Analysis of Weather-Related Helicopter Accidents and Incidents in the United States

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Helicopters typically operate at lower altitudes than fixed-wing aircraft and can take-off and land away from airports. Thus, helicopter pilots have decreased access to weather information due to connectivity issues or sparsity of weather coverage in those areas and at those altitudes. Moreover, regulations allow most rotorcraft to operate in marginal weather conditions. Therefore, weather is a challenge to rotorcraft operations. In this study, rotorcraft events in the United States between 2008 and 2018 in which weather was determined to be a factor are analyzed using the National Transportation Safety Board aviation database. Results show that weather was a factor in 28% of rotorcraft fatal accidents. Wind was involved in most incidents but more rarely involved in fatalities. Bad visibility conditions due to a combination of low illumination and clouds were responsible for most fatal weather-related accidents. Personal flights had the highest accident and incident rates. Finally, the Helicopter Air Ambulance industry had the largest number of incidents and accidents related to visibility conditions out of all other industries. The authors recommend improving awareness of the conditions in which weather events occur and improving training to maintain control of the aircraft in windy conditions or during inadvertent instrument meteorological conditions.

1 Introduction

The Federal Aviation Administration analysis of helicopter accident data shows that between 2009 and 2018 the helicopter fatal accident rate has remained around 0.67 per 100,000 flight hours and has been trending upward since 2015 [1]. The United States Helicopter Safety Team (USHST) goal is to reduce the rate of helicopter fatal accidents to 0.55 per 100,000 flight hours by 2025 [2]. To improve safety, it is necessary to better understand the causes and factors of helicopter accidents and incidents.

Most helicopter operations fall under part 91 or part 135 of the FAR AIM regulations, which correspond respectively to general aviation (GA) and commuter and on-demand operations. Previous studies have shown that weather is a significant factor in a number of GA accidents. In 2001, Capobianco found that 20% of GA accidents between 1995 and 1998 mentioned a weather condition, and that of those 27% were fatal. This study also showed that although most weather accidents involved non-IFR rated pilots, 56% of fatal weather accidents involved an IFR rated pilot [3]. More recently, Fultz and Ashley found that weather was a factor in 35% of GA fatal accidents between 1982 and 2013. In this same study, they found that, although wind was the most commonly mentioned weather hazard in GA accidents, only 7.8% of those were fatal. Ceiling, visibility and precipitation were found to be the deadliest weather hazards, accounting for 71% of fatal accidents [4].

An issue with studies that consider all GA and part 135 operations accidents is that fixed-wing aircraft make up the bulk of such operations. Indeed, looking at the FAA GA and part 135 survey for 2018 shows that fixed wing accounted for 7.2 times more flight hours than rotorcraft [5]. It is important to consider rotorcraft operations separately because they are significantly different than fixed-wing operations. Rotorcraft routinely operate at altitudes lower than 2000 feet AGL and fly at slower speed, they can take-off and land away from airfields, most rotorcraft operations can be conducted under VFR as long as the aircraft remains clear of clouds when fixed-wing have more stringent weather minimums, a large portion of the helicopter fleet is not certified for IFR operations, rotorcraft face unique aerodynamics challenges

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such as loss of tail rotor effectiveness (LTE) or vortex ring state (VRS), and finally whereas personal flights accounted for 30% of fixed wing flight hours in 2018 they only accounted for 3% of rotorcraft flight hours [5] indicating a very different pilot population. This is why a dedicated study of rotorcraft operations is required in order to understand their specific challenges and expand on existing studies that focused more on fixed-wings or considered all GA and part 135 accidents without making distinctions.

There have been some studies specifically on rotorcraft safety, which although they do not focus on weather specifically, have underlined the importance of weather in helicopter accidents. Risks associated with night flying and the high rate of IIMC accidents were underlined in a technical paper by Matthews et al. [6]. Other studies have found similar results but have focused on a specific industry and/or area. In 2014, Nascimento et al. introduced a framework to study helicopter accidents and applied it in the oil and gas industry worldwide. They found that the Gulf of Mexico had a significantly higher rate of accidents compared to other areas, and that night operations were significantly riskier [7]. In 2014, Butler studied fatal helicopter air ambulance (HAA) accidents and found that 47% of them involved weather, as a result he recommended that HAA weather minimums be raised for unaided night operations [8]. It is of interest to see how these results generalize to other industries and to do a more in depth analysis of weather accidents in order to identify what could be done to improve safety for all helicopter operations.

In the 2001 study by Capobianco, the authors concluded that systems to avoid adverse weather events should be developed that allow pilots to get continuously updated weather information and forecast in the cockpit. Since then there has been a significant injection of weather technology in the cockpit. Mobile devices are now very present in GA, and through the prevalence of satellite subscriptions and Automatic Dependent Surveillance - Broadcast (ADS-B) systems, pilots are able to access radar data and airport weather reports while in the air. Due to these recent technology changes, the scope of this study will focus on events from 2008 to 2018. This decade will more accurately represent current challenges faced by rotorcraft pilots.

In this study, an in-depth analysis of helicopter accidents and incidents in the United States is performed. First, the data and methods used in the study are introduced. Then, in the results section, helicopter events are analyzed and the following questions are answered:

- What types of weather cause helicopter events and what type of helicopter events do they cause?
- Where do weather related events occur in the United States?
- Are weather-related events more common in areas that are not well-covered by weather sources?
- When do weather-related events occur?
- Are certain types of pilots or industry more susceptible to be involved in a weather event?
- Do certain types of rotorcraft have higher weather-related accident rates than other?

Finally, the discussion section summarizes results and draws conclusion to improve helicopter safety with respect to weather.

2 Data and Methods

The analyses presented in this study relied on several data sources: the NTSB aviation accident database, the FAA GA and part 135 aviation survey, and government open data for the location of airports, weather stations and radar stations. These different sources and how they were processed are presented in this section. A special emphasis is placed on the NTSB aviation accident database as it is the primary data source used in all analyses. Technical terms used by the NTSB to characterize accidents and incidents are defined here. The words “incidents” and “accidents” are specific terms that carry information about the severity of the event (injury, fatality, mechanical damage), when talking about incidents or accidents without indication to their severity the term event is used subsequently in this paper.

2.1 NTSB database

The NTSB maintains a database containing detailed information pertaining to each of their investigations since 1983. A copy of this database is publicly available as a Microsoft Access database and is updated once a month at [9]. The information in the database for a specific event can be accessed by making a request through the web interface and downloading the auto-generated reports as PDFs or HTML web-pages. When a specific event is referenced in this paper using its ten character event identification number, the reader is directed to use this interface to query the relevant NTSB reports and obtain more details if desired [10]. The results presented here are based on data downloaded in May 2020.

The NTSB database has been commonly used in many previous aviation safety studies [3, 4, 8, 11–15]. The data and documentation are of very good quality but there can be some small inconsistencies in the database. For instance, accident *ERA12MA122* in 2011 in Florida does not mention weather in the list of its findings even though the cause of the accident was identified to be UIMC due to mist, fog and low cloud ceilings at the accident site. A few errors in events location have also been identified. For instance in *ERA11FA272* the longitude is positive instead of negative and in *ERA11CA082* the latitude and longitude were reversed. These small errors should not impact significantly the analysis.

Data in the database is structured in tables. The main table is the *Events* table. It contains information related to the incident or accident, such as location, date, weather or severity, that were used in many of the subsequent analyses. The tables are linked by one-to-many relationships, i.e. each event can be linked to one or several aircraft, which are themselves linked to multiple findings, flight events and flight crew. Care was taken in the analysis to not count events multiple times. The *aircraft* table was used to filter events based on the type of aircraft (helicopter, fixed-wing) and the number of engines. Only events that involved at least one aircraft of type helicopter were considered to be helicopter events.

