.

To analyze the spatial aspects, geographic coordinate data associated with the accidents were mapped and analyzed using a 60-km grid. The gridded data were also smoothed using a low pass filter to reveal the broad patterns of these events and implement some form of objectivity. The smoothed data are meant to visually represent the general locations, and caution should be used because of edge effects and removal of fine detail. The gridded data are the preferred visualization method because they show the overall distribution as well as the variability associated with the data (Ashley, 2007; Ashley et al., 2015).

Accidents with missing coordinate data were geocoded using the latitude and longitude of the city listed by the NTSB as a proxy for the event. In some cases, the coordinate data listed by the NTSB were incorrect. For these, and for accidents with no associated coordinate data, the associated city was used as the representative event location because the NTSB lists the nearest city to the accident rather than the nearest airport. Lastly, state accident rates were calculated from 1999 through 2013 relative to the annual number of active aircraft and the annual number of hours flown to determine the most recent at-risk states for fatal weather-related general aviation accidents.

Results

Weather-related accidents

From 1982 to 2013, there were 58,687 general aviation accidents in the United States, of which 11,354 (19.3%) were fatal, producing a total of 20,660 fatalities. During this 32-year period, general aviation operations resulted in an average of 355 fatal accidents, or 645 fatalities per year, which represented 79% of all aviation-related fatalities (Figure 1). Weather was a cause or contributing factor in 25%, or 15,439, general aviation accidents over the period of record. These findings are slightly higher than those of the FAA (2010), who found that weather was associated with 20% of general aviation accidents from 2003 to 2007. There were 3,972 fatal weather-related accidents, or 8,052 fatalities, from 1982 through 2013,

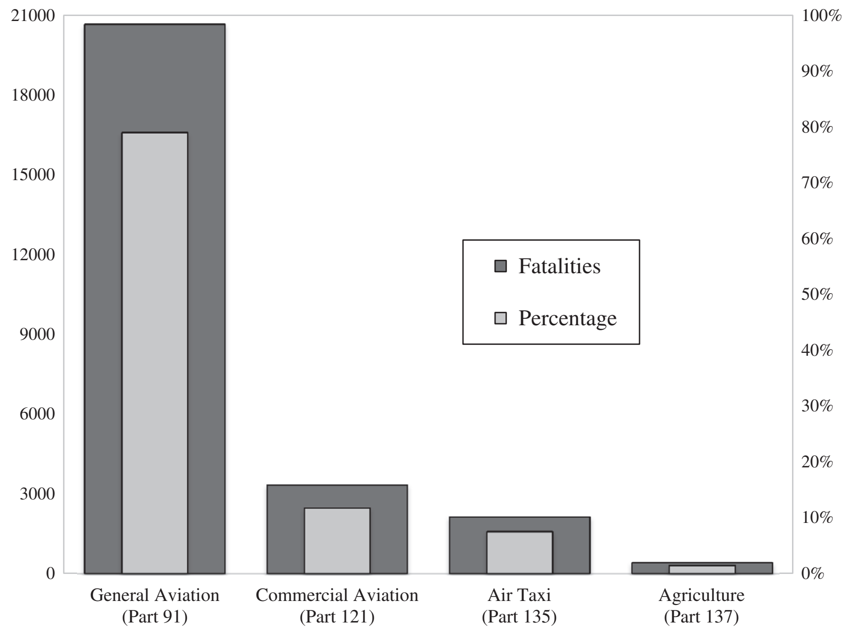

Figure 1. Aviation fatalities and percentage contribution by category for those fatal accidents that occurred in the United States from 1982 through 2013.

producing an annual average of 124 fatal accidents, or 252 fatalities, associated with weather during this time period. While weather was a cause or contributing factor in 25% of general aviation accidents during the study period, weather was attributed to 35%, or 3,972, of fatal general aviation accidents in the United States from 1982 through 2013.

During this period, general aviation accidents declined by 50%, and weather-related accidents declined by 70%. However, weather-related and fatal weather-related accidents have decreased at slower rates than those of all general aviation accidents. Weather-related accidents decreased at a rate 2.57 times slower than that of all general aviation accidents, and fatal weather-related accidents decreased at a rate 1.73 times slower than that of all fatal general aviation accidents. Despite these declining rates, weather-related general aviation accidents continue to result in almost 100 fatalities annually (Figure 2). Instrument meteorological conditions – conditions for which pilots must fly the airplane solely by referencing the instruments – were present in only 20% of general aviation accidents, yet these same conditions were associated with 60% of fatal weather-related accidents. These results show that visibility-related conditions continue to play a notable role in a number of fatal weather-related general aviation accidents each year.

Wind was the most commonly cited weather hazard, which was associated with 8,809 of the weather-related accidents from 1982 through 2013 (Table 2). However, only 7.8% of wind-related accidents during this period were fatal. Overall, wind was linked to more than 50(15)% of weather-related accidents (fatalities). This hazard category involved a variety of factors such as gusts, crosswinds, and tailwinds (Online Supplement Table A.1). Crosswinds were listed as a cause or contributing factor in 40% of non-fatal wind-related accidents, yet they were only associated with 13% of fatal wind-related accidents. Capobianco and Lee (2001) explained that wind-related accidents result in fewer fatalities because these

