Collegiate Aviation Review International

Volume 40 | Issue 1 Peer Reviewed Article #2

1-27-2022

Analysis of Weather-Related Accident and Incident Data Associated with Section 14 CFR Part 91 Operations

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Onboard weather equipment has gained popularity in recent years, and various types of equipment have been introduced into the cockpit. Despite their effectiveness, they do not always handle all weather-related events, such as high winds, turbulence, and wind shear. This paper studied the mortality linked to flying phases and weather events. The data for the analysis came from the National Transportation Safety Board (NTSB) and the Aviation Safety Reporting System (ASRS) databases. The weather conditions associated with general aviation-related accidents and incidents were investigated to better understand the specific factors that were most frequently discovered for various weather-related events. The two databases yielded 30,877 accident/incident records. This study reviewed 17,325 accidents and incidents from the NTSB database under 14 CFR Part 91 General Operations and Flight Rules to identify which ones were caused by weather. There were 1,382 weather-related accidents and incidents throughout this investigation. The phases of flight with the highest deaths were maneuvering and en route (28 %). Of the 30,877 total accident/incident records, 13,552 reports were within the ASRS database. Three hundred fifty-eight were weather-related. En route (52 %) was the leading phase of flight with the most severe weather-related accidents/incidents.

Recommended Citation:
Long, T. (2022). Analysis of weather-related accident and incident data associated with Section 14 CFR Part 91 Operations. *Collegiate Aviation Review International, 40*(1), 25-39. Retrieved from http://ojs.library.okstate.edu/osu/index.php/CARI/article/view/8442/7728

Despite the growth of aircraft with weather advisory capabilities and subscription services for a range of meteorological products, a review of NTSB Aviation Accident reports and NASA's Aviation Safety Reporting System shows that general aviation weather accident numbers have remained relatively stable from 2009 to 2018. The widespread availability of onboard meteorological equipment has substantially increased the ability to obtain extensive weather data while flying. Some of these systems deliver precise data instantaneously, while others may take a while to respond. However, onboard weather equipment is rarely mentioned in NTSB accident reports, making it difficult to determine whether the technology is alerting pilots to impending weather in time to avoid convective weather events.

The study aimed to quantify and describe weather-related accidents reported involving onboard meteorological equipment equipped aircraft operating under FAR Part 91 General Aviation Flight rules using publicly available government accident reporting sites.

Research questions of this study include: What were the most significant weather events that had the most predominant impact on general aviation flights? What effect has onboard weather equipment had during these weather events? What was the most dangerous phase of the flight? Were there any fatal accidents involving aircraft that had operational onboard weather equipment during weather-related events?

This study looks at five critical weather-related areas in the NTSB and ASRS reports to analyze the relationship between accidents and incidents: 1) fatalities that occur during each phase of flight; 2) accident reports by determination and category; 3) accidents and incidents to stage of flight operations, 4) impacts of onboard weather equipment on the survival of passengers, and 5) accidents and incidents to the type of weather-related events.

Literature Review

Between 1990 and 1996, small General Aviation (GA) aircraft were involved in nearly 85% of all aviation accidents and nearly 85% of all accident fatalities (Chamberlain & Latorella, 2001). Weather forces are powerful and unpredictable, difficult to predict and control, and physically demanding to avoid or control (Knecht & Lenz, 2010). In adverse weather conditions, pilots of all classes of aviation can spend a significant amount of time acquiring and analyzing the necessary weather data, both preflight and in flight (Crabill & Dash, 1991). Pilots of small GA aircraft currently have limited in-flight information about convective weather activity, especially when compared to pilots of larger aircraft (Chamberlain & Latorella, 2001).

According to the FAA Weather-Related Aviation Accident Study (2010), wind was the leading cause or contributing factor in weather-related accidents from 2003 to 2007. Within this FAA study, the FAA reported aircraft operating under Part 91 were involved in more

weather-related accidents than aircraft operating under any other 14 CFR Part (FAA, 2010). Research conducted by Fultz and Ashley (2016) also found the wind to be the most cited weather hazard, from 1982 to 2013, as their study discovered 7.8 % of wind-related accidents were fatal. Between 2000 and 2011, Gultepe et al. (2019) noted that adverse winds were the leading cause of weather-related accidents for small, noncommercial aircraft (Part 91 class), followed by low ceilings. Capobianco and Lee (2001) discovered most wind-related accidents occur during takeoff or landing when the aircraft is at or near the surface, as these types of accidents occur at much lower speeds and altitudes. Many wind-related accidents happen when pilots lose control of their planes during takeoff or landing in gusty conditions (FAA, 2010).