Events' causes or factors are listed in the *Findings* table, they are added to the database once the NTSB investigation into the event is completed. Events that did not have any associated findings were filtered out for this study. Between 2008 and 2018, there are 1576 helicopter events in the database. 126 of those, or 8%, don't have any associated findings and are excluded from the analysis. The NTSB uses codes to classify findings into different categories. Categories are organized in a 4-tier structure. Each tier provides an additional level of detail on the finding. For instance, all findings starting by '03' are external issues, those starting by '0303' are weather findings, weather being a subcategory of external issues. Codes starting by '030340' are wind findings, and finally '03034045' is a wind gust finding. In the following analyses, the findings were classified using tier 2, tier 3 or tier 4 categories depending on the level of detail required. A modifier code which depends on the tier 1 category can also be added to the finding to provide some additional details. The list of all the codes and their meanings is available in the data dictionary table in the database, there are 4 tier 1 categories, 20 tier 2 categories (a list is provided in Appendix II), 129 tier 3 categories, and 1020 tier 4 categories. In the study presented here, all events that have at least one weather finding (i.e. a finding which code starts with '0303'), were categorized as weather-related events. There are six categories of tier 3 weather findings: . (1) wind, (2) ceiling, visibility and precipitations, (3) light conditions, (4) temperature, humidity and pressure, (5) turbulence, and (6) convective weather. To study differences between findings, we define a finding's fatality ratio as the number of fatal accidents in which the finding was mentioned over the total number of events that mentioned the finding.

In the database, the investigation is broken down into a sequence of specific flight events which describe the timeline of the overall event. Each flight event is composed of a phase of flight and an aviation occurrence, for instance *Enroute - Loss of control in flight*. Similarly, to the findings these categories are coded and the code definition is available in the database data dictionary. The categories used by the NTSB are based on the International Civil Aviation Organization (ICAO) taxonomy. One flight event per accident/incident can be marked in the database as the defining event. This defining event is the one that best represents the accident/incident and is used in this study to characterize the accident/incident type. Between 2008 and 2018, 254 total weather-related helicopter events were identified, two of which do not have a defining event.

To determine the flight purpose, several columns from the aircraft table were used. The *site_seeing* column was used to identify air tour flights, while the *air_medical* column was used to identify Helicopter Air Ambulance (HAA) flights. For flights that did not belong in either of those categories, the *type_fly* column was used. If that column was unspecified and the flight was conducted under FAR Part 135 and was unscheduled (*far_part* and *oper_sched*) then it was categorized as an Air Taxi flight.

To gather information regarding the experience level of the Pilot-In-Command (PIC), the PIC's total number of flight hours in all makes and models of helicopter is in the *Flight_Crew* table. It may be noted that for instructional flights, this can either be the student pilot or the flight instructor.

2.2 FAA GA and Part 135 aviation survey

The FAA GA surveys from 2008 to 2018 [1] were used to estimate the number of flight hours by helicopter type and industry. Survey data is not available for the year 2011.

[1] https://www.faa.gov/data_research/aviation_data_statistics/general_aviation/

2.3 Weather information sources

To perform a geographical analysis of events location with respect to different weather sources some additional computations and datasets were required. The goal was to identify potential gaps in weather-reporting coverage across the United States, but also whether there were any trends in events distance to the nearest weather source. The first part of the weather information source analysis looked at the locations of all FAA-recognized ASOS/AWOS airport-based weather reporting stations. A dataset containing a list of FAA-approved weather stations and their ICAO identifiers [16] was cross-referenced with the list of airports published on the National Transportation Atlas Database [17] to obtain the stations' coordinates. The distance between an event and the nearest weather station is written in the *events* table. The second study looked at weather radar stations. The coordinates of weather radar stations were obtained from Homeland Infrastructure[18] and the distance between an event and the nearest radar station were computed using a python script.

3 Results

The analysis focused on different aspects of helicopter accidents. First, an overview of weather-related accidents is given and provides insight into the weather findings most commonly involved in helicopter events and the type of incident or accident they are linked to. A second section shows where these events occur geographically in the United States and compares these locations with the positions of weather reporting stations and radars. Finally, flight purpose, pilot experience and helicopter types are considered.

3.1 The Role of Weather in Helicopter Events

Weather-related events make up a significant portion of reportable events to the NTSB. About 17% of reportable events have at least one weather-related finding and as displayed in Figure 1, the proportion of weather-related events to the total number of reported events has been relatively constant throughout the last decade. When examining fatal accidents only, the share of weather-related events to total events increases to 28%. The fatality ratio of weather-related events is 25%, i.e. a quarter of weather-related events are fatal, which is the highest of the ten most common tier 2 category findings associated with helicopter events.

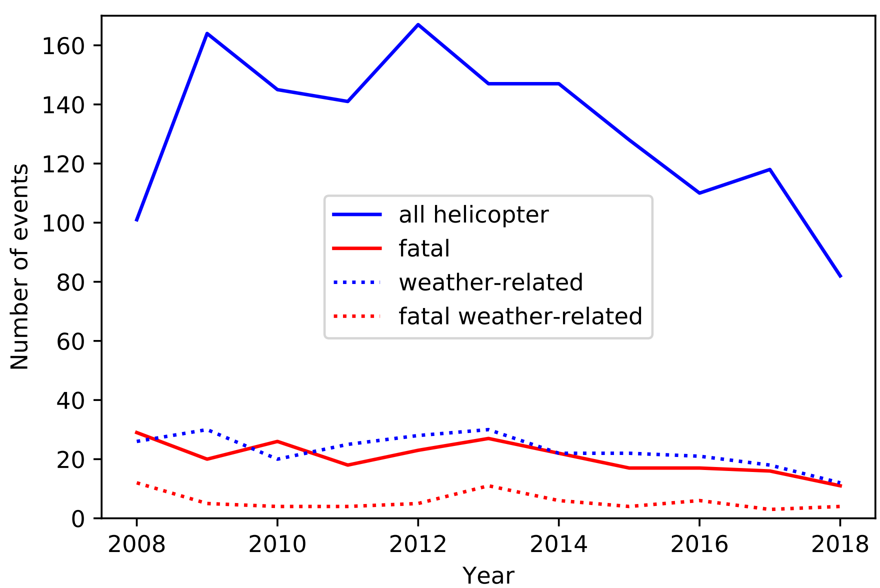


Fig. 1 Number of helicopter events per year from 2008-2018

Due to the multi-factorial nature of aviation events, it is interesting to examine findings that are frequently associated with weather findings. The finding categories most often associated with weather are: *aircraft operations performance and capabilities* (68%), *task performance* (57%) and *action/decision* (45%). These categories generally point toward pilot failure to plan and/or improper mitigation of risk to prevent the loss of control of the aircraft. Looking deeper into what types of weather are most commonly associated with NTSB helicopter events shows large variations between weather types. Figure 2 shows the weather findings associated with helicopter events from 2008-2018. Wind is the most commonly mentioned weather finding, but it has a very low fatality ratio. Conversely, the next most common findings, ceiling visibility, precipitation, and light conditions, have a very high fatality ratio. Note that it is common for events to have multiple weather findings associated with them; accordingly, the categories in Figure 2 are not independent. This is similar to the results of [4] which was conducted for all types of aircraft.

It is interesting that convective weather, a dangerous condition for smaller aircraft, is an uncommon finding in helicopter events. This is likely because convective weather is easier to detect with modern weather tools in tandem with environmental cues. Pilots can also alter their flight routes to navigate around convective weather much more easily than other types of weather.

