A Review on Weather Impact on Aviation Operations: Visibility, Wind, Precipitation, Icing

From the Editor-in-Chief

August 14, 2023

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Abstract

Meteorological conditions affect aviation, marine, and land transportation, and play an important role in aviation accidents and operations. Wind (Uh), visibility (Vis), and Precipitation rate and amount (PR and PA) are the most important meteorological parameters that affect the terminal weather and in-flight conditions. Weather is considered a causal factor in about 30% of all US aviation accidents (NASA, 1999). Fatal aviation accidents based on the NTSB data related to ceiling, fog, and wind are estimated at 20%, 14%, and 10%, correspondingly. Knowing weather conditions can help to improve operational planning, including fuel consumption and people safety. Wind shear and gust, and turbulence need to be measured or predicted for the flight route and airport terminal weather.

Doi: https://doi.org/10.56801/jaoam.v2i1.1

In addition, low Vis and ceiling are the second most important weather events affecting aviation operations. Lastly, precipitation type, rate and amount are the third important group of parameters that severely affect the flight operations such as de-icing. Earlier analysis of these events suggested that the meteorological conditions need to be studied in detail to better predict and monitor weather conditions for operational needs. In this respect, both observations quality and numerical weather predictions model simulations should be improved, and both new technologies and statistical models such as machine learning and artificial intelligence analysis should be developed for the aviation operations.

1. Introduction

The goal of this review is to emphasize the most important weather events that affect aviation operations and create challenges for plots and ground crew. Although many adverse weather processes, snow storms, low visibility (Vis), and turbulence are interconnected, our intention is to summarize their effect on aviation operations and explain how difficult to study them.

Weather conditions can affect the safety of flights, operations, and lead to financial losses and dead. Henry (1930) emphasizes that the special form of weather, generating hazardous conditions, can be important for aviation operations. These hazards stated by him were mainly fog and sleet. His work also suggested that icing conditions, precipitation types, and instruments should be considered in detail for aircraft safety and training the plots. Fultz and Ashley (2016) stated that weather types affecting aviation operations can be classified to 53 categories. These categories are given by them as (1) temperature, humidity, and pressure, (2) turbulence, (3) convective weather, (4) wind, and (5) ceiling, visibility, and precipitation.

A total of 1520 general aviation accidents during 1995-1998 period suggested that at least one weather condition was a contributing factor for aviation accidents reported by the National Transportation Safety Board (NTSB) (Capabianco and Lee 2001). Their analysis focused on the accident year, injury severity, phase of operation, probable causes, contributing factors, meteorological and light conditions, pilot ratings and pilot experience. Overall, their results suggested that the most prevalent factors in fatal weather accidents were low ceiling (20%), fog (14%), and wind (10%). Precipitation effects on aviation performance was found at about 6% that was related to precipitation.

One of the important factors to study aviation related accidents and fatalities was suggested by Capobianco and Lee (2001) and that was the weather-related interactive conditions. In the aviation community, general aviation (GA) operations are strongly related to weather-related aviation accidents, and this was realized in the earlier studies and are provided below. The NTSB during 2000-2011 indicated that among 19,441 GA accidents, there were about 29% weather related accidents (King et al 2021; Elick 2014). One of the reasons for these accidents was the lack of training.

In respect to training of the pilots, many challenges during preflight planning can exist (King et al. 2018). This work stated that poor weather product interpretation, decision making biases and errors, and inadequate aviation weather experience can play an important role in decision making during the flights. The new technologies such as a preflight decision support systems can be used to guide pilots through the preflight analysis of weather systems. The work of King et al (2021) suggested that weather related accidents generally occur when pilots are operating under Visual Flight Rules (VFR) and inadvertently encounter the Instrument Meteorological Conditions (IMC). This is called as VFR into IMC condition. Overall, both preflight training and good knowledge of weather conditions affect flight planning and consequences. Pilots usually require for evaluating meteorological conditions and analyze the Meteorological Terminal Air Report (METAR), Pilot Reports (PIREPS), and Terminal Airport Forecasts (TAFs) (Lanicci et al., 2012; Parson et al., 2005).