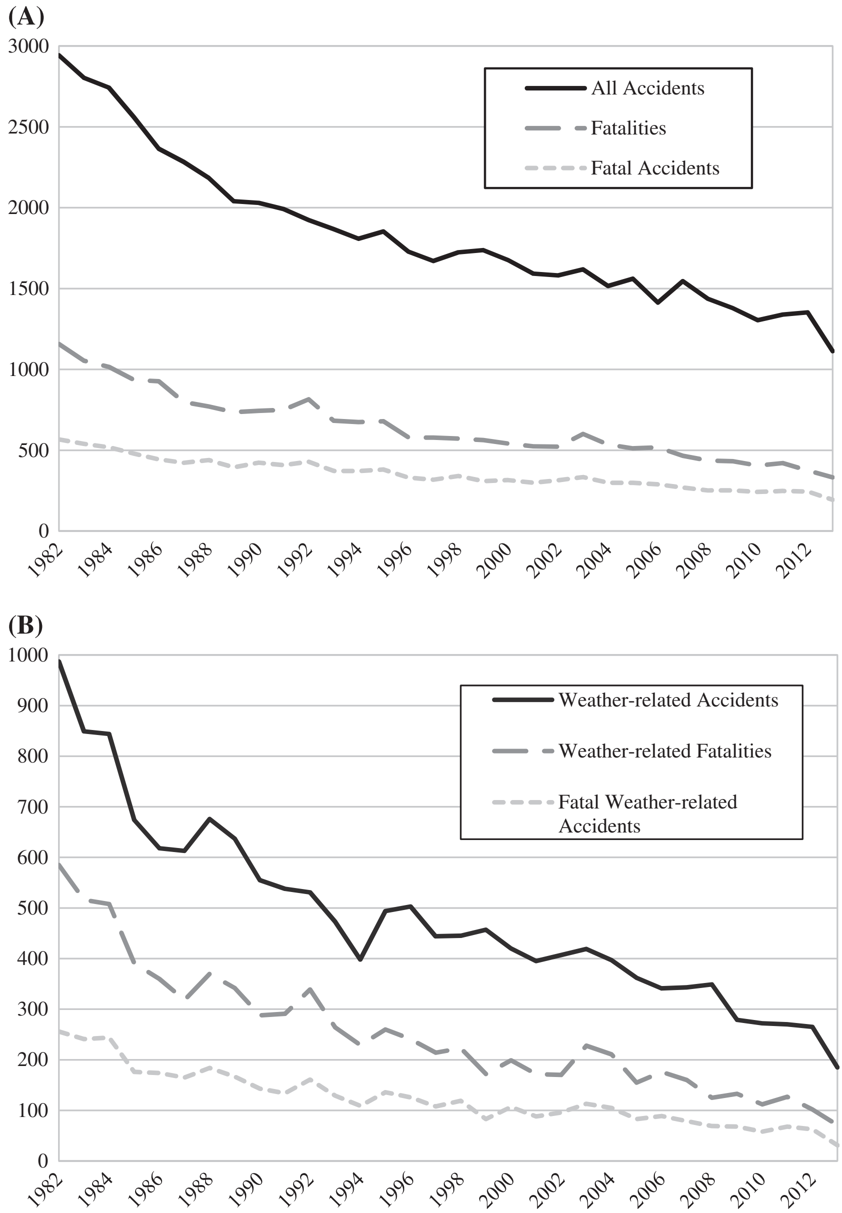

Figure 2. Total number of (A) all general aviation accidents, fatal accidents, and fatalities, and (B) weather-related general aviation accidents, fatal accidents, and fatalities that occurred in the United States from 1982 through 2013 by year.

accidents usually occur during takeoff and landing when the aircraft is flying slower and closer to the ground. Fatal wind-related accidents most commonly involved gusts (31%), tailwinds (26%), and high winds (22%) during the 32-year period (Online Supplement Table A.1). Microbursts, the least frequent among wind-related factors, were only involved in five fatal accidents.

Table 2. Weather hazard categories and total number of accidents, fatal accidents, and fatalities occurring within each from 1982 through 2013.

	Accident statistics			Fatal accident statistics				Fatality percentage		
Hazard category	Accidents	Percentage weather-related accidents	Percentage all accidents	Fatal accidents	Percentage fatal in category	Percentage Fatal weather-related accidents	Percentage all fatal accidents	Fatalities	Percentage weather-related fatalities	Percentage all fatalities
Ceiling, visibility, and precipitation	4,105	26.5	7.0	2,745	66.9	69.1	24.2	5,681	70.6	27.5
Temperature, humidity, and pressure	3,008	19.4	5.1	694	23.1	17.5	6.1	1,468	18.2	7.1
Wind	8,809	57.0	15.0	685	7.8	17.2	6.0	1,239	15.4	6.0
Turbulence	811	5.2	1.4	387	47.7	9.7	3.4	883	11.0	4.3
Convective weather	419	2.7	0.7	271	64.7	6.8	2.4	597	7.4	2.9

Notes: Since accidents can have multiple weather factors attributed to them, percentages will add to more than 100% and the accidents/fatal accidents/fatalities column totals will not add up to the totals in the caption. During this time period, there were a total of 58,687 (15,439) accidents (weather-related), 11,354 (3,971) fatal (weather-related) accidents, and 20,640 (8,049) fatalities (weather-related).

Temperature, humidity, and pressure-related factors were listed as causes or contributing factors for fewer than 20% of weather-related accidents and fatalities during the study period (Table 2). Though this category was associated with only 9 more fatal accidents than that of wind, 23.1% of temperature, humidity, and pressure-related accidents were fatal. This category includes a broad range of factors from high density altitude – lower atmospheric density at higher altitudes and/or warmer temperatures that cause a decrease in aircraft performance – to icing conditions – the formation of ice on the aircraft or within the engine's carburetor (Online Supplement Table A.2). High-density altitude and carburetor icing were the most commonly cited factors within this category and were attributed to 1,268 (42%) and 1,019 (34%) accidents, respectively. Carburetor icing, however, was a cause or contributing factor in only 79 fatal accidents while high-density altitude was associated with 297 fatal accidents. More than 50% of the accidents occurring within this category were attributed to structural icing – the formation of ice on the aircraft's wings, propeller, landing gear, etc. – yet this factor was associated with only 8% of all fatal weather-related accidents (Online Supplement Table A.2).

Turbulence and convective weather accounted for the fewest weather-related accidents and fatalities from 1982 through 2013; however, almost 48% of turbulence-related events and almost 65% of convective weather-related events were fatal (Table 2). Convective weather involves weather factors that are typically described as violent and destructive, such as hail and lightning (Online Supplement Table A.3). Turbulence-related hazards include factors such as convective turbulence and clear air turbulence, several of which were removed after 2008 (Online Supplement Table A.4). Turbulence was a cause or contributing factor in 811 accidents and 387 fatal accidents, of which "general" turbulence was associated with more than 50% of the fatalities affiliated with the turbulence hazard category. Thunderstorms were listed as a cause or contributing factor in almost 96% of fatal accidents within the convective weather category, yet they were attributed to less than 8% of all weather related fatalities (Table 2). Certain wind-related factors (e.g. microbursts) could have also occurred while thunderstorms were present; thus, their total contribution to weather-related accidents may be greater. There were no events associated with tornadoes or hurricanes during the study period. That fewer accidents and fatalities are attributed to convective weather suggests that pilots are more aware of the dangers that thunderstorms and turbulence pose on aviation safety and that pilots tend to avoid flying among these weather hazards (Capobianco & Lee, 2001).