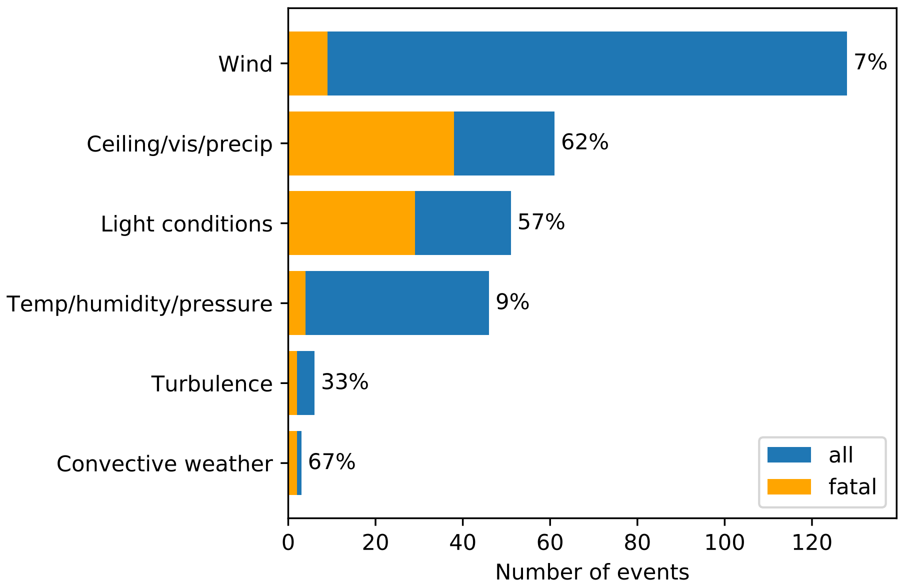


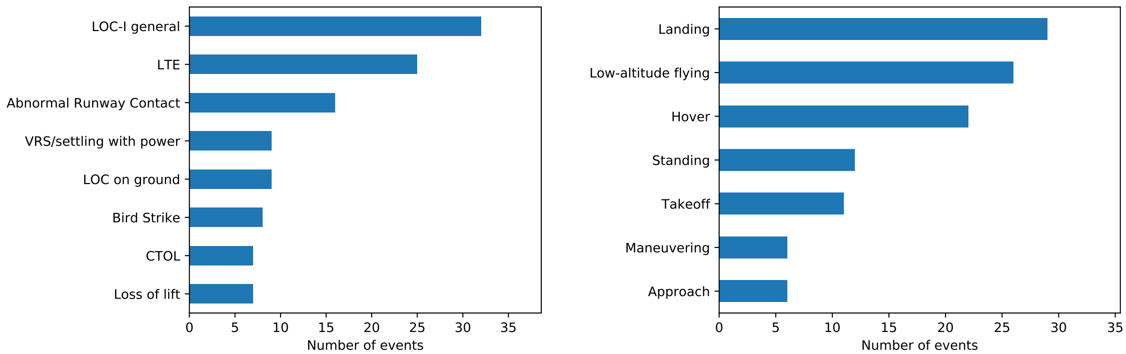
Fig. 2 Frequency of the different weather findings and their fatality rate

3.1.1 Wind

Wind values, if available, are recorded even if wind was not mentioned as a finding in the reportable event. Wind values or wind gust values higher than 25 knots are uncommon: out of the 1576 helicopter events identified from the NTSB database, only 54 (3%) were associated with such values. Half of those 54 events reported a wind finding. Wind gusts are reported only 24% of helicopter events, but are present in 60% of wind-related events. Looking at it another way, the presence of wind gusts increases the probability that wind was mentioned in the findings of the events. Indeed, among events that reported wind gusts 21% mention wind in their findings, whereas only 9% of all events mention wind in their findings.

As shown on Figure 3, defining events associated with a wind finding are usually related to a loss of control in the air (LOC-I) or a loss of control on the ground (LOC-Ground). The LOC-I occurence is broken down in three different categories: Vortex Ring State and settling with power (VRS) , Loss of Tail Rotor Effectiveness (LTE), and unspecified (LOC-I general). VRS and LTE are aerodynamic conditions that a helicopter can enter due to an improper airspeed and/or descent rate. Ideally, pilots will avoid these states, but once encountered, the pilot must recognize the aerodynamic condition and apply the proper recovery technique.

The *Abnormal Runway Contact* and *Collision with Obstacle during Takeoff and Landing* (CTOL) occurrences both indicate improper control of the helicopter during takeoff or landing. For any aircraft, wind is primarily an issue when performing ground reference maneuvers such as take-offs, landings, and approaches, or while performing low-altitude activities, such as pipeline inspection or aerial photography. This is backed up through Figure 3b, which shows that the vast majority of wind-related events occur in a low-altitude phases of flight. The six most common flight phases in which a wind-related event occur all involve flight close to the ground. The fact that wind-related events occur close to the ground and at relatively low flight speeds leads to relatively low-energy impacts, which explains why their fatality ratio is low.



(a) Occurrence **(b) Phase of flight**

Fig. 3 Defining event type for wind-related incidents/accidents (categories with fewer than 5 incidences were truncated)

When looking at the tier 2 findings associated with wind that are not weather related, the two most common are *aircraft operation, performance and capability* (78%) and *task performance* (63%). This points at a failure of the skills or abilities of the pilot to maintain control of the aircraft in windy condition. The finding *Action/Decision* is only mentioned in 36% of cases, meaning in most cases the NTSB investigation did not fault the pilot's decision making.

3.1.2 Precipitation, Ceiling, Visibility and Light Conditions

Figure 4 shows that apart from flat light and snow, most of the weather conditions in the *Precipitation, Ceiling, Visibility* and *Light Conditions* categories have very high fatality ratio (greater than 70%). These two types of findings will be grouped together in the rest of the report and events that have one of those listed as a finding will be referred to as "visibility events". These findings point to the presence of IMC conditions at the accident site. Most helicopters operate under VFR only and are poorly equipped to deal with IFR flight conditions.

As can be seen on Figure 4, dark conditions and clouds (clouds or low ceilings) make up the most of the visibility findings. A look at the reported weather conditions in terms of illumination, cloud layer types and ceilings reinforce those findings. Similarly to what was done for the wind a comparison with all helicopter events can give an idea of how common these weather conditions are for helicopter operations. Looking at all helicopter events 88% of events occur during the day. As seen in Figure 5a, 56% of visibility events occur at night (dark night conditions, and night conditions). This is to be expected, as spatial disorientation is more likely to occur at night when there are few visual points of reference for the pilot. Moreover, clouds are more difficult to see at night without the light reflecting on them, which increases the risk of UIMC.

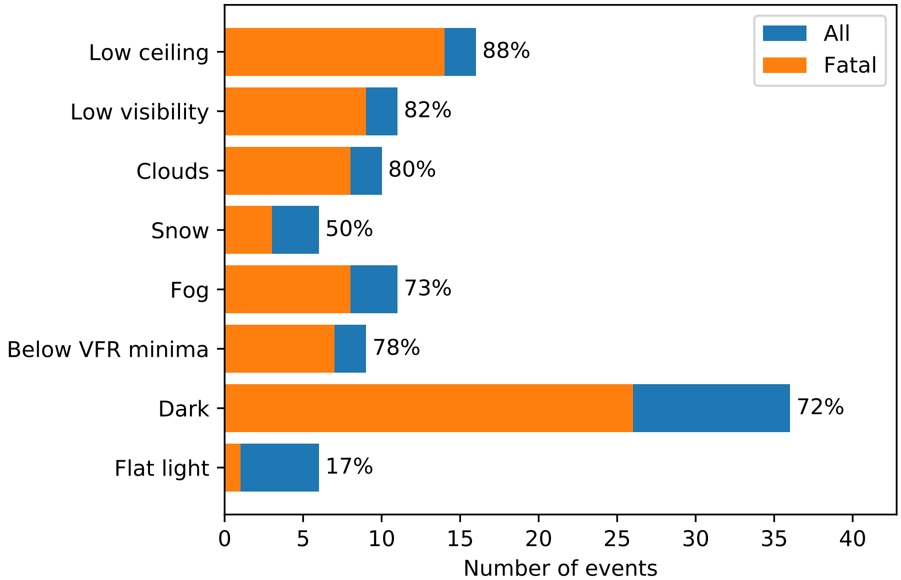
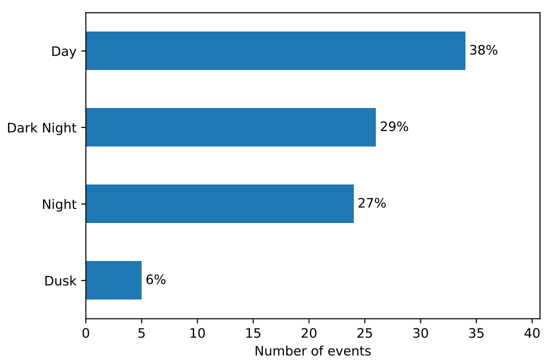
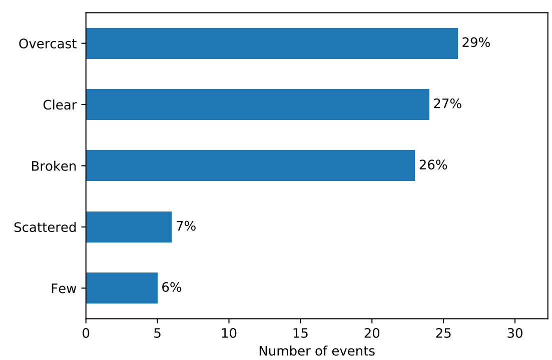