The Terminal Aerodrome Forecast (TAF), Aerodrome Routine Meteorological Report (METAR), irregularly issued Special Meteorological Report (SPECI) as well as remote sensing platform observations can help the pilots to visualize the weather conditions and to take caution in adverse weather conditions (Novotny et al 2020).

Weather is considered to being a causal factor in about 30% of all US aviation accidents (NASA, 1999). Weather knowledge is critical for aviation operations i as documented by the FAA (report # Preflight Guide v. 1.1, Table 1). This report provides a weather synopsis, sky conditions, and Vis as well as weather conditions at the departure, en-route, and destination points. The weather conditions, having the cloud tops, dew point, icing conditions, surface winds, winds aloft, temperature, thunderstorm activity, precipitation, precipitation intensity, and visibility obscuration, should be included in the briefings that cover PIREPs, AIRMETs, SIGMETs, and Notices to Airmen (NOTAMs) (NOAA 1998). AIRMET and SIGMET weather advisories are issued to warn pilots for potentially hazardous weather conditions in an area. The AIRman's METeorological Information (AIRMETs) are less severe and consist of turbulence, visibility, and icing. The Significant Meteorological Information (SIGMET) is more severe, including thunderstorms, tropical cyclones, volcanic ash, and dust storms, or similar. The ASOS and AWOS (Automated Surface Observing System and automated weather Observing System) broadcasts can also be used for the enroute weather conditions that include Vis conditions and possible some icing info (NOAA, 1998).

Based on the above studies, how important weather conditions for aviation operations can be seen by analyzing the recorded deadly accidents. The Canary Islands, KLM flight 4805 in 1977 lost the top off the Pan Am flight 1736 during a takeoff, and weather reports indicated heavy fog/low visibility covered the airport during the accident. This accident led to killing of 574 people (Dreifus 1978). There are many other fog related aviation accidents that indicated how dangerous fog and low visibility conditions (Gultepe et al 2019a,b) and this work stated that fatal accidents due to fog and low visibility financial losses can easily reach to a few million dollars to commercial travel companies.

Since air travel is a significant contributor to climate change, a resolution was passed by IATA member airlines at the 77th IATA Annual General Meeting in Boston, USA, on 4 October 2021, committing them to achieving net-zero carbon emissions from their operations by 2050. Achieving this goal will require a combination of maximum elimination of emissions at the source, offsetting and carbon capture technologies. The plan advocates for using Sustainable Aviation Fuel (SAF) and redeveloping old technology by creating better engines, modeling more aerodynamic planes, and employing technology that ensures planes travel as quickly as possible while leaving the smallest possible carbon footprint. Furthermore, aviation fuel and engines are evolving, with the industry evaluating hydrogen, creating biofuels, and inventing new cleaner mixtures. Likewise, the concept of electric airplanes is widely popular. Finally, the industry is reimagining its daily operations in an effort to reduce flight duration, shorten routes, and become more sustainable overall. The process will be lengthy, but the industry has already made tremendous progress.

Fuel efficiency:

Fuel efficiency gains more and more importance not only for environmental reasons but also as a major contributor to airline's financial efficiency. Since nearly three decades ago, the availability and cost of aviation fuel have remained one of the most significant economic factors affecting the airline industry. Alternative fuels have not had a significant impact; consequently, maintaining fuel efficiency is one of the aviation industry's primary challenges. Jet fuel prices put financial pressure on airlines and travelers. According to the latest IATA's jet fuel price monitor, global prices in December 2022 were about 50 percent higher than in December 2021. This rise is largely due to the sanctions on Russian oil and gas put in place as a response to the war in Ukraine. Given that fuel can account for as much as 40 percent of annual expenditures, this is obviously a concerning development for airlines. The degree to which airlines are affected depends on their fuel hedging strategies.