The most deadly weather hazard category for general aviation is ceiling, visibility, and precipitation. While these hazards only account for 27% of all weather-related accidents, these hazards are associated with 71%, or 5,681, of the fatalities associated with weather in general aviation during the period of record (Table 2). This category includes many factors that are responsible for IMCs, such as low ceiling, low visibility, and fog (Online Supplement Table A.5). The majority of accidents occurring within this category were attributed to low ceilings, or low cloud layers, which were causes or contributing factors for 1,574, or 57%, of fatal accidents within this hazard category and more than 40% of all weather-related fatalities. Fog, the second-most fatal factor, was associated with 40% of all accidents, fatal accidents, and fatalities within the ceiling, visibility, or precipitation-related category. To legally fly in many of the weather conditions included in this category, a pilot must possess an instrument rating. An instrument rating allows pilots to fly in weather conditions not suitable to operating an aircraft using visual references. Not all accidents found within this

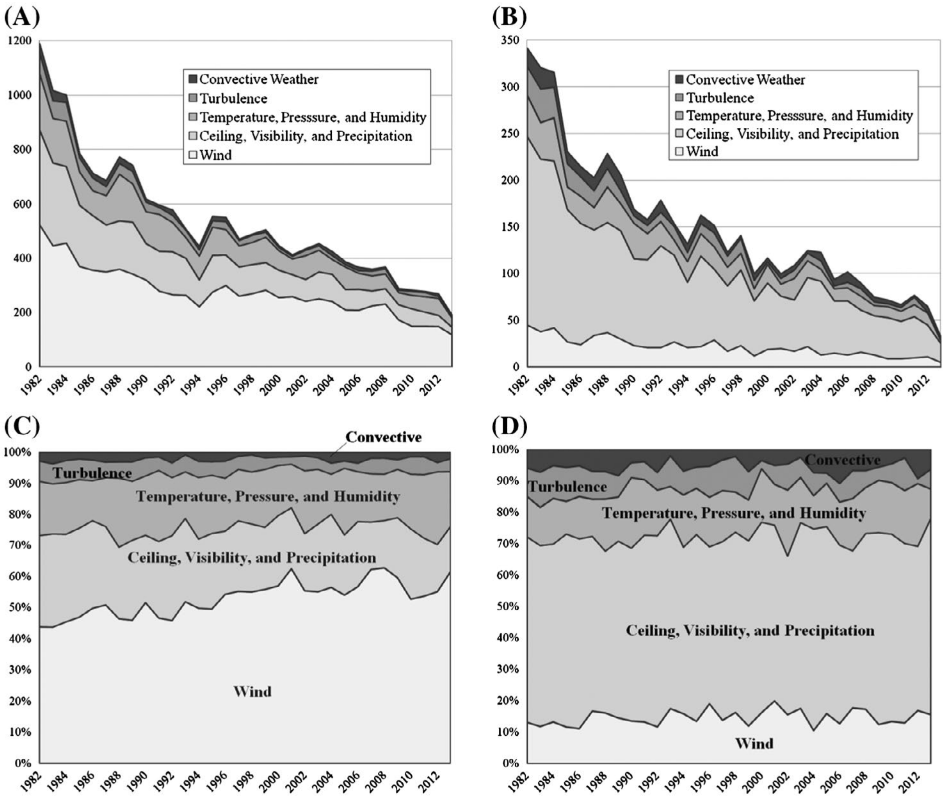

Figure 3. Absolute frequency contribution of the five weather hazard categories for (A) all weather-related accidents and (B) fatal weather-related accidents that occurred in the United States from 1982 through 2013 by year; (C) and (D) represent the percentage contribution of each weather hazard to all weather-related accidents and fatal weather-related accidents during the same period, respectively.

category, however, involve instrument-rated pilots. Examination of the narratives associated with the accidents occurring within this category revealed that these events often involve pilots flying by visual flight rules (VFR) who pushed the limits/capabilities of both the aircraft and themselves (e.g. so-called "scud running," where a pilot lowers their altitude to avoid flying in clouds, and "get-home-itis" where a pilot's desire to get home overrides logic and sound decision-making (FAA, 2008)). These findings are consistent with general aviation accidents examined by Capobianco and Lee (2001), who found that these events were often attributed to pilot error involving "VFR flight into IMC" and "flight into adverse weather." Low ceilings alone were associated with 1,574 fatal accidents that resulted in 3,259 fatalities, while fog was associated with 1,122 fatal accidents that resulted in 2,269 fatalities (Online Supplement Table A.5).

Spatiotemporal analysis

Given that weather-related accidents have decreased since the early 1980s, the percentage contribution of each weather hazard category was assessed to determine the yearly categorical trend of all weather-related accidents and fatal weather-related accidents (Figure 3).

The results show that the percentage of wind-related accidents increased from about 44% in 1982 to around 60% in 2013. In contrast, ceiling, visibility, and precipitation-related accidents decreased from about 30% to around 15% during the study period (Figure 3(C)). Since it was previously determined that ceiling, visibility, and precipitation-related factors are associated with the greatest number of fatalities, this 15% decrease is encouraging; however, the percentage contribution to fatal weather-related accidents reveals a slightly different story. There are no evident trends to the percentage contribution of fatal weather-related hazards (Figure 3(D)). Overall, ceiling, visibility, and precipitation have continued to make up about 60% of fatal weather-related accidents from 1982 through 2013. The percentage of turbulence-related accidents appears to have decreased slightly since the first half of the study period, but as a whole, these accidents made up a small percentage of fatal accidents anyway (Figure 3(D)). This suggests that the decrease in fatal weather-related accidents is not due to pilots having better technology or an improved understanding of weather and how to avoid hazardous situations as suggested by Humphreys (1930), but might actually be due to the overall decrease in general aviation activity or other unknown/unidentified variables.

Seasonally, general aviation accidents and fatal accidents occur most frequently during the warm season (Figure 4(A)). This might be because, according to the FAA Air Traffic Activity System, more general aviation activity occurs during the months of March through October [http://aspm.faa.gov/opsnet/systematizes/Main.asp]. Examining weather-related accidents revealed that they, too, occur predominantly during the warm season; however, fatal weather-related accidents have a different seasonal character, peaking during the early winter months with a secondary peak in the spring (Figure 4(B)). To further understand this seasonality, we examined weather-related accident trends based on the five NTSB weather hazard categories (Figure 5). Accidents associated with ceiling, visibility, and precipitation-related factors were the only accidents with increased frequency during the cool season, while accidents associated with other hazard categories peaked during the warm season. Since general aviation operations often involve recreational activities, the day-to-day aspects of general aviation accidents should reflect the times that these activities most often occur. Regardless of whether they are associated with weather, general aviation accidents and fatalities occur most frequently during weekends. Diurnally, most fatal weather-related accidents occur during daylight hours, with the lowest frequency between midnight and the 0600-h (Figure 6(A)). Fatal weather-related accidents tend to increase after sunrise, level off around midday, decrease slightly through the early afternoon, and peak during the 1800 to 1859-h. Since the amount of daylight varies by location and day of year, we postulate that fatal weather-related general aviation accidents peak during this timeframe for a variety of reasons: (1) this time-frame roughly corresponds to the peak of diurnal thunderstorm activity; (2) it occurs at the end of the work day when many general aviation pilots might be returning home, enjoying a short local flight, etc.; (3) many locations see a dramatic change in the amount of daylight at this time; and (4) during the cool season, this could be the first hour of complete darkness. Though daylight hours tend to account for the highest frequency of fatal weather-related accidents, a greater percentage of fatal weather-related accidents occur during the nighttime hours (Figure 6(B)). As discovered previously, weather-related factors are attributed to 35% of fatal general aviation accidents, yet more than 50% of fatal accidents occurring during the early morning hours are weather-related.