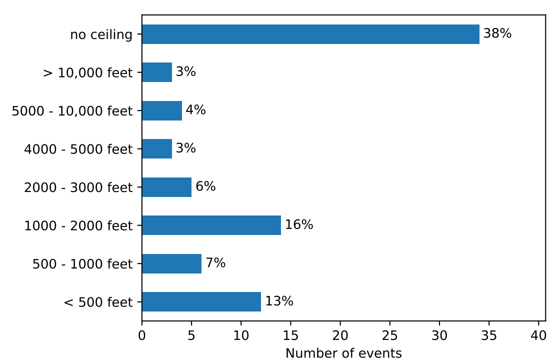
Fig. 4 Frequency of Precipitation, Ceiling, Visibility and Light Conditions findings and their fatality rate (limited to findings mentioned strictly more than 5 times)



(a) Illumination



(b) Cloud layer types



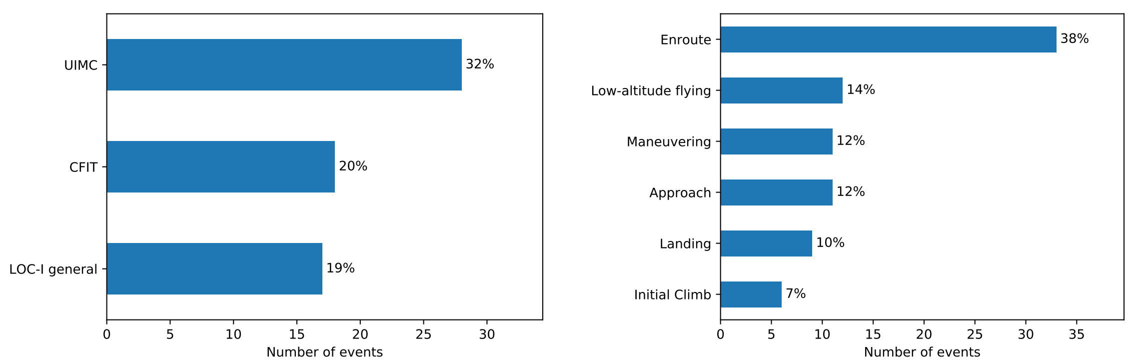
(c) Ceiling height

Fig. 5 Weather for visibility events. Only cloud layer types that appear at least 5 times are displayed.

As could be expected, visibility events are associated with a high ratio of cloud covers, overcast or broken ceilings are found in 55% of those events. To give a point of comparison, 48% of all helicopter events occurred with a clear sky with almost no clouds, and only 25% with a broken or overcast ceiling. Figure 5b shows the type of clouds present at the time of the events. In cases where there was no ceiling (i.e. no layer of clouds had a sufficient coverage to be qualified of overcast or broken), the non-ceiling layer (scattered or few) is indicated. Somewhat counter-intuitively, 27% of helicopter visibility events occur while the sky is clear.However, 71% of those clear sky visibility events occurred at night or dusk, which means that low illumination alone can cause spatial disorientation. This still means that there are some visibility events that occurred on a clear bright day, which prompted an additional check. Looking deeper into the 7 clear daylight condition events identified showed that 2 of them have findings related to drizzle or snow, which points again at some inconsistencies in the database since there must have been clouds at the time of these events. The other 5 events were linked to sun glare, brownout (dust kicked up by the rotorcraft downdraft obscured the pilot's field of view) or haze/smoke.

Finally, Figure 5c shows that 36% of visibility events occurred while the ceiling was lower than 2000 feet, this is to be compared to the 5% of all helicopter events that reported a ceiling lower than 2000 feet. When looking at this graph it is important to remember that no ceiling or a high value of ceiling does not mean that they were no clouds at low altitude but that the cloud cover was sparse enough to be categorized as few or scattered and not qualify as a ceiling.

As shown in Figure 6, the defining events associated with these weather conditions are UIMC, controlled flight into terrain (CFIT), and loss of control in flight (LOC-I). Both CFIT and LOC-I can be consequences of UIMC, but the NTSB cannot always prove that there was UIMC due to the lack of in-cockpit recording and as a result might not include it in the sequence of event. CFIT occurs when the pilot maintains overall control of the aircraft, but flies into an obstacle or terrain feature without realizing the presence of the obstacle, usually because of IMC. Spatial disorientation which can be triggered by a lack of visual reference will result in a loss of control if not mitigated. As shown in Figure 6b, the defining event often occurs during the cruise (or enroute) portion of the flight. Whereas in wind-related incidents the flight phases were slow and low to the ground, enroute phases of flight typically occur at much higher speeds and altitudes. This inherently implies that the helicopter impacts the terrain with significant momentum. The high fatality ratio can be explained as follows: if a pilots fail to exit IMC, then the accident will most likely be fatal; however, if the pilot successfully exits IMC, the pilot should be able to regain control of the situation and resume the flight safely, avoiding an NTSB reportable event.



(a) Occurrence **(b) Phase of flight**

Fig. 6 Defining event type for ceiling/visibility/precipitations or light conditions incidents/accidents (categories with fewer than 5 incidences were truncated)

Looking at the tier 2 findings most commonly associated with a visibility event shows that an *Action/Decision* finding is the most common (62%) followed closely by an *Aircraft operations, performance or capability findings* finding (56%). This points first to an improper decision from the pilot to start or continue the flight in adverse weather and then to a lack of skills or abilities to recover from IIMC.

3.2 The Role of Geography in Helicopter Events

It is of interest to examine whether there are any recognizable high-level geographical trends that relate to reported weather events.

The geographical breakdown of all rotorcraft accidents between 2008 and 2018 depicted in Figure 7 indicates a correlation between accident frequency and population density. Areas surrounding San Francisco, Los Angeles, Dallas, Houston, southern Florida, and New England have a high density of accidents, whereas more rural areas of the United States have comparatively smaller accident counts. This might be due to the fact that there are also more helicopters flying in these areas. However, to learn more about the potential role of weather in these events, we examine the weather-related and non-weather-related events. As illustrated, the weather-related events are frequent enough to be visible, but there are no obvious geographical trends with respect to their locations. If anything, they appear to occur in the more remote areas of the United States, areas that have lower population densities.