On this respect, freezing fog and ice fog can also play an important role in the accidents occurring northern airports but these were not studied in detail (Gultepe et al 2019).
In addition to low Vis and wind impact conditions on aviation operations, both icing and snow precipitation can also lead to serious accidents. NTBS reported in 1982 that 78 people were dead after Air Florida flight 90 accident after takeoff. Icing conditions on the aircraft surfaces, wings, and tail can reduce the lifting meanwhile increasing the drag, leading to underestimated aircraft position and even malfunctioning aircraft navigation system (Leroy et al 2017; Politovich and Bernstein 1995; Politovich 1989; Lewis 1947). Freezing fog conditions can also lead to icing conditions in airports and taxing aircraft surfaces (Gultepe et al 2017a,c).

The goal of this work is to review the preexisting conditions that can lead to aviation accidents covering financial losses and dead. In the following section, wind and turbulence conditions, as the most significant weather factors related to aviation accidents will be evaluated, and other factors such as freezing precipitation and icing will be discussed.

2. High Impact Weather

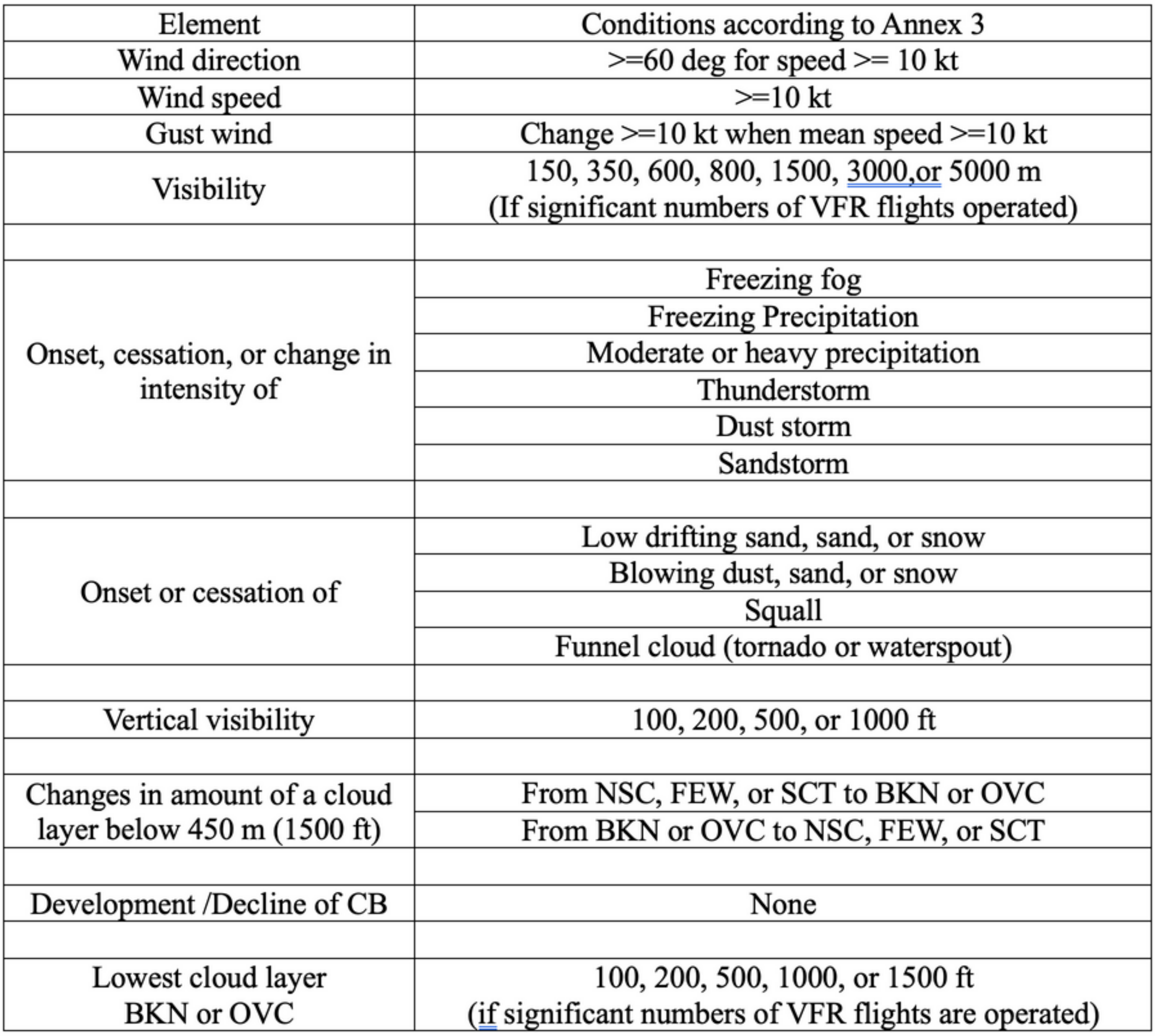
In this section, the most important weather events are summarized and their role in affecting flight operations are described.
High impact weather can be defined as the weather events that interrupt the regular life systems extensively such as tornadoes, hurricanes, wind shear and gust, snow-storm, freezing fog and precipitation, heavy fog, high temperatures, as well as floods and droughts. These weather events interrupt social and economic life. All these also affect aviation operations, including flight path and terminal weather planning. Gultepe and Feltz (2019a) provided a detailed review on aviation meteorology that emphasized important issues affecting aviation operations. These issues, using observations and model-based results, are described in their study.