Fatal weather-related general aviation accidents were recorded in all 50 states during the study period and, as suggested by Ungs (1995) and Grabowski et al. (2002), most commonly

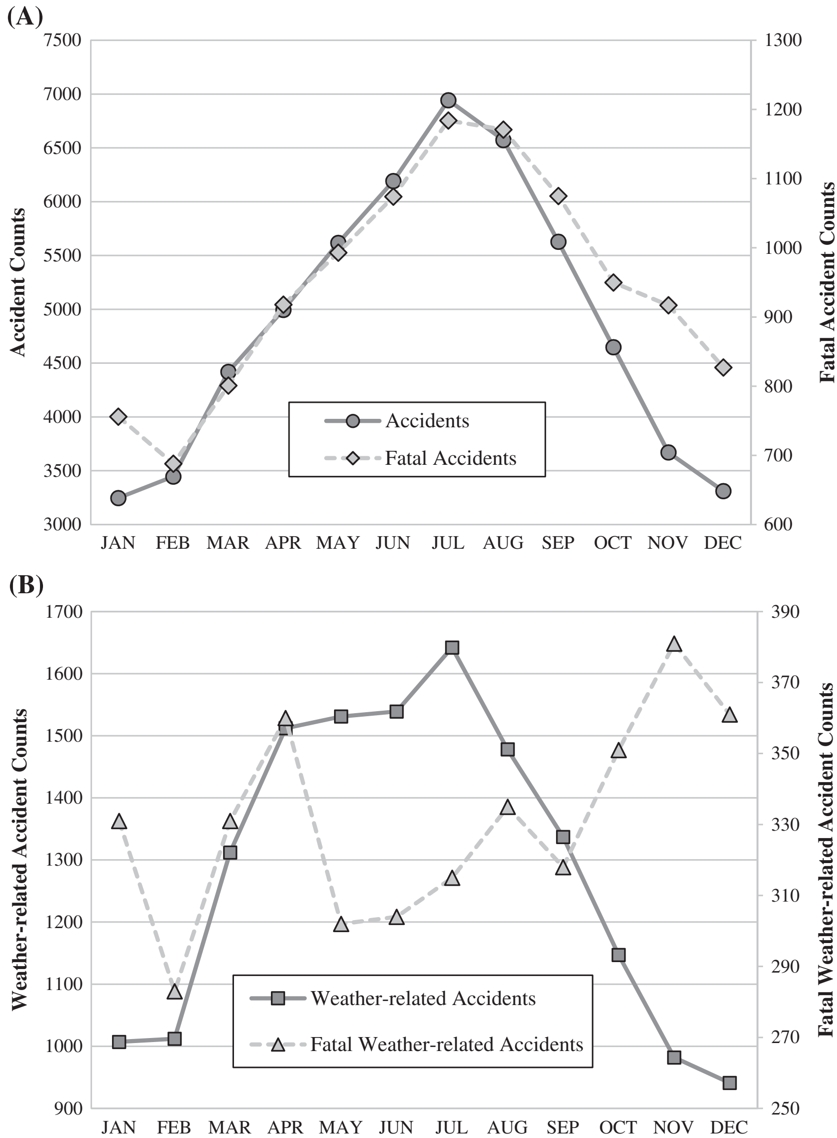

Figure 4. Total number of (A) all general aviation accidents and fatal general aviation accidents, and (B) all weather-related accidents and fatal weather-related accidents that occurred in the United States from 1982 through 2013 by month.

occurred in states containing large population centers (e.g. Los Angeles, CA, Seattle, WA, Denver, CO, Dallas, TX, Washington DC, Boston, MA), located along coastal and/or within mountainous regions (Figure 7). States with the largest number of weather-related fatalities from 1982 through 2013 were California (1,254), Texas (480), Colorado (373), Florida (317), and Alaska (269). Normalizing the data by area reveals that many of the northeastern states, Florida, and California experience the most weather-related general aviation fatalities, while North Dakota, South Dakota, Montana, and Alaska contribute the fewest weather-related fatalities (Figure 7).

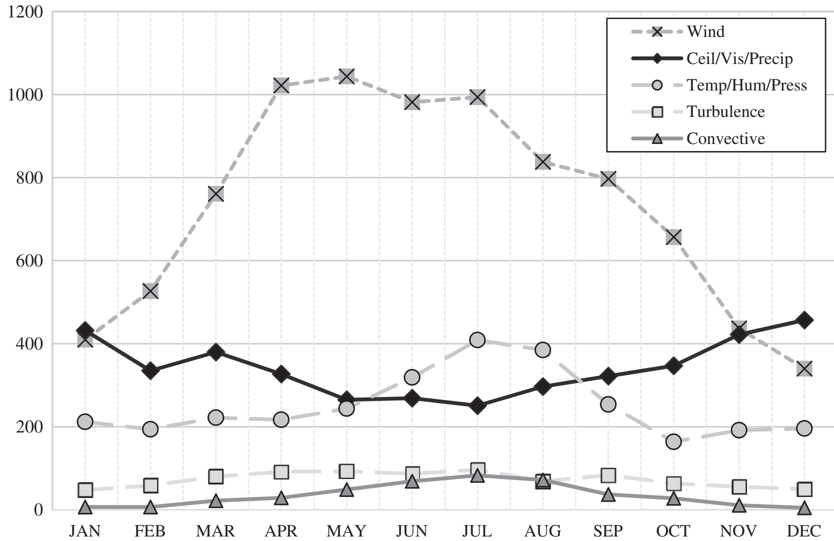

Figure 5. Weather-related general aviation accidents for each weather hazard category that occurred within the United States from 1982 through 2013 by month.