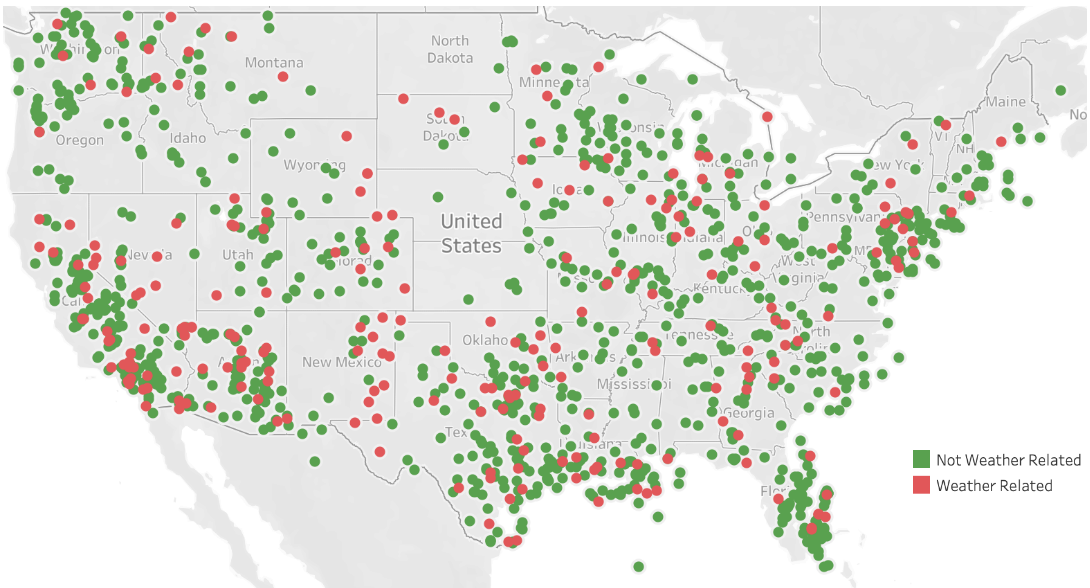


Fig. 7 Geographic breakdown of weather-related and non-weather-related events from 2008-2018

3.3 Proximity to a Weather Reporting Source

Although weather-related events are often linked to lapses in situation awareness and/or poor decision-making from the pilot, the research team was prompted to investigate whether weather-accidents could be linked to pilots having insufficient weather information at their disposal. As shown in NTSB accident *CEN19FA072*, the limited range or limited applicability of localized weather coverage is not always clear to pilots and can contribute to bad decisions.

3.3.1 Weather Reporting Stations

As shown on Figure 8, FAA-approved weather reporting stations are installed all over the country, with a high density near large urban centers and poorer coverage in less densely populated areas of the Midwest. These stations are installed at airports and provide information pertaining to the localized weather at their respective location, such as the temperature and dew point spread, the wind direction and velocity, and ceiling and visibility information. The weather reports can be completely automated or augmented by human observations if the airport has a tower. Although the weather information provided is only local, pilots often use the different weather stations in one area to interpolate what the weather could be like in between stations. Pilots can access this information on the ground through a web interface, or in the air via radio, ADS-B, or satellite weather transmissions.

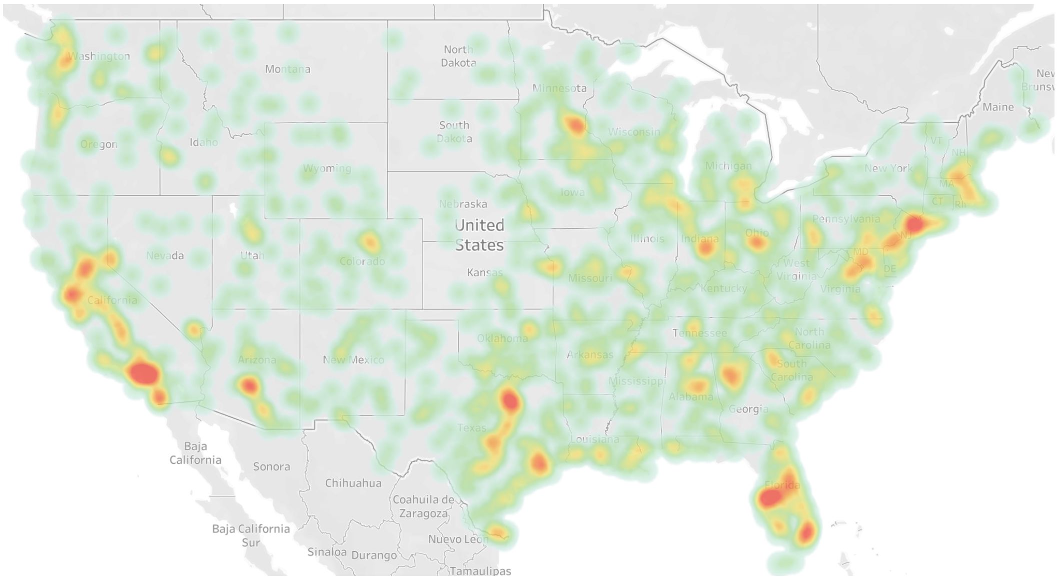
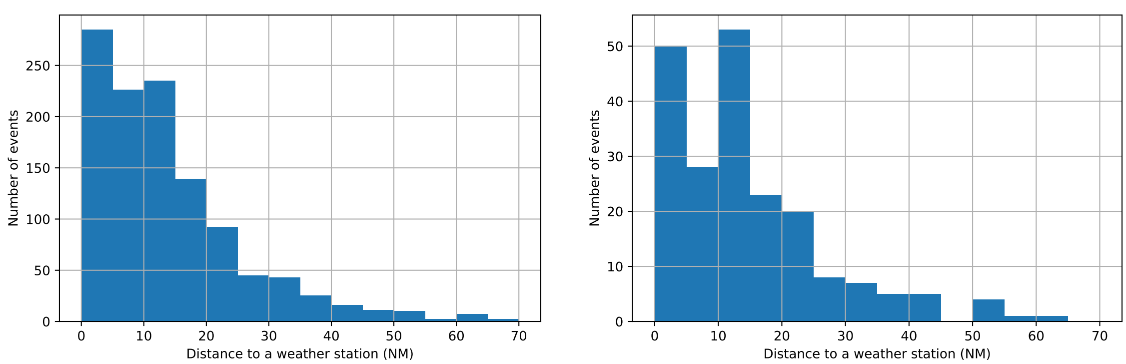


Fig. 8 Heatmap depicting geographical density of FAA-recognized airport-based weather reporting stations in the continental United States

As shown in Figure 9 the incidence of events decrease with the distance to a weather station: 96% of helicopter events occurred within 50NM (the FAA distance for a flight to be considered cross-country) of a weather station. This is most likely because even though helicopters can land off-field, they most often start and finish their missions at airports where fuel and hangars are available, and a large fraction of their operations occur close to population centers and their airports. As shown on Figure 9b there is no significant difference between the distribution of weather-related events and all helicopter events. It does not appear that the proximity to a weather station impact the risk for the pilot of getting into a weather event. The spike seen for a distance of 10 to 15 nautical miles on Figure 9b is due to a spike at 10 NM. When defining smaller ranges for the histograms, spikes for round numbers appear. This is probably because the column containing the distance to the nearest weather station is populated by hand and investigators must tend to round their numbers. When looking at differently sized bins, the spike between 10 and 15 is smoothed.



(a) All helicopter events

(b) Weather-related events

Fig. 9 Histogram of the distance to a weather station

3.3.2 Weather Radar Stations

Contrary to local weather reporting stations, weather radar stations can indicate precipitation and report ceilings over a large region. As shown on Figure 10, their coverage decreases with altitude, and some areas are not covered below 3000 ft. As most helicopter operations occur below 2000 ft AGL, precipitation and clouds that appear at the altitudes where helicopters fly might not be properly captured when operating at some distance from a weather radar station.