Non-instrument rated pilots tended to fly the least weather-capable aircraft (Knecht & Lenz, 2010). Capobianco and Lee (2001) explained the most common probable causes of fatal weather accidents reported from 1995 to 1998 were VFR to IMC flight and flight into adverse weather during the cruise phase. Sixty-three percent of fatal weather events occurred during the cruise phase of flight (Capobianco & Lee, 2001). Between the mid-1970s and the mid-1980s, general aviation accidents involving VFR flight into IMC accounted for roughly 19% of all GA fatalities in the United States (Goh & Wiegmann, 2001). Approximately 76 % of VFR –IMC accidents appeared to involve intentional flight into adverse weather (Goh & Wiegmann, 2001).

Electronic flight displays (EFDs) were first installed in general aviation planes in 2003, and with a few exceptions, they are now standard equipment on all newly manufactured planes and available as an aftermarket upgrade for older general aviation aircraft (Boyd, 2016). These new products on the market display graphical weather data in the cockpit (Fraim, Cairns, & Ramirez, 2020). Even with today's technological advances, such as in-cockpit radar availability via satellite, weather remains a significant barrier to general aviation safety (Fultz & Ashley, 2016).

The goal of this research was to determine the most significant weather events that had the greatest impact on general aviation flight phases, the type of weather events, and the presence of onboard weather equipment. Research conducted by Capobianco & Lee showed the most dangerous phase of flight to be En Route (Cruise) phase. Researchers have discovered wind as the predominant factor in accidents.

Even though onboard weather equipment was mentioned in the literature, no studies mentioned weather-related accidents or incidents involving aircraft with onboard weather equipment. This study will look into onboard weather equipment accidents and incidents.

Methodology

The International Civil Aviation Organization (ICAO) Aviation Occurrence Categories (ICAO, 2013) and Phase of Flight Definitions and Usage Notes (ICAO, 2012) are used in this study to characterize accidents and incidents in both the NTSB and ASRS databases (Table 1).

Federal Air Regulations section 14 CFR Part 91 addresses noncommercial general aviation operations, including corporate aviation operations. The study reviewed Part 91

operations within two databases for 2009–2018: The NTSB accidents and incidents database and NASA's ASRS database. All operations that fall within 14 CFR Part 91 were analyzed. A record that noted a flight into heavy convective activity would be considered one where the weather was a primary factor, whereas a record describing an engine failure due to carburetor icing would not be considered weather-related since ICAO classifies carburetor icing as a fuel-related issue. Weather, flying conditions (IMC, Marginal, Mixed, or VMC), lighting, flight plan, and flight phase were the primary search criteria for both NTSB and ASRS reports under 14 CFR Part 91 activities.

NTSB database

The NTSB has two areas analyzed within the database: the Aviation Accident Final Reports and the Pilot/Operator Aircraft Accident/Incident Reports (NTSB Form 6120.1) found under Dockets. Each year's Aviation Accident Final Report data was downloaded into an excel datasheet to be analyzed for weather events that caused the accident/incident. All accident numbers were reviewed from the NTSB Accident Reports and screened for any mention of weather as a probable cause or findings. All those reports that were not weather-related were counted towards the total number of accidents and incidents for the year and not included as a weather event. There were also accidents reported that were listed as probable cause undetermined. Those reports were also only used for the overall accident count.

The NTSB reports were further filtered to find those that included onboard weather equipment. The number of NTSB accident reports mentioning such technologies is scarce and fluctuates from year to year. The accident numbers were then used to review those NTSB Form 6120.1 reports to determine if there were any mention of onboard weather equipment. These forms comprise factual reports, and the information investigators analyze to create a probable cause is stored in the NTSB database under Dockets.

In the event of an accident or incident, the surviving pilot of the aircraft is required to complete an NTSB Form 6120.1 and submit it to the appropriate NTSB office in accordance with 49 CFR Part 830.5(a). NTSB Form 6120.1. The NTSB uses data from this form to determine the facts, conditions, and circumstances to prevent aircraft accidents and compile statistics. Prior to 2011, the NTSB Form 6120.1 lacked an "Additional Equipment" list for pilots to make selections of additional equipment onboard the aircraft. After 2011, the pilot can choose from a list of options in the NTSB Form 6120.1 "Additional Equipment" listing to select onboard weather equipment, ADS-B, and satellite tracking devices.