Spatial analysis (Figure 8(A)) reveals that the most pronounced locations for all fatal general aviation accidents are found among major urban areas, which include central and southern California, the Pacific Northwest, the Colorado Rockies, Florida, the Appalachians, the Northeast coast, and the Great Lakes region. The fewest fatal accidents are located in eastern Montana and the Dakotas (Figure 8(B)). This is likely due to the combination of harsh winters that reduce the number of flights, as well as the relatively low population density in this region. Another area of interest also includes Nevada, presumably because of the large amount of restricted airspace for all non-military operations within this area (e.g. "area 51"). There are very few spatial differences between fatal weather-related events and all fatal events (Figures 8(C) and (D)). To further understand the spatial aspects of fatal weather-related accidents, we studied each hazard category to determine if regional differences/similarities exist among them.

Since visibility, ceiling, and precipitation-related accidents are associated with the largest number of fatalities within the United States, it should be expected that these weather hazards would follow the same overall spatial pattern for all fatal weather-related accidents (Figure 9(A) and (B)). Fog and low clouds are the primary factors within this category and, therefore, fatal ceiling, visibility, and precipitation-related accidents should occur in similar locations to those that most frequently experience vision-related weather factors, such as fog and low visibility. In a recent study involving automobile accidents due to fog and obscured vision, Ashley et al. (2015) noted that there is little research regarding the spatiotemporal aspects of fog in the United States. However, they did discover that Peace (1969) and Hardwick (1973) found the most fog-prone locations to include California and the Pacific Northwest, the Gulf Coast, the Appalachians, the Great Lakes region, and New England. The results from this study show that the primary locations for fatal visibility, ceiling, and precipitation-related accidents are also found in frequent fog locations, specifically along the West Coast, in the Appalachians, and in the Northeast (Figure 9(B)). Several of

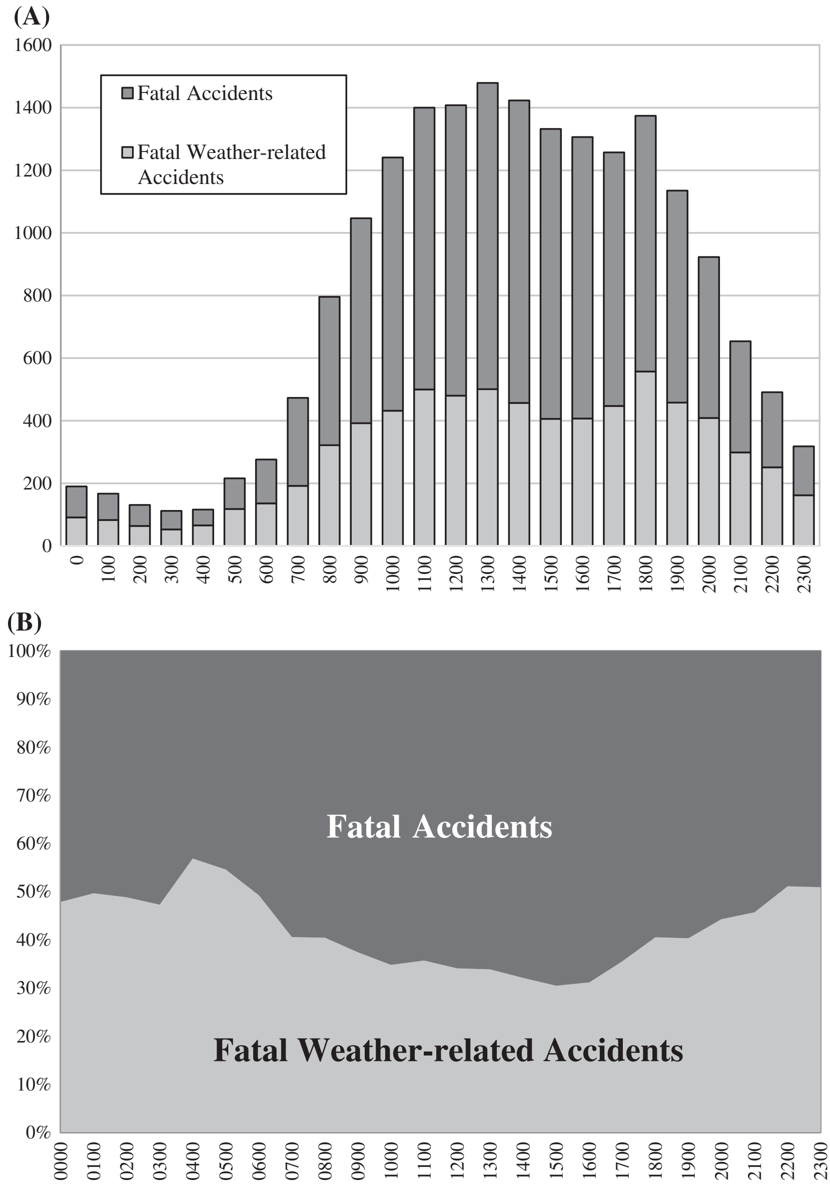

Figure 6. (A) All fatal general aviation accidents and all fatal weather-related general aviation accidents that occurred in the United States from 1982 through 2013 by local time of day; (B) represents the percentage contribution for each of the classifications occurring in (A).

Notes: Accidents occurred within the specified hour. For example, an accident that occurred from 1100 to 1159 local time would be counted in the 1100-h category.

these fog-prone locations are also located in mountainous regions, where a disoriented pilot would be at a much higher risk of crashing into the rising terrain during low visibility situations, sometimes unknowingly. For example, Black and Mote (2015) noted that more than a third of aviation accidents associated with winter-precipitation involved controlled flight into terrain.

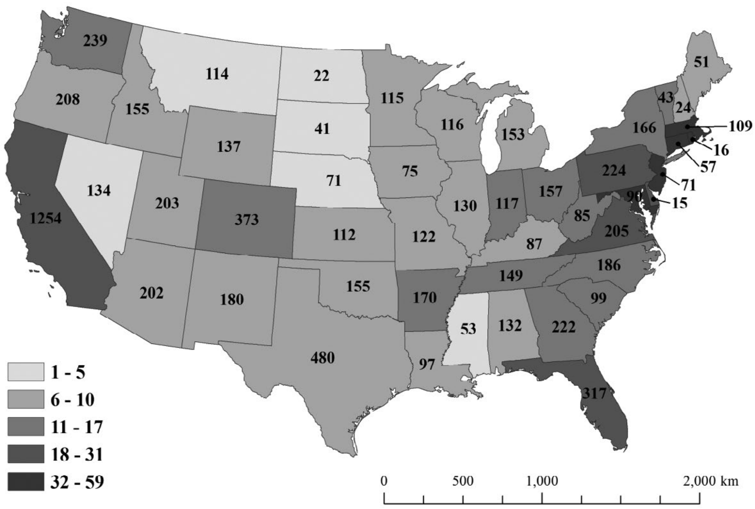

Figure 7. Weather-related general aviation fatalities normalized by area (10,000 km^2) for each state.