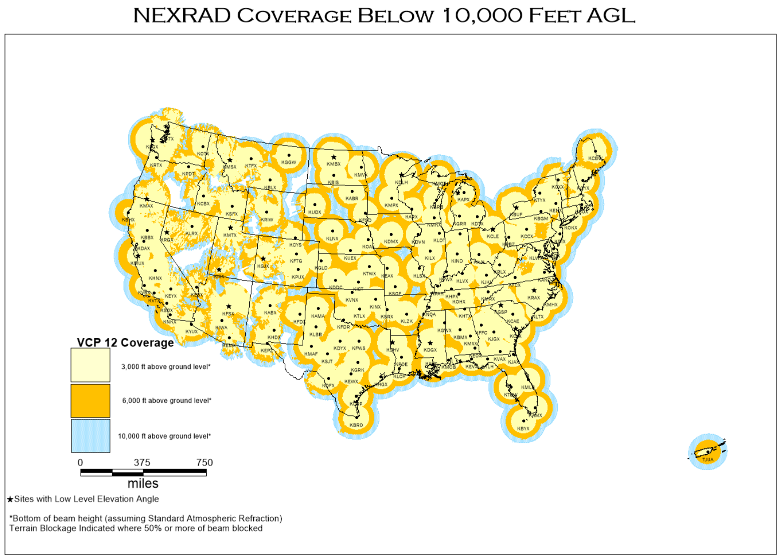
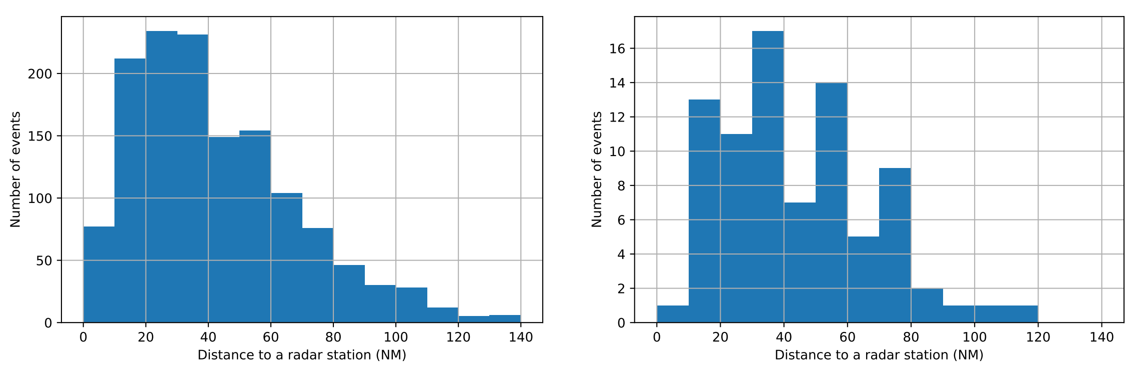


Fig. 10 Weather radar coverage at different altitudes over the United States [19]

As shown in Figure 11, event counts tend to decrease with distance from a radar station, which is similar to the trend for the distance to a weather reporting station. Contrary to weather reporting stations however, the peak of the distribution does not occur at a distance of less than five miles. In this case, the expected value of the distance to a radar station would be approximately 30-35 miles. This is likely because radar stations are not installed at airports, but rather in peripheral areas due to technical constraints. Indeed, radar stations must be installed in an area with few obstructions to have a clear line of sight and radar stations provide very limited coverage in the area right above the station (cone of silence), which explains why they are not installed directly at airports. Figure 11a and Figure 11b show very similar trends. It does not appear that the proximity to a radar station protect helicopter pilots from visibility related events.



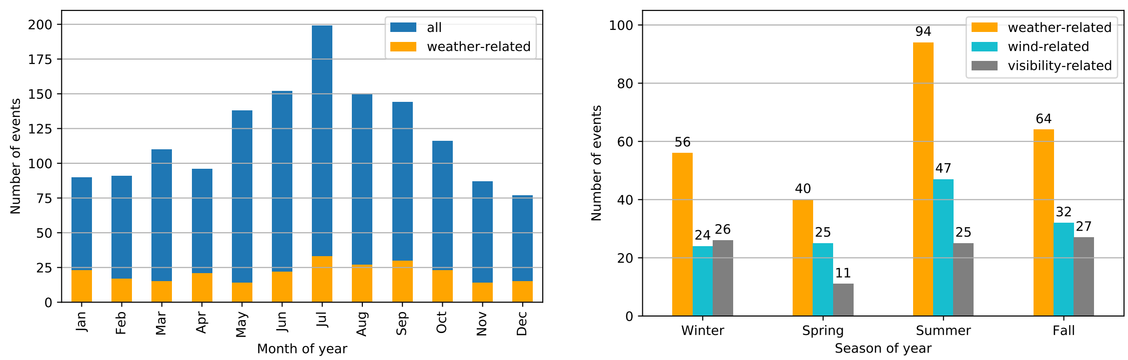
(a) All helicopter events

(b) Ceiling/visibility/precipitations events

Fig. 11 Histogram of the distance to a radar weather station

3.4 Temporal Analysis of Helicopter Events

As can be seen in Figure 12a, there is a spike of helicopter events during the summer months, probably due to an increase in flying activity between the months of May and September. However, the number of weather-related events does not vary as much throughout the year. As a result the share of helicopter events related to weather is more important during the Fall and Winter (20%) than during Spring (15%) and Summer (16%), as illustrated on Figure 12b. In the Fall and Winter the share of weather-related events that are visibility-related increases (42%, 46%) compared to Spring and Summer (28%, 27%). This makes sense as the meteorological conditions associated with visibility events (low clouds, precipitations) are more common than in the summer and spring, and the days are shorter. Although the visibility events ratio is reduced in Summer, the actual number of visibility events is roughly the same in Summer as in the Winter and Fall. There also appear to be some seasonality associated with wind events although the variations are not as marked as for visibility events. Wind events account for half of weather-related events in Summer and Fall, 43% in Winter and 63% in Spring.



(a) Helicopter events by month

(b) Helicopter weather-related events per season

Fig. 12 Seasonality of helicopter events

3.5 Event Flight Purpose

According to the GA surveys published by the FAA between 2008 and 2018 and summarized on Figure 13, most helicopter flight hours are flown for other purposes than instructional or personal flights. Personal flights only accounted for 3% of flight hours during that decade.

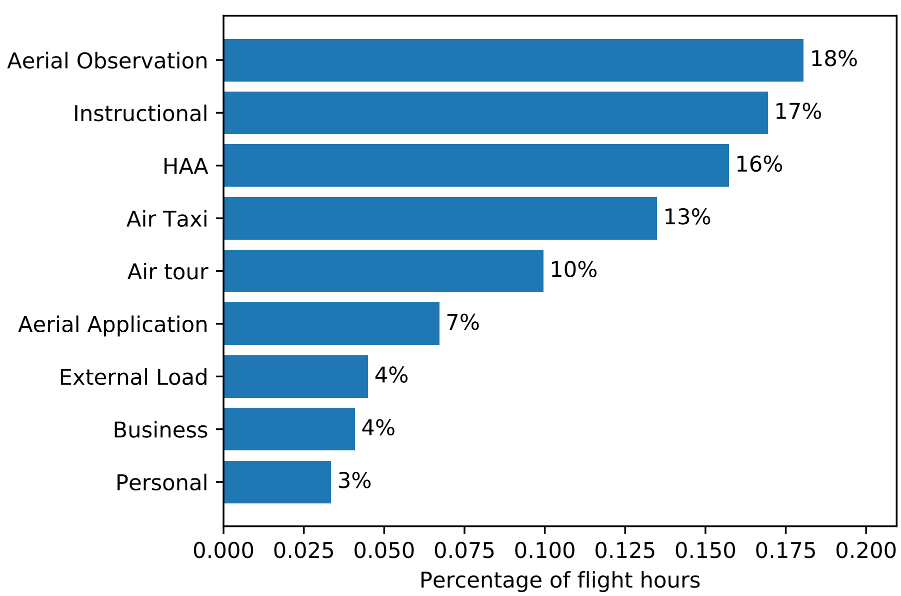


Fig. 13 Distribution of rotorcraft flight hours with respect to flight purpose from 2008-2018