Finally, a closer look at the downloaded accident report spreadsheet revealed fatalities, seriously injured people, minor injuries, and no injuries. The phases of flight were also investigated, despite the fact that a small number of accidents per year did not specify which phase of flight the accident occurred. These were counted as weather-related accidents/incidents but not as phases of flight in those cases.

ASRS database

The ASRS relies on self-reporting to detect anomalies in the National Airspace System. It's a completely voluntary program in which pilots can report safety incidents solely to alert the system. The Federal Aviation Administration (FAA) does not use these reports to impose disciplinary or other adverse measures against the pilot (ASRS, 2019). Because NASA does not accept ASRS reports involving aircraft accidents, pilots report such incidents to the NTSB.

A query was done on the database for the date and report numbers, environment, aircraft, person, event assessment, and narrative/synopsis. Each year's data was downloaded into an excel datasheet are reviewed for weather events, phases of flight, and the presents of onboard weather equipment. Non-weather reports were not evaluated but were included in the total number of events for the year.

Table 1

International Civil Aviation Organization - Phase of Flight Definitions

Phase of Flight	Definitions
Takeoff	The application of takeoff power, through rotation and to an altitude of 35 feet above runway elevation, or until gear-up selection, whichever comes first.
Initial Climb	From the end of the Takeoff sub-phase to the first prescribed power reduction, or until reaching 1,000 feet above the runway elevation or the VFR pattern, whichever comes first.
En Route	Instrument Flight Rules (IFR) From the completion of initial climb through cruise altitude and completion of controlled descent to the initial approach fix (IAF). VFR from the initial climb through the cruise and controlled descent to the VFR pattern altitude or 1,000 feet about the runway elevation or whichever comes first. This covers climb, cruise, descent, and holding. En Route is comprised of Climb to Cruise, Cruise, Descent, Change of Cruise Level, and Holding.
Maneuvering	Low altitude/aerobatic flight operations
Approach	Instrument Flight Rules (IFR), From the Initial Approach Fix (IAF) to the beginning of the landing flare. VFR from the point of VFR pattern entry, or 1,000 feet above the runway elevation, to the beginning of the landing flare. The approach covers Initial and final approaches as well as missed approaches/Go-Arounds.
Landings	The beginning of the landing flare until the aircraft exits the landing runway, comes to a stop on the runway, or when power is applied for takeoff in the case of a touch-and-go landing.

Results and Discussion

The author examined the phases of flight concerning fatal and non-fatal accidents in this study, then examined weather-related accidents and incidents before concluding with a connected analysis of onboard meteorological data utilization. The findings revealed the importance of weather as a cause or contributing factor in aircraft accidents at various stages of a flight and the link between the occurrence of accidents and the data provided by onboard weather equipment.

NTSB Records Analysis

The NTSB's Aviation Accident Final Reports database received 17,325 accidents from 2009 to 2018 (Table 2). During this study period, an average of 1,733 reports was submitted each year. The number of deadly occurrences has fluctuated over the study period, with the number of fatal incidents in 2018 falling to 36 fatal incidents. Weather-related deaths fell by 61%, from 113 in 2009 to only 69 in 2018.

The NTSB rarely mentions onboard meteorological equipment in the Aviation Accident Final Reports but reviewing the Pilot/Operator Aircraft Accident/Incident Reports indicates a different narrative. Until September 30, 2011, the title "Additional Equipment" was not included in the docket forms. As a result, there was no apparent onboard weather equipment in the cockpit. Between 9/30/2011 and 5/31/2017, additional equipment listing was added to include a checklist of ADS-B, Onboard Weather, and Satellite Tracking Devices. The forms within the dockets were only for the surviving pilots who had filed the proper papers with the FAA following an accident.

The rate of fatal weather-related incidents ranged from 2009 to 2018, with the highest incidence of 58 % in 2013. In 2016, only 11% of fatal accidents occurred, making it the year with the lowest fatal accident rate. Of the 276 weather-related accidents reported in 2009, 51 (18%) events were fatal (Table 2).