Notes: The number in each state represents the total number of weather-related general aviation fatalities from 1982 through 2013, while the color represents the number of fatalities normalized by area. Alaska and Hawaii (not shown) experienced 269 (1.56) and 47 (16.6) weather-related fatalities (fatalities normalized by area), respectively.

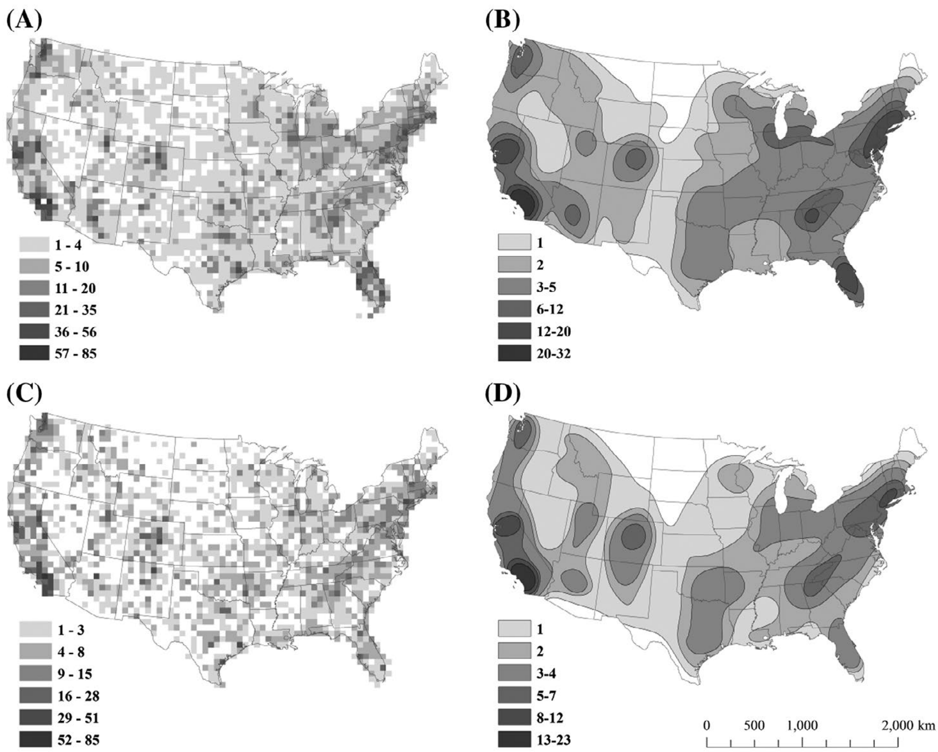

Figure 8. The frequency of (A) all fatal general aviation accidents, (B) smoothed fatal general aviation accidents, (C) fatal weather-related general aviation accidents, and (D) smoothed fatal weather-related general aviation accidents from 1982 through 2013; (A) and (C) are frequency counts on a 60 × 60 km grid and (B) and (D) are the same data smoothed using a low pass filter.

Note: Scales are relative to each category.

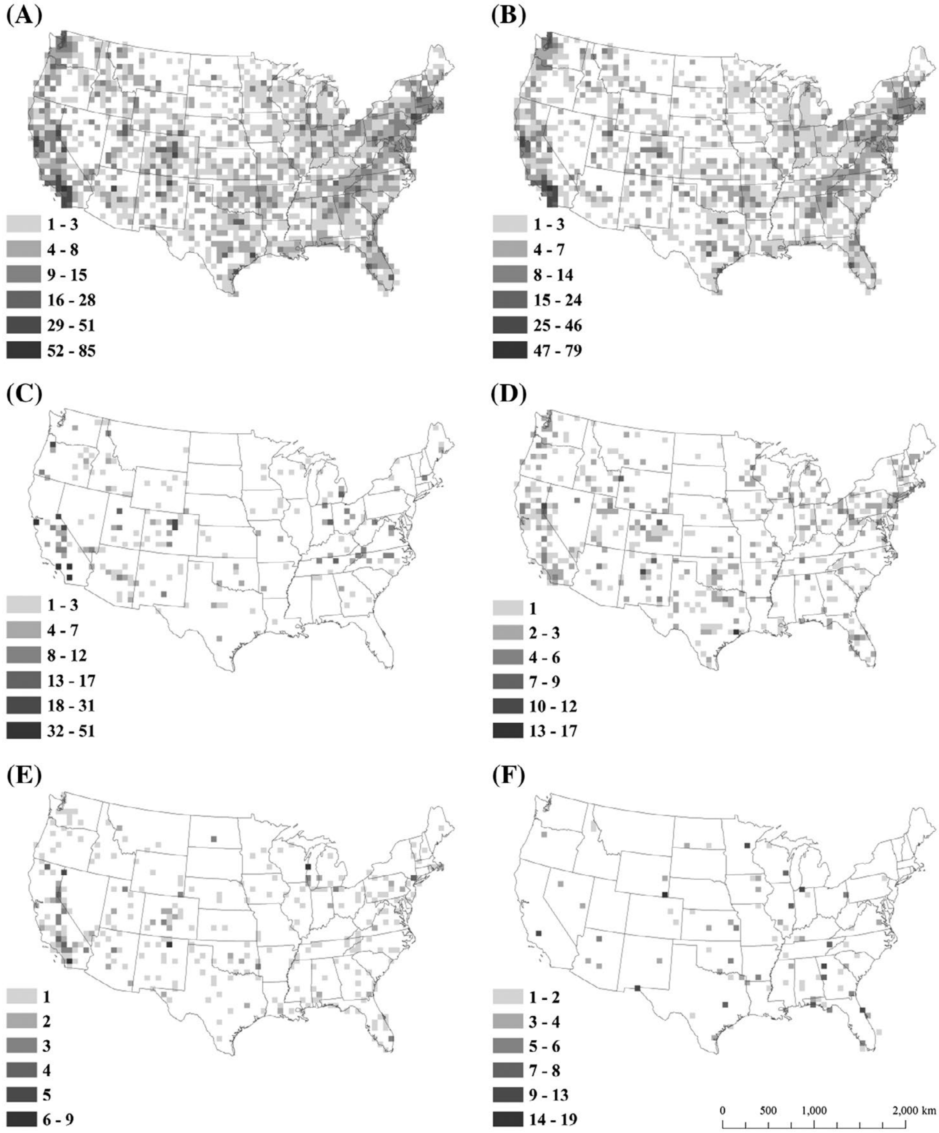

Figure 9. Conterminous 60-km grid showing the spatial distribution of (A) all fatal weather-related general aviation accidents, (B) fatal ceiling, visibility, and precipitation-related accidents, (C) fatal temperature, humidity, and pressure-related accidents, (D) fatal wind-related accidents, (E) fatal turbulence-related accidents, and (F) fatal convective weather-related accidents from 1982 through 2013.
Note: Scales are relative to each hazard.