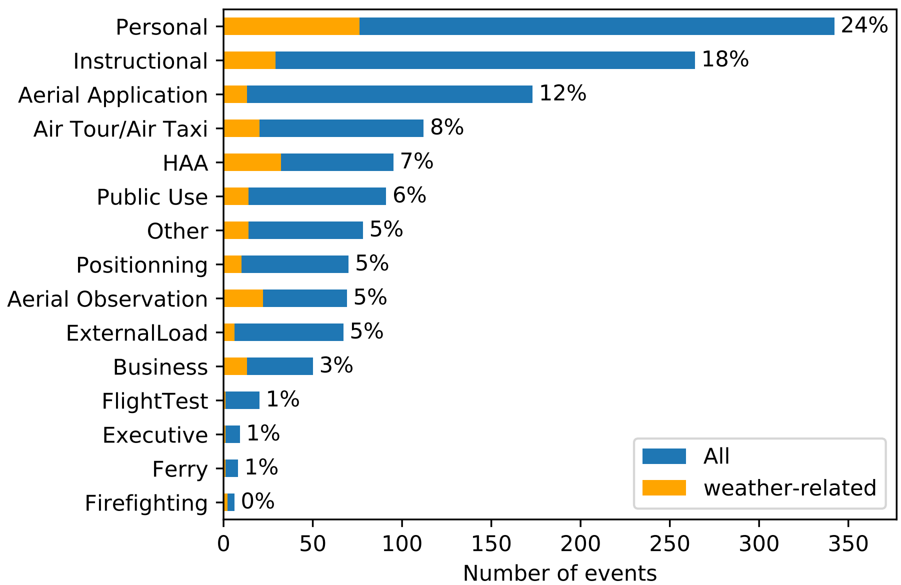
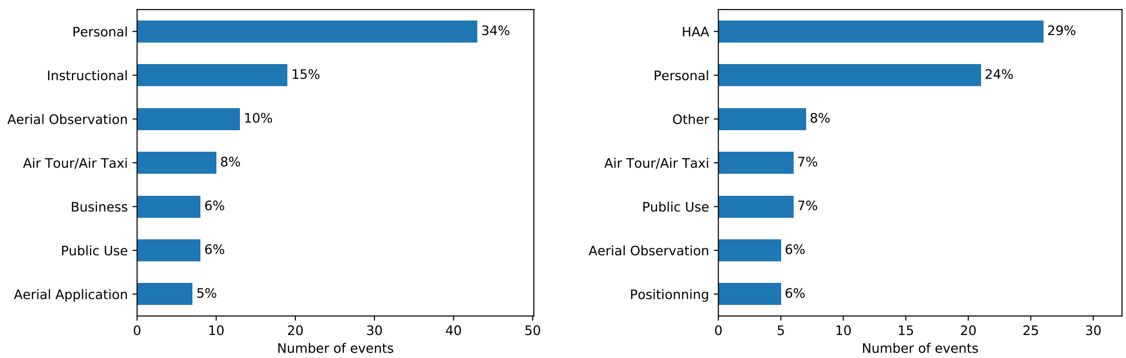


Fig. 14 Distribution of rotorcraft events with respect to flight purpose from 2008-2018. The percentage indicates the percentage of all helicopter events that were conducted for that flight purpose.

The makeup of flight purpose among the reported NTSB events is quite different from the FAA GA surveys' indication of the most flown operations. Figure 14 illustrates the distribution of rotorcraft accidents with respect to the flight purpose. As can be seen, personal flights account for the highest percentage of events (24%). Instructional flights are a close second with 18% of events. Around 5% of events do not have a defined flight purpose and are marked as 'Other' in the figure.

As shown on Figure 15, narrowing the scope to examine how the two most common weather findings affect these industries shows that different trends emerge. For example, Figure 15a shows that personal flights account for 34% of wind-related events. One interesting finding is that air ambulance flights account for the highest proportion (29%) of events in which precipitation/ceiling/visibility or light conditions were a finding as depicted in Figure 15b. Air ambulance flights appear particularly susceptible to weather conditions that are linked to UIMC occurrences. A potential explanation for this is that these flights have more external pressure to operate in poor weather conditions and at night than other industries that conduct less time-sensitive operations. Aerial observation flights, for instance, are unlikely to occur in poor visibility conditions that hinder their main task, but due to operating in close reference to the ground, they are more susceptible to wind-related events. Although, HAA crews and helicopters might be better equipped to deal with weather than other industries they are not always IFR capable and might find themselves in a corner due to bad visibility conditions. On the other hand, there were only 4 HAA events associated with a wind finding either because HAA pilots are more experienced or because larger and more powerful helicopter can better handle windy conditions.



(a) Wind-related events **(b) Ceiling, visibility, and light conditions**

Fig. 15 Breakdown of flight purpose for two types of weather events (categories with fewer than 5% of events are excluded)

3.6 Pilot Experience

Helicopter events are significantly more likely to occur to pilots with lower total flight hours. As shown in Figure 16, the trend is the same whether looking at all types of events or only weather-related events. Pilots with less than 1000 hours of experience account for 27% of weather-related events, and 26% of all events. It makes sense that pilot experience plays an important role in aviation events. The high event rate of personal and instructional flights can also be explained by this, as those flights are generally conducted by pilots with less experience than professional pilots. Anecdotal evidence gathered while talking to professional helicopter pilots showed that pilots grew more conservative (higher weather minimums) with experience.

When looking at specific weather, such as wind and poor visibility conditions, pilots with less than 1000 hours of experience account for the most events.

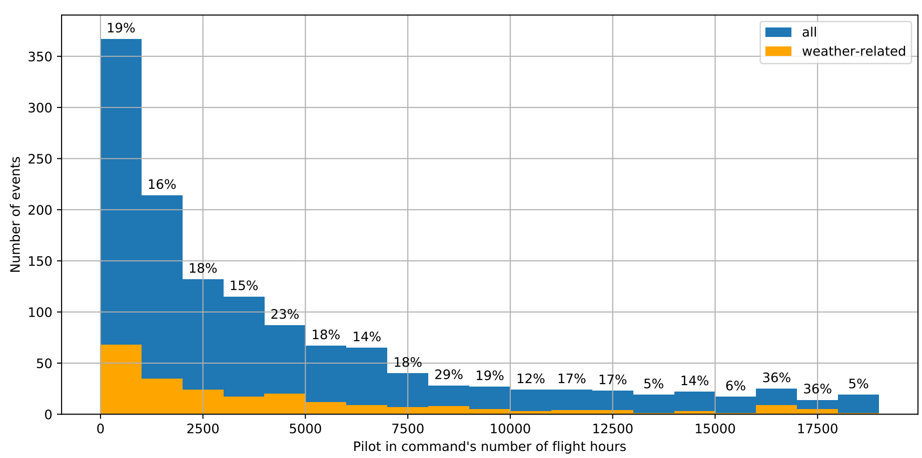


Fig. 16 Number of events as a function of experience in total flight hours of pilots who were involved in all types of helicopter events and in weather-related helicopter events. The percentage indicates the ratio of weather-related events for each category.

3.7 Helicopter Types

Multi-engine helicopters have a better safety rate than single engine helicopters.

According to the FAA GA surveys, twin-engine helicopters represented 16% of the helicopter fleet in the US between 2008 and 2018. Multi engine turbine helicopters fly more hours on average than single engine piston helicopters, and accounted for 18% of the total rotorcraft flight hours on that same period.

Multi-engine helicopters account for only 6% of all reported helicopter events and just 7% of weather-related events. Their share increases to 10% and 11% when considering fatal accidents only.