The TAFs are important for the aviation weather operations (Hansen et al 2010)). In comparison with METARs and SPECIs, TAFs provide specific weather info for the airports landing and takeoff conditions (ICAO 2018; Table 1). Clearly weather events can be subdivided to represent unique weather conditions (Novetny et al 2021) to minimize the possible accidents during terminal landing and take-off.

Figure 1 suggests that weather impact on aviation related accidents is about 30%. Lee et al (2009) stated lately that turbulence intensity and its occurrence will increase if climate change happens. Climate change is a major global issue, affecting aviation operations, environmental development and structures related to airports. The recent climate changes are presently giving a lot of concern to the aviation industry (Abbas et al 2012). Climate change presents significant challenges for the aviation sector (Burbidge et al. 2023). First, the sector's impact on climate, including both CO2 and other greenhouse gas (GHG) emissions, and non-CO2 effects needs to be reduced. Second, adaptation to the changing climate is required. Changing climate also affect air density and aircraft performance depends on density altitude. Density altitude depends on air temperature (T), pressure (P), and relative humidity (RH) (Goodman and Griswold 2018). Lower air density leads to the higher drag forces that negatively impacts the the engine performance and lift. Therefore, reducing the maximum weight of the aircraft and increasing the distance are required to achieve safe takeoff and landing (Coffel and Horton 2015).

Nowcasting of wind and related parameters such as turbulence is a critical parameter at the airports, as well low-level wind shear, turbulence, and gust that play an important role for terminal weather. Verified against observations, Doppler wind lidar and an AWOS, and 3D sonic anemometers can be used for the low-level wind (LLW) shear event detection that can be used for the evaluation of the temporal and spatial features of the boundary layer (BL). Without Doppler lidar, spatial and time scales of low-level wind shear cannot be accurately mapped (Thobois et al 2019; Li et al 2020).

Table 1: The criteria used for the inclusion of change in the TAF presentations (ICAO App5 1.3). The NSC, no significant clouds; FEW, few clouds; CB, cumulonimbus



Element	Conditions according to Annex 3
Wind direction	>=60 deg for speed >= 10 kt
Wind speed	>=10 kt
Gust wind	Change >=10 kt when mean speed >=10 kt
Visibility	150, 350, 600, 800, 1500, 3000,or 5000 m (If significant numbers of VFR flights operated)
Onset, cessation, or change in intensity of	Freezing fog
	Freezing Precipitation
	Moderate or heavy precipitation
	Thunderstorm
	Dust storm
	Sandstorm
Onset or cessation of	Low drifting sand, sand, or snow
	Blowing dust, sand, or snow
	Squall
	Funnel cloud (tornado or waterspout)
Vertical visibility	100, 200, 500, or 1000 ft
Changes in amount of a cloud layer below 450 m (1500 ft)	From NSC, FEW, or SCT to BKN or OVC
	From BKN or OVC to NSC, FEW, or SCT
Development /Decline of CB	None
Lowest cloud layer BKN or OVC	100, 200, 500, 1000, or 1500 ft (if significant numbers of VFR flights are operated)

The microphysics of clouds and fog are the most important events that affect visibility (Gultepe et al 2017a,b; Gultepe and Heymsfield 2016) and the icing rate (Gultepe et al 2006a) that play a major role on aviation operations. Earlier studies emphasized the importance of icing on the airplane flight characteristics including lifting and drag conditions. Bernstein et al (2005) developed an algorithm using both model based simulations and observations; suggested that icing predictions are improved significantly. Current Icing Potential (CIP) product (developed by Bernstein et al 2005), showing icing potential, are being used by FAA operations (Kulesa 2002).