Though fatal accidents associated with ceiling, visibility, and precipitation-related weather factors are found in locations that frequently experience fog and low visibility conditions, they are not the only weather hazards attributed to accidents occurring within these locations. This is likely due to the multifactorial aspect of weather-related accidents. There are, however, some regional differences and similarities among individual hazard categories. Fatal weather-related accidents occurring along the Northeast Coast, for example, involve

Table 3. Fatal weather-related general aviation accidents and fatalities from 1999 through 2013, normalized by state area, annual active aircraft, and annual hours flown. Bolded values represent the 10 highest ranked states in each category.

			Normalized by state area (km^2)			Normalized by annual active aircraft			Normalized by annual hours flown		
State	Fatal weather-related accidents	Weather-related fatalities	Area (km^2)	Fatal accidents/area [$(km^2)^{-1}$(×10,000)]	Rank	Average active aircraft	Fatal accidents/active aircraft [×1000]	Rank	Annual hours flown	Fatal accidents/hour [×100,000]	Rank
WY	24	49	253,335	0.95	38	1,136	21.13	**1**	127,648	18.80	**1**
WV	14	29	62,756	2.23	14	1,050	13.34	**4**	89,480	15.65	**2**
UT	38	86	219,882	1.73	22	1,946	19.53	**2**	315,120	12.06	**3**
CO	63	116	269,601	2.34	12	5,476	11.50	**5**	668,698	9.42	**4**
VT	5	12	24,906	2.01	18	586	8.54	**10**	53,395	9.36	**5**
KY	17	43	104,656	1.62	23	1,920	8.85	**8**	191,766	8.86	**6**
NM	26	43	314,917	0.83	40	2,932	8.87	**9**	300,603	8.65	**7**
RI	3	7	4,001	7.50	**1**	332	9.04	**7**	37,224	8.06	**8**
ID	21	44	216,443	0.97	37	2,612	8.04	11	280,979	7.47	**9**
MT	18	34	380,831	0.47	46	2,366	7.61	12	251,601	7.15	**10**
AR	28	55	137,732	2.03	17	2,782	10.07	**6**	393,852	7.11	11
SC	16	35	82,933	1.93	19	2,518	6.35	18	268,324	5.96	12
CA	166	314	423,967	3.92	**5**	23,518	7.06	13	2,817,300	5.89	13
MO	24	54	180,540	1.33	28	3,912	6.13	20	413,761	5.80	14
OR	35	71	254,799	1.37	26	5,011	6.99	14	631,053	5.55	15
NC	38	70	139,391	2.73	**9**	5,738	6.62	16	706,331	5.38	16
GA	36	63	153,910	2.34	11	5,517	6.53	17	673,280	5.35	17
AK	37	66	1723,337	0.21	49	5,932	6.24	19	711,700	5.20	18
IA	16	30	145,746	1.10	34	2,929	5.46	23	308,975	5.18	19
MN	25	47	225,163	1.11	32	5,011	4.99	28	505,030	4.95	20
AL	21	40	135,767	1.55	24	3,675	5.71	21	446,339	4.70	21
HI	7	15	28,313	2.47	**10**	472	14.84	**3**	148,958	4.70	22
MA	14	29	27,336	5.12	**3**	2,613	5.36	24	304,484	4.60	23
NV	18	34	286,380	0.63	44	2,595	6.94	15	392,034	4.59	24
IN	18	38	94,326	1.91	20	3,945	4.56	33	396,145	4.54	25
ME	5	7	91,633	0.55	45	1,220	4.10	37	113,760	4.40	26
VA	24	54	110,787	2.17	16	4,554	5.27	26	546,209	4.39	27
WI	20	36	169,635	1.18	29	4,957	4.03	38	461,154	4.34	28
SD	6	7	199,729	0.30	48	1,279	4.69	31	142,423	4.21	29
AZ	33	67	295,234	1.12	31	6,253	5.28	25	821,489	4.02	30
TN	19	39	109,153	1.74	21	3,946	4.82	30	494,892	3.84	31

(*Continued*)

Table 3. (*Continued*)

State	Fatal weather-related accidents	Weather-related fatalities	Normalized by state area (km^2): Area (km^2)	Fatal accidents/area [$(km^2)^{-1}$(×10,000)]	Rank	Normalized by annual active aircraft: Average active aircraft	Fatal accidents/active aircraft [×1000]	Rank	Normalized by annual hours flown: Annual hours flown	Fatal accidents/hour [×100,000]	Rank
PA	26	49	119,280	2.18	15	5,972	4.35	34	704,025	3.69	32
WA	27	52	184,661	1.46	25	6,910	3.91	41	734,498	3.68	33
KS	16	31	213,100	0.75	43	3,475	4.60	32	439,336	3.64	34
MD + DC	11	21	32,308	3.40	**6**	2,845	3.87	42	317,275	3.47	35
NE	8	16	200,330	0.40	47	2,038	3.93	40	232,327	3.44	36
TX	76	138	695,662	1.09	35	17,962	4.23	36	2,280,314	3.33	37
CT	10	16	14,357	6.97	**2**	1,807	5.53	22	301,826	3.31	38
OH	26	49	116,098	2.24	13	6,496	4.00	39	794,541	3.27	39
MI	20	39	250,487	0.80	41	6,471	3.09	45	633,382	3.16	40
MS	10	21	125,438	0.80	42	2,059	4.86	29	324,703	3.08	41
NY	19	28	141,297	1.34	27	5,813	3.27	43	635,211	2.99	42
IL	17	34	149,995	1.13	30	6,224	2.73	46	668,811	2.54	43
OK	18	34	181,037	0.99	36	4,169	4.32	35	732,370	2.46	44
FL	49	93	170,312	2.88	**8**	15,142	3.24	44	2,080,616	2.36	45
LA	15	27	135,659	1.11	33	2,984	5.03	27	720,623	2.08	46
NJ	9	20	22,591	3.98	**4**	3,404	2.64	47	445,291	2.02	47
ND	3	3	183,108	0.16	50	1,285	2.33	48	230,200	1.30	48
NH	2	2	24,214	0.83	39	1,413	1.42	49	157,559	1.27	49
DE	2	3	6,446	3.10	**7**	2,046	0.98	50	305,666	0.65	50
US	1,199	2,310	9,833,519	1.22	–	217,247	5.52	–	26,752,581	4.48	–