Table 2

Relation of NTSB Accidents to the type of injury in weather-related events occurring during 2009 - 2018

Year	Total Accident Records	Total Weather-Related Accidents	Fatal Events Weather-Related	% Fatal weather-related accidents	Fatalities # of people	Serious # of people	Minor # of people	Uninjured # of people
2018	1,745	146	36	25%	69	14	39	165
2017	1,693	182	40	22%	85	20	40	179
2016	1,748	119	13	11%	38	11	27	126
2015	1,635	115	39	34%	78	27	24	106
2014	1,579	172	44	25%	78	30	50	175
2013	1,606	55	32	58%	69	9	16	32
2012	1,871	73	36	49%	74	18	24	52
2011	1,866	126	70	56%	147	23	22	51
2010	1,797	114	46	40%	94	21	19	91
2009	1,785	276	51	18%	113	12	21	56
Totals	17,325	1,382	407	29%	845	185	282	1,033

From 2009 through 2018, general aviation accidents stayed relatively constant, averaging 1,733 per year. Weather-related events accounted for 8% of all accident reports. Four-hundred seven (29.4%) of the 1,382 weather-related accidents were fatal, resulting in 845 fatalities, for an annual average of 84.5 (34%) fatalities. Throughout the study period, 2009-2018, fatalities occurred on an average of 72% of IMC flights and 21% of VMC flights. (Table 3).

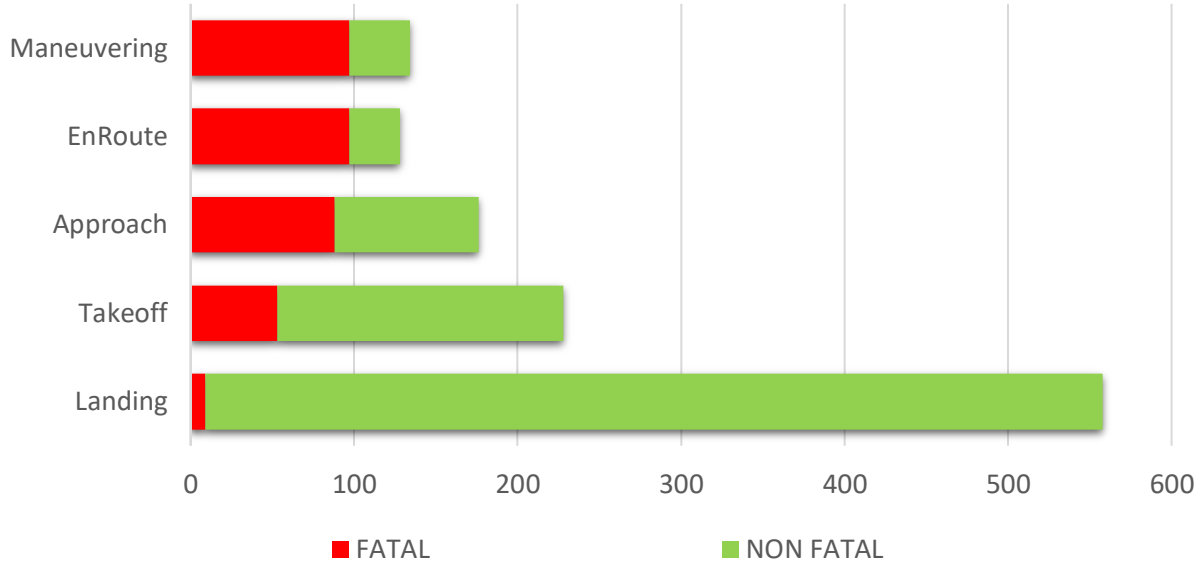
Table 3

NTSB Reports of accidents in which weather was the probable cause/contributing factor for years 2009 - 2018

Years	Total Weather-Related Accidents	Total IMC Events	Fatal IMC Flights	% IMC Fatal	Total VMC Events	Fatal VMC Flights	% VMC Fatal
2018	146	20	17	85	126	16	13
2017	182	35	26	74	147	14	10
2016	119	14	7	50	105	6	6
2015	116	26	21	81	90	18	20
2014	175	28	23	82	147	20	14
2013	55	14	12	86	41	18	44
2012	73	17	12	71	56	29	52
2011	126	22	16	73	104	54	52
2010	114	32	11	34	82	33	40
2009	276	63	51	81	213	24	11
Totals	1,382	271	196	72	1,111	232	21

During this period, 28% of fatalities occurred during the Maneuvering and EnRoute phases of flight. Landings had the lowest accident rate of any phase of flight, with fatalities occurring in 3% of those landings (Figure 1). The fatal rate on En Route in this study yields a lower finding than that of Capobianco & Lee, 2001), where they showed that among all the fatal weather causes, 63% occur during the cruise phase of flight during 1995-1998.

Figure 1.
Relation of weather-related accidents to phase of flight operations for years 2009 to 2018



Note: Not all reported events stated whether there was a phase of flight associated with the accident or incident.