Pilot experience could be an explanation for why single engine helicopters are more often involved in reportable events. On average, pilots involved in a twin engine helicopter event had more than 10 thousand flight hours, whereas pilots involved in single engine helicopter event had an average of 5 thousand flight hours. Multi-engine ratings require significantly more training, flight hours, and experience.

Another contributing factor could be that multi-engine helicopters are typically specialty aircraft, and are therefore outfitted with more advanced avionics (autopilots, TAWS, radar altimeter, onboard weather radar, etc..). Moreover, between 1999 and 2019 there was no single-engine helicopter certified for IFR operations, so all IFR helicopters were multi-engine. This made single-engine helicopters particularly sensitive to poor visibility conditions. To look into that effect we focused on the HAA industry which employs highly trained pilots (all but one pilot that were involved in an HAA event had more than 2000 hours of experience). 69% of HAA visibility events involved a single engine helicopter. This is to be compared to the fact that in 2018, only 58% of air ambulance flight hours were conducted in a single engine helicopter. HAA multi-engine operations have a lower visibility event rate than HAA single-engine operations. Events occurring with an IFR flight plan are very rare. Only one out of the 95 HAA events reported the pilot having filed an IFR flight plan. 84% of HAA events occurred while the operation was conducted with a company VFR flight plan and 10% without a flight plan.

4 Discussion

This study shows that the two main weather factors involved in helicopter events are wind and poor visibility (encompassing ceilings, visibility, precipitation, and light conditions).

Wind events disproportionately affect private pilots flying for personal reasons or pilots in training. They are usually linked to a poor handling of the aircraft in low altitude flight, which leads to collisions with the landing and take-off areas or with obstacles nearby. These loss of control events are rarely fatal due to their low energy impacts and could probably be avoided by improving training for gusty wind conditions.

Poor visibility conditions, on the other hand, affect trained, well-equipped air ambulance pilots as well as more inexperienced pilots. These events, which either result in an enroute loss of control due to spatial disorientation or CFIT are most often fatal due to the high energy impact associated with cruise speeds. Although low ceilings were frequently associated with these events, the main risk factor appeared to be night operations. The NTSB frequently associated decision-making findings in its investigation of these events. This suggests that helping pilot make better decision before and during the flight when confronted to low-visibility conditions would reduce the number of such events.

Changes were made to air ambulance legislation in 2014 which mandated risk assessments and enforced higher weather minimums with the goal of reducing spatial disorientation events [20]. Some of those changes, such as FAR/AIM 135.603 which mandates that HAA pilots must hold an IFR rating or an ATP rating not restricted to VFR, only took effect in 2017, and thus it is still too early to see if they will prove to be efficient in reducing the rate of poor visibility condition events in the air ambulance industry.

Although pilots sometimes complain about the lack of weather data at the altitude and in the remote areas where they operate, no clear trends were found with respect to the event's distance to a weather source. There is a good coverage of weather stations in high population density areas, which tend to have the most flights. It is likely that any lack of data pushes pilots to cancel or postpone flights due to uncertainty and safety concerns. The fact that the trends between all events and weather-related events are the same with respect with distance to weather station or radar station would tend to show that these stations might not help pilots avoid those adverse weather conditions. This could either be because these weather information sources lack information pertinent for helicopter pilots such as fog or altitude of low clouds, or because pilots cannot access the pertinent information due to connectivity issue, lack of appropriate equipment or workload.

In conclusion, the authors recommend improving helicopter pilot's training for maneuvers in gusty and windy conditions to reduce the number of weather-related incidents. Training for decision making in poor visibility conditions should also be improved as decision-making was found to be an important co-factor of visibility accidents. The enroute decision point (EDP) protocol developed by the National EMS Pilot Association (NEMSPA) could be more widely advertised to all types of helicopter pilots. The EDP is a set of minimum altitude and airspeed that are used as in-flight triggers to indicate to the pilots that they should initiate a return to base, emergency landing or IFR filing. This helps pilots realize that the weather has significantly degraded and that it is time to amend the flight. An outreach effort should

Table 1 Some important categories of helicopter weather-related events

Flight Purpose	Pilot Experience	Weather Type	Helicopter Type	Percent of All Weather-Events
Aerial Application or Observation	more than 1000 flight hours	Wind	single engine	6%
Instructional or Personal	more than 1000 flight hours	Wind	single engine	15%
Instructional or Personal	less than 1000 flight hours	Wind	single engine	9%
Instructional or Personal	less than 1000 flight hours	Bad Visibility	single engine	6%
Instructional or Personal	more than 1000 flight hours	Bad Visibility	single engine	3%
HAA	more than 1000 flight hours	Bad Visibility	single engine	7%
HAA	more than 1000 flight hours	Bad Visibility	twin engine	3%

also be made to improve safety among private helicopter pilots who, although they represent a minority of helicopter flight hours, account for a large number of accidents and incidents.

Acknowledgments

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Appendix I - Nomenclature

$ADS-B$	=	Automatic Dependent Surveillance - Broadcast
$AOPA$	=	Aircraft Owners and Pilots Association
$CFIT$	=	Controlled Flight Into Terrain
$CTOL$	=	Collision with obstacle(s) during Take-Off and Landing
FAA	=	Federal Aviation Administration
GA	=	General Aviation
HAA	=	Helicopter Air Ambulance
HAI	=	Helicopter Association International
$HOWI$	=	Helicopter Operations Weather Information
$HTML$	=	HyperText Markup Language
$ICAO$	=	International Civil Aviation Organization
IFR	=	Instrument Flight Rules
$IHSF$	=	International Helicopter Safety Foundation
IMC	=	Instrument Meteorological Conditions
LOC	=	Loss of Control
$LOC-I$	=	Loss of Control In-Flight
LTE	=	Loss of Tail Rotor Effectiveness
$NTSB$	=	National Transportation Safety Board
$PEGASAS$	=	Partnership to Enhance General Aviation Safety, Accessibility and Sustainability
$UIMC$	=	Unintended Instrument Meteorological Conditions
$USHST$	=	United States Helicopter Safety Team
VFR	=	Visual Flight Rules
VMC	=	Visual Meteorological Conditions
VRS	=	Vortex Ring State
$WTIC$	=	Weather Technology In Cockpit

Appendix II - Findings

List of Tier 1 and Tier 2 findings:

- Aircraft
  - Aircraft handling/service
  - Aircraft oper/perf/capability
  - Aircraft power plant
  - Aircraft propeller/rotor
  - Aircraft systems
  - Fluids/misc hardware
- Environmental issues
  - Conditions/weather/phenomena
  - Operating environment
  - Physical environment
  - Task environment
- Organizational issues
  - Development
  - Management
  - Support/oversight/monitoring
- Personnel Issues
  - Action/decision
  - Experience/knowledge
  - Miscellaneous
  - Physical
  - Psychological
  - Task performance

Appendix III - Flight Purpose Definition

Depending on the type of task being conducted helicopter operations fall under different areas of the regulations which mandate different safety standards and weather minimums.

- Personal: flights conducted under part 91 not in furtherance of a business
- Instructional: flights conducted by a student or under the supervision of a CFI
- Helicopter Air Ambulance (HAA): flights conducted under part 135 to transport patients or medical personnel. A change in regulations occurred in 2014.
- Air Taxi: unscheduled flights for compensation or hire conducted under part 135
- Air Tour: sightseeing flights for compensation or hire conducted under part 135 or 91
- Public Use: the aircraft is owned or leased by a local, state or federal government. This can include police department or environmental agencies
- Aerial Observations: flights conducted under part 91 for aerial photography or infrastructure inspections
- Aerial Applications: flights conducted under part 137 for tasks such as spraying crops
- External Load: flights conducted under part 133 in which the helicopter is used to transport cargo outside its hull
- Business or executive flights: flights conducted under part 91 in the furtherance of a business and the aircraft is owned by the company and its primary commercial purpose is not the transport of persons or cargo.

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