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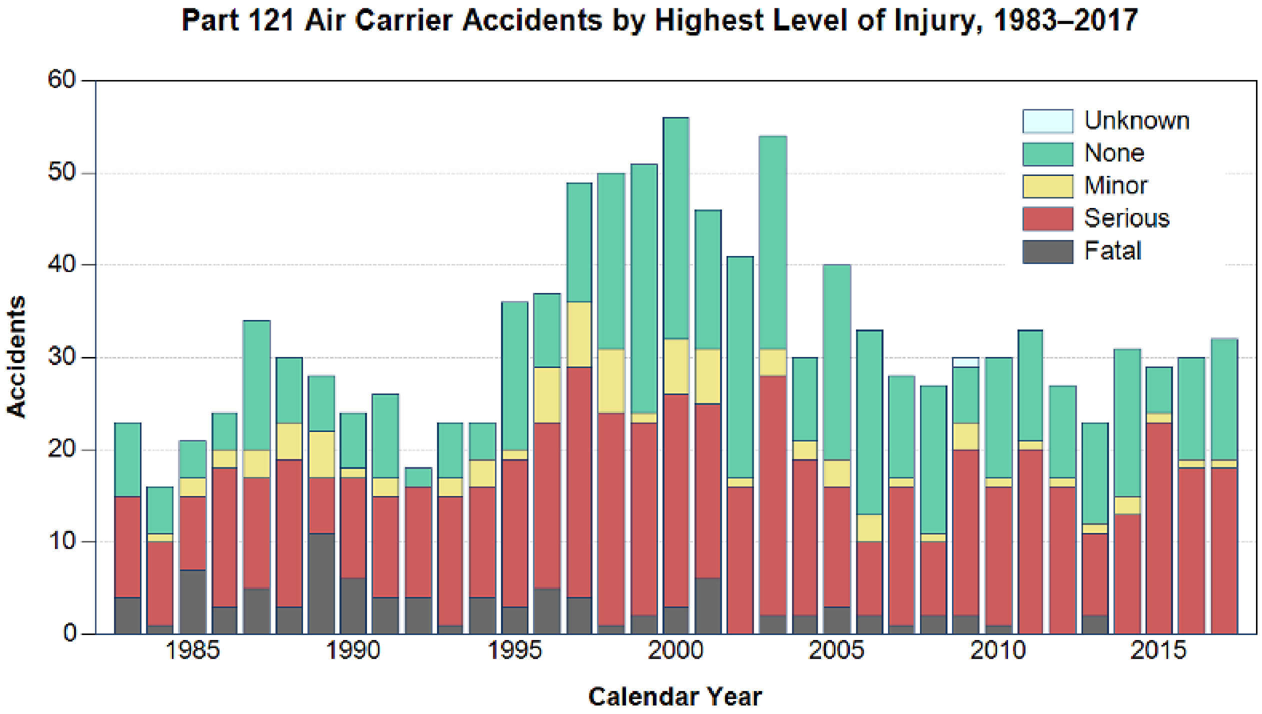

Figure 1: Part 121 Air Carrier Accidents by the highest level of Injury from 1983 to 2017 (Adapted from NTSB 2020)

Visibility is affected by the precipitation, cloud and fog, and aerosols as well as dust particles. A definition of visibility is given as that an eye can detect a white object compared to dark background, and its definition is given based on extinction coefficient and particle size distribution, transmitted radiation radiation wave length, and extinction efficiency parameter (Kunkel 1984, Gultepe et a 2006b). Particle shape for the ice crystals, leading to irregular scattered and absorption radiation and chemical composition affect extinction light (Gultepe et al 2015). Overall, extinction of light in a volume is the strong function of density, concentration of the particles, and their size, and a path that is taken by transmitted radiation.