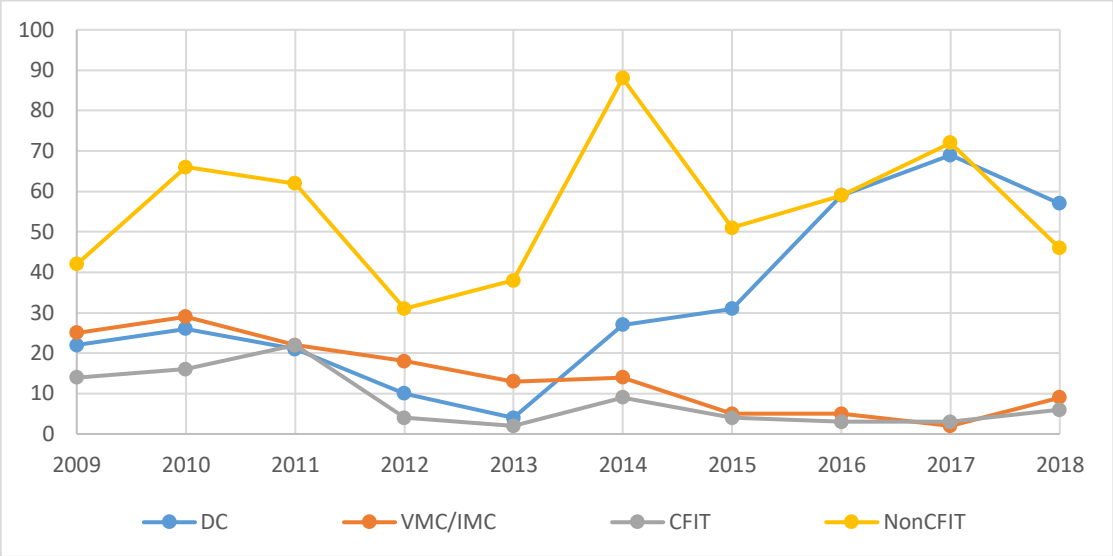
Accident Determinations

Non-Controlled Flight into Terrain (NFIT), Controlled Flight into Terrain (CFIT), Loss of Directional Control (DC), and VFR into IMC are the four types of accident determinations. From 2009 to 2017, an uncontrolled flight into terrain was the most critical determinant (Figure 2). Controlled Flight into Terrain (CFIT) occurs when an airworthy aircraft flies into the ground, water, or obstacles while under the control of a qualified pilot who is unaware of his position. Accidents involving uncontrolled flying into terrain occur when the aircraft is out of control at the time of the collision. An unintentional departure of an airplane from a controlled flight is a Loss of Control accident.

The proportion of VMC into IMC has been steadily decreasing since 2010, with a slight uptick in 2018 (Figure 2). Until 2018, the most common determination was a Non-Controlled Flight into Terrain. Several mishaps involving onboard radar were recorded in NTSB reports during this investigation. Loss of Directional Control and Non-Controlled Flight into Terrain were linked to 47 % of all weather-related accidents and incidents in 2016. Strong wind gusts caused the majority of these incidents. Throughout the study, 31 % of those accidents and incidents reported a loss of directional control.