Note: States are listed by number of fatal accidents per 100,000 h flown.

accidents from all categories, yet they are primarily due in part to three hazard categories: (1) ceiling, visibility, and precipitation, (2) wind, and (3) turbulence (Figure 9(B), (D), and (F)). In contrast to all fatal weather-related accidents, convective weather-related accidents are the only accidents that occur most often in the central and southeastern portions of the country (Figure 9(F)). This spatial difference can be explained because the central and southeastern regions of the country are the most common locations for thunderstorms, which are the major cause or contributing factor within this category. Fatal temperature, humidity, and pressure-related accidents, fatal wind-related accidents, and fatal turbulence-related accidents are all more common in the western portion of the country or, more specifically, in central California and the Colorado Rockies (Figure 9(C)). These locations are prone to high-density altitude conditions, especially in elevated regions. Since high-density altitude was frequently cited in fatal weather-related accidents, it is expected that fatal temperature, humidity, and pressure-related accidents dominate the western portion of the country. Overall, California is a particularly interesting area of concern because it is the only region in the United States associated with the highest frequency of fatal weather-related accidents within four of the five weather hazard categories.

Fatal weather-related accidents from 1999 through 2013

To understand better the trends and current aspects of accidents in the contemporary part of the record, the most recent 15 years were examined using general aviation activity data. Earlier years were not analyzed using these data because annual general aviation activity by state was not available prior to 1999. During this period, the United States experienced an average of 4.48 fatal weather-related accidents per 100,000 flight hours, with an annual mean of 80 fatal weather-related accidents, or 154 fatalities. The top-ranked states for fatal weather-related accidents per 100,000 flight hours include Wyoming (18.8), West Virginia (15.65), Utah (12.06), Colorado (9.42), and Vermont (9.36). Fatal weather-related accident rates based on flight hours suggest that mountainous regions continue to be the most dangerous locations for general aviation operations (Table 3). State-ranked results based on the number of accidents per 100,000 flight hours are similar to that of states with the highest fatal crash rates determined by Kearney and Li (2000). Using the same criteria (accidents per 100,000 flight hours), they found that Wyoming had the highest fatal crash rate during the 3-year period of their study, from 1992–1994. Similarly, Black and Mote (2015) found that winter-precipitation-related aviation crashes occurred primarily in the mountainous regions of the western United States. Their results, along with those from this study, suggest that mitigation efforts should continue to be directed towards educating pilots on the risks of operating within mountainous locations, especially when weather could be a concern.

Conclusion

General aviation is a complex, socio-technological system, and accidents that occur with this form of transportation are often multifactorial. We focused on weather as one of many possible factors that can influence, and possibly cause, general aviation accidents. Findings revealed that hazardous weather conditions were associated with 35% of general aviation fatalities, resulting in 124 fatal accidents and 252 fatalities on average annually from 1982 through 2013. Though general aviation accidents have declined by 50% during this time period, general aviation operations continue to make up almost 80% of the United States aviation-related fatalities. Knowing and understanding the spatiotemporal aspects of fatal weather-related accidents provides important information for pilots to use during flight planning and in-flight decision-making. While past research has examined accidents due to specific weather hazards or spatial components of specific factors, there has been no literature on the spatial aspects of all weather-related general aviation accidents over an extended period. This study examined the spatiotemporal aspects of fatal weather-related general aviation accidents over a 32-year period, producing a "climatology" that can be used as a foundation for future research.

Results reveal that fatal weather-related general aviation accidents are most prevalent among major populated areas along the West Coast, in the Rocky Mountains and Appalachians, and in the Northeast. These locations coincide with a combination of frequent visibility-related weather factors and variable terrain. Weather-related issues in mountainous regions place pilots in conditions in which they have little time to react before colliding with the terrain should there be an equipment or engine failure. The states with the most fatalities normalized by general aviation activity since 1999 were commonly in mountainous regions and include Wyoming, West Virginia, Utah, Colorado, and Vermont. Seasonally, most fatalities occurred during the cool season from October through April, when visibility-related weather conditions are more prevalent due to conditions such as low ceilings, winter precipitation, or fog.

Wind-related factors were most common during the warm season and were associated with 57% of all weather-related accidents, yet ceiling, visibility, and precipitation-related weather hazards, which were responsible for the increase in fatalities during the cool season, were associated with 71% of weather-related fatalities. Further, 15 of the 17 weather-related accidents producing the highest number of fatalities from 1982 through 2013 were associated with ceiling, visibility, and precipitation-related hazards. Although the category "below VFR minima" was only introduced in 2008, more than 90% of the 52 accidents in that category ended fatally. These events alone should be closely monitored and examined more closely in the future. The top ten weather factors linked to the highest number of weather-related fatalities during the study period were low ceiling (40%), fog (28%), clouds (20%), obscuration (10%), structural icing (9%), high-density altitude (8%), thunderstorms (8%), turbulence (6%), gusts (4%), and tailwinds (4%). Visibility and its impact on aviation safety have appeared consistently in the literature since the 1930s. Thus, these results continue to support the need to focus on ways to minimize the number of fatalities associated with restricted visibility.

This study presented a synoptic view of fatal weather-related accidents in the United States, providing a foundation for future work regarding weather-related general aviation accidents. Regional studies, especially in the western and northeastern regions, are needed to determine if any local differences exist. A better understanding among specific weather factors is also required. In particular, an analysis of the factors falling within the ceiling, visibility, and precipitation-related category – such as fog and low ceilings – could be beneficial for supporting mitigation efforts regarding fatal weather-related accidents. Continued efforts that assess the relationship between weather and other general aviation factors – for example the use of in-cockpit radar via satellite, trip length, aircraft type, and how general aviation pilots interact with air traffic controllers in stressful weather conditions – are also important topics for future endeavors. In conclusion, this study showed the most hazardous locations and times for general aviation activity based on weather-related accidents. Educating current and new pilots about these aspects could not only benefit those operating aircraft within these locations, but this information is also beneficial for academic researchers, the FAA, the NTSB, as well as other aviation organizations concerned with continuing to make aviation transportation as safe as possible.

Disclosure statement

No potential conflict of interest was reported by the authors.

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