Other weather events affect the aviation operations through low visibility is the winter storms with heavy snow accumulation related to strong winds and rain-storms and convective systems that include tornadoes, hurricanes, and tropical storms (NTSB 2014; 2005). Heavy precipitation, rather than fog, can also influence visibility, aircraft surface mass loadings, and deicing due to freezing precipitation. Therefore, aircraft hold-off time can be extended due to freezing precipitation that severely affects aircraft operations. It should be noted that environmental conditions can be affected by the chemical used in the deicing of the aircraft during winter conditions.

3. Observing Systems for aviation weather

Weather instruments used for aviation operations can include ground based in-situ and remote sensing platforms, airborne platforms, and space borne systems such as satellites. Overall, integration of these observations with NWP models can also be used for weather decision support systems. The Automated Surface Observing System (ASOS, Landolt et al 2020) is one of the primary weather observing systems in the United States that includes over 900 stations across the country. These systems are maintained and supported by the multiple organizations such as NOAA National Weather Service (NWS), Federal Aviation Administration (FAA), and Department of Defense (DOD).

Most of these systems are located at airports and provide meteorological observations used in developing aviation routine weather reports (METARs) and TAFs that are critical for aircraft operations (Landolt et al 2020).

The ASOS provides standard meteorological measurements of temperature, pressure, humidity, wind velocity, sky condition, visibility, obstructions to visibility, and liquid equivalent precipitation accumulation (Landolt et al 2020). The ASOS can also provide a limited determination 0f the precipitation types that includes rain, snow and freezing rain or drizzle. Rain and snow observations are derived using the Light Emitting Diode Weather Identifier (LEDWI) sensor measurement and ambient air temperature. The LEDWI operates based on the frequency change in an emitted light beam. Hydrometeors passing through the beam introduce different frequencies that are a function of the size and fall velocity of the hydrometeors (Starr and Wang 1989; Wade 2003). Icing sensor used on the ASOS has the small, vertically pointing rod at the top for detecting icing conditions.

In addition to ASOS systems, individual sensors are also used for visibility, and precipitation type detection called the present weather detectors (PWDs). These are commonly used for precipitation type and visibility at the airports and became part of the larger observing systems (Gultepe et al 2021a; 2019a,b). Visibility used in ASOS systems can be measured by the transmissiometer (Wang et al 2023; Perelet et al 2021), optical instruments (present weather sensors (PWDs) such as Sentry ad PWD50, and particle measuring instruments (Gultepe et al 2019a,c) (FM120, CDPs and BCP by DMT Inc.). Most common PWDs are Sentry and PWD50, as well as FD70p (Minder et al. 2023). The Vis measurements usually are performed at the airport weather stations for METARs and pilot presented PIREPS. Aircraft based sensors such as AMDAR (Aircraft Meteorological Data Relay) system is initiated by WMO. The AMDAR system provides approximately 700000 high-quality observations per day that includes temperature, pressure, wind speed and direction, humidity, and turbulence as well as navigation information. Sherman (1985) suggested use of AMDAR measurements for gust estimation in Australia.

The AMDAR knowledge specifically provides sounding observations near the airports. The WMO and International Air Transport Association (IATA) is working on developing a collaborative study to enhance AMDAR observations for both aviation and weather communities (WMO 2014).

Radars and lidars are also used for aviation weather predictions, specifically at the airports (Thobois et al 2019; Li et al 2020;Lakshmanan and Smith 2009). The Multi-Radar Multi-Sensor (MRMS) system (Zhang et al 2016) is now operational at the National Centers for Environmental Prediction (NCEP) (Smith et al 2023). The MRMS system consists of the Warning Decision Support System–Integrated Information (WDSS-II; Eilts et al 1995; Lakshmanan and Smith 2009) suite of severe weather and aviation products that uses the quantitative precipitation estimation (QPE) products (Zhang et al. 2011). The MRMS system provides operational guidance for severe convective weather, QPE, and aviation hazards on a 3D grid system created at a spatial resolution of 0.01°at 33 vertical levels per 2 min time intervals over the United States (CONUS) and southern Canada.