Figure 2

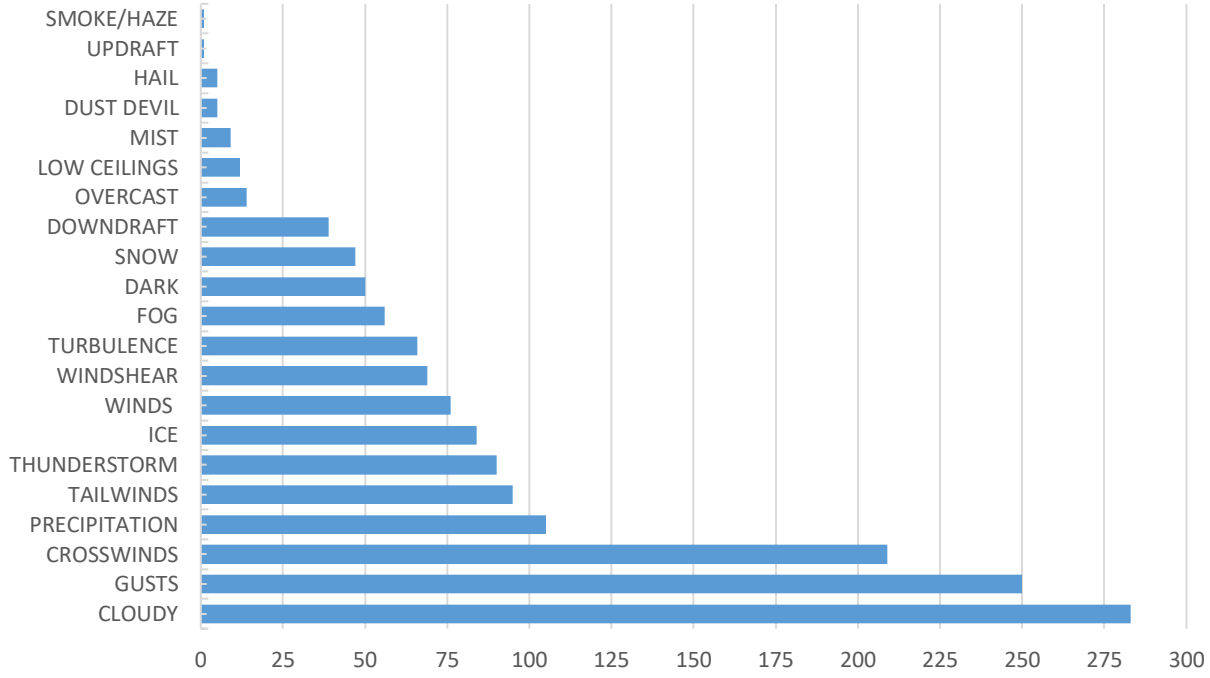
NTSB Part 91 Weather-Related Accident reports by determination, 2009 to 2018



The 1,382 weather-related incidents were categorized into 21 different weather-related categories (Figure 3). The overwhelming weather occurrences in the NTSB accident reports were cloudy, gusts, and crosswinds (Figure 3). Cloudy weather accounted for 18% of all weather-related incidents, with gusts accounting for 16% and crosswinds accounting for 13%. Precipitation made up 7% of the total.

Figure 3

NTSB weather-related accidents and incidence experienced during flight for years 2009 through 2018

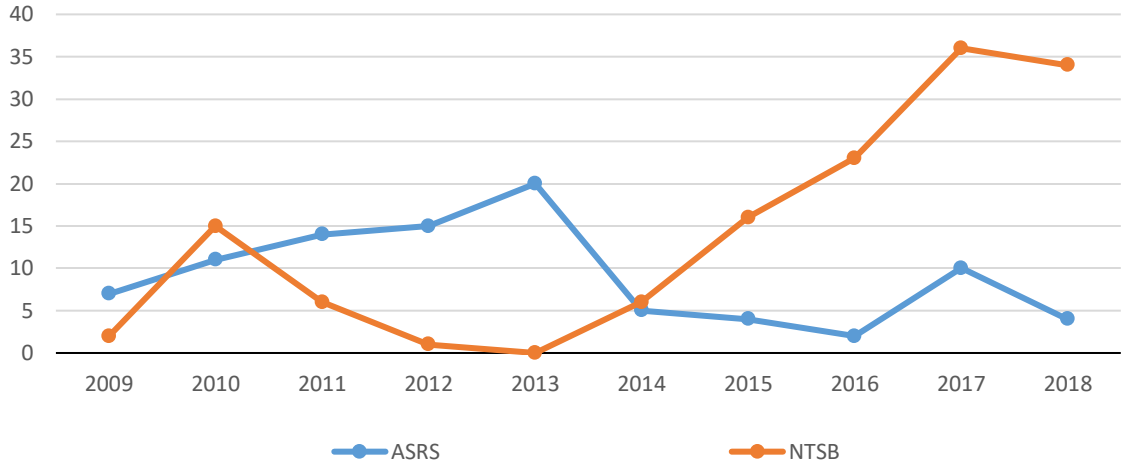


The NTSB recorded two fatal (2) events in 2009 in which onboard weather

equipment was present. One had weather radar, a storm scope weather mapping sensor, and an XM satellite receiver. Weather radar was reported to be present at the second event. Both of these occurrences coincided with thunderstorms. According to the NTSB Form 6120.1 reports, three (3) of the 40 fatal weather-related events in 2017 featured aircraft equipped with onboard weather and ADS-B, but there was no indication that the pilot had used the onboard weather equipment during the accident.

Figure 4

ASRS and NTSB reports were onboard weather equipment reported from 2009 to 2018



ASRS Records Analysis

The ASRS database has 13,552 accident reports from 2009 to 2018, of which 358 (3%) were weather-related. Over this period, the annual number of reports fluctuated from 1,327 in 2009 to 1,166 in 2018 (Table 4). Only 358 (3%) of the 13,552 data filed between 2009 and 2018 indicated that meteorological conditions directly influenced the incident.

Since 2009, the percentage of ASRS reports where the weather was a primary factor in the incident has remained relatively steady, between 2% and 4% of each yearly report. Table 4 shows the most common weather-causative factors identified in ASRS reports. VFR into Mixed, IMC, and Marginal were-the most common elements linked to these occurrences, according to those pilot reports within ASRS. The number of reports in which onboard weather equipment was referenced in the cockpit was counted.

Each year from 2009 to 2018, the percentage of weather-related incidence increased from 2% in 2009 to 4% in 2017-2018; however, the percentage of weather-related accidents to onboard weather equipment was widely variable, from a low of 4% in 2016 to a high of 71% in 2013. Table 4 suggests that the use of onboard weather equipment may be linked to an increase in total weather-related accidents and incidents. Adverse winds, turbulence, and icing are among the most common of these occurrences.

Of all the weather-related accidents each year, flights from VFR into IMC, Mixed, and Marginal weather conditions have shown to be extremely minimal. (Table 4)

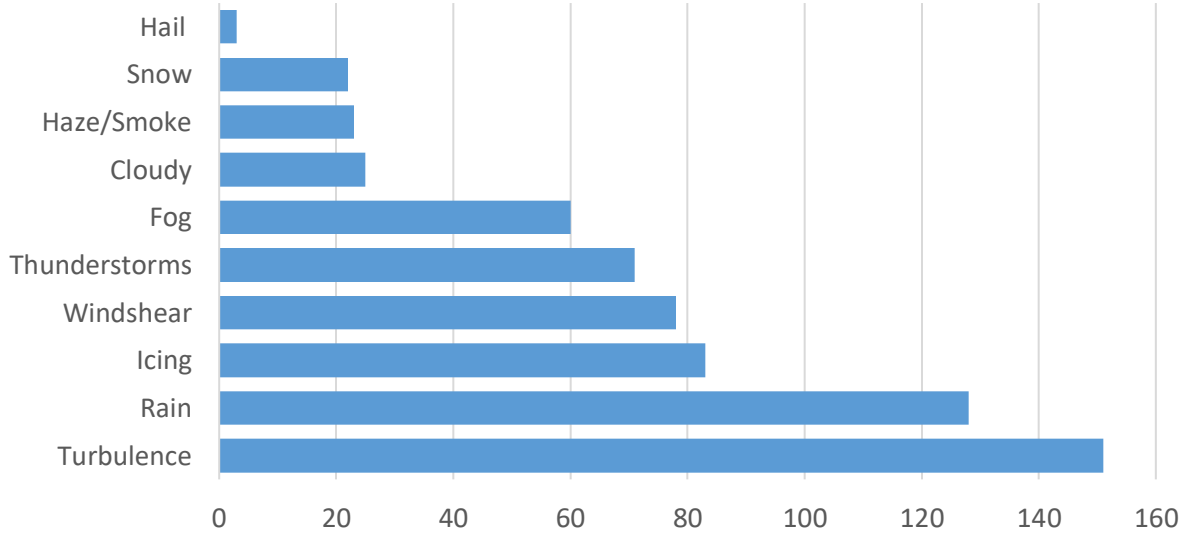
Table 4
Total ASRS Weather Reports showing VMC into IMC from 2009 to 2018

Year	Total Number of Reports	Total Weather-Related Accidents	Onboard Weather Equipment Noted	% OBWE to Total Weather-Related Accidents	VMC to IMC	VFR into MIXED	VFR into MARGINAL
2018	1,166	42	4	10	1	0	1
2017	1,547	62	10	16	2	4	1
2016	1,597	48	2	4	1	2	2
2015	1,580	30	4	13	2	0	0
2014	1,240	28	5	18	1	0	0
2013	1,174	28	20	71	0	0	0
2012	1,402	24	15	63	1	1	3
2011	1,338	42	14	33	0	1	0
2010	1,181	26	11	42	1	0	1
2009	1,327	28	7	25	1	3	1
Totals	13,552	358	92		10	11	9