Aviation products based on satellite observations include icing, visibility, and cloud and fog microphysics, as well as surface and upper atmospheric products for convective activity and turbulence (Smith et al 2023). Presently, fog and visibility conditions for marine environments can be obtained using geostationary satellites such as USA GOES-R (Gultepe et al 2021a; Smith et al 2023), Japanese HIMAWARI (Huang et al 2019), and Korean GOCI-I-II; GK2A (Kim et al 2021). These satellite products are also used in the aviation weather decision systems and include ML and AI techniques.

4. Wind and Turbulence

In addition to visibility, precipitation, and icing, wind and gust, turbulence, wind shear, gust, and microburst (McCarthy 2022) can also be critical for aviation accidents assessment.

Gao and Fu (2019) stated that a low-altitude wind shear can affect aircraft flying into dangers during takeoff and landing. According to their study, flight phases of takeoff and landing only occupy 6% of the total flight time of civil aircraft. However, 61% aviation occurs during takeoff and landing. They also stated that 66% of accidents during takeoff and landing are the result of wind shear or pilots' response to wind shear. Further studies of Sharman et al (2006) and, Frehlich and Sharman (2004) showed that wind related dynamical weather conditions significantly affect aircraft flight conditions. Lately, Burbidge (2023) study suggested that due to climate change, atmospheric wind conditions are also changing. Non-convective turbulence in clear environments such as clear air turbulence (CAT) is also a major aviation hazard when it occurs along the planned flights. All aircraft, depending on their physical characteristics and weight, can be influenced by the turbulent motions and wind shear (Kulesa 2002; Sharman and Lane 2016; Sharman et al 2014). Kim and Chun (2010) studied turbulence occurrence over South Korea from 1957 to 2020s and stated that turbulence is responsible for 24% of the aircraft accidents caused by weather. This makes it a significant contributor to weather-related accidents. Aviation and Railway Accident Investigation Board (ARAIB) provides this finding available at http://www.araib.go.kr]). Their work emphasized the how important turbulence and wind effects for assessing the aircraft related accidents. Aviation turbulence can be generated by the convective systems (Kim and Chun 2011) Pantley and Lester 1990; Lane et al.2003), jet streams along with upper-level fronts (Dutton and Panofsky 1970; Ellrod and Knapp 1992), complex terrain (Clark et al. 2000; Doyle et al. 2005), and inertial instabilities (Koch et al. 2005; Knox et al. 2008). Main reason for turbulence occurrence is not well documented but micro-scale wind motion and spatial distribution of atmospheric conditions can explain some conditions leading to turbulence formation (Lane et al. 2003, Lane ad Sharman 2008; Kim and Chun 2011). The CAT (Clear-air turbulence) can occur et various levels and has a major impact on efficiency of flight planning, rerouting, and delays.

Based on statistics published by the NTSC records, atmospheric turbulence is the major source of aircraft accidents and deteriorates the riding comfort. On the other hand, significant risks and financial lost are possible with turbulence and gust, and these include fuel loss, aircraft structure damages, and human injuries. This suggests that the turbulence and CAT should be analyzed in more detail.

One of the major wind-related phenomena called microburst is the result of wind shear while aircraft taking off or landing, and that lead to several aviation accidents. Wind shear accidents have been responsible for more than 1,400 fatalities worldwide since 1943 that includes 400 deaths in the USA from1973 to 1985 (McCarthy et al 2022). Fujita (1976) hypothesized that a low-altitude wind shear can can be a good reason the aircraft crashes. He named this phenomenon a "downburst" and later he named it as a small-scale downbursts phenomena with a diameter of less than 4 km and called it as "microbursts" (Fig. 2). This was the scale most dangerous to commercial aircraft (McCarthy and Wilson 1984 After his work, Robert Serafin and Clifford Murino of the National Center for Atmospheric Research (NCAR) (McCharty et al 2022) suggested to use NCAR's Doppler radars to verify the existence of downbursts.