Note: OBWE - Onboard Weather Equipment

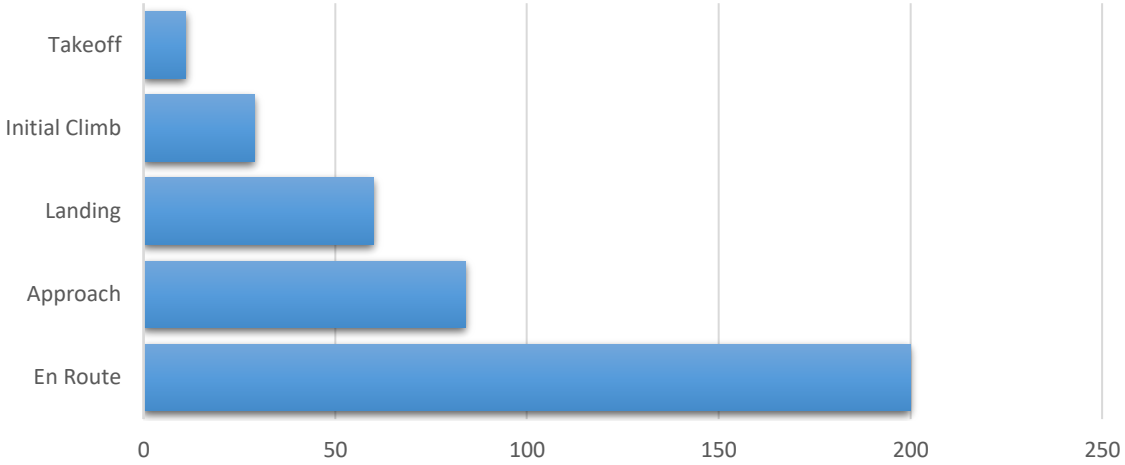
Turbulence accounted for 42 % of the total 358 weather events in the ASRS data, whereas hail accounted for only 0.8 % of the incidences (Figure 5).

Figure 5
ASRS Weather-related accidents and incidence experienced during flight for years 2009-2018



The different incidents that occurred during the various phases of flight are depicted in Figure 6. This was the most-risky flight section, with 52 % of all accidents and incidents occurring En Route. Approaches were responsible for 22% of all flights, while landings were responsible for 16%. The initial rise was responsible for 8% of all flights, while takeoff was responsible for 2%.

Figure 6
ASRS Weather-related accidents or incidents per phase of flight from 2009-2018



Note: Not all reported events stated whether there was a phase of flight associated with the accident or incident.

Conclusion

Interpreting and categorizing narrative data sources into standard categories with minimal bias is difficult because of subjectivity. The most commonly reported weather conditions in NTSB reports were cloudy, gusts, and crosswinds, whereas the ASRS analysis is consistent with widespread knowledge and possibly pilot intuition, with turbulence, rain, icing, wind shear, thunderstorms, and fog as the most frequently reported weather conditions. Winds and overcast conditions were not as dominant a weather-related factor in this study as previous studies suggested.

The use of onboard weather equipment is rarely mentioned in NTSB Accident Reports and even less so in ASRS reports. It was discovered that almost all of the accidents involving onboard weather equipment in aircraft resulted in minor to no injuries. In those accidents that resulted in fatalities, the NTSB made little to no mention of onboard weather equipment in their investigations. As a result, it is impossible to say whether the fatal accidents that occurred during a weather-related event had any operational onboard weather equipment.

After 2011, NTSB Form 6120.1 included a list of Additional Equipment, which included ADS-B, but did not specify whether the equipment had weather capabilities. In those accidents that resulted in fatalities, the NTSB made little to no mention of onboard weather equipment in their investigations. As a result, it is impossible to say whether the fatal accidents that occurred during a weather-related event had any operational onboard weather equipment.

Recommendations

More research into the definition of "onboard weather equipment" is needed. According to the findings of this study, such technologies have evolved in recent years, resulting in a significantly broader range of options. Prior to 2010, most technologies sent

textual information, often in an audio format, such as flight service reports or Automatic Terminal Information Service (ATIS), Automated Weather Observing System (AWOS), or Automated Surface Observing System (ASOS) transmissions; or in-panel radar systems, such as onboard radar or storm scope systems. A new technology category has recently emerged, most notably the development of third-party radar.

There is no connection between the reported use of onboard weather equipment and any other criteria considered during the investigation, such as flight phase or final cause decision. Such findings necessitate further investigation into how the use of onboard weather equipment can be properly included as part of an accident investigation and consistently documented. With the availability of more affordable onboard weather equipment technology on the market, it was expected that the number of reports containing some narrative about the use of such products would increase, particularly for those reports in which weather was a factor.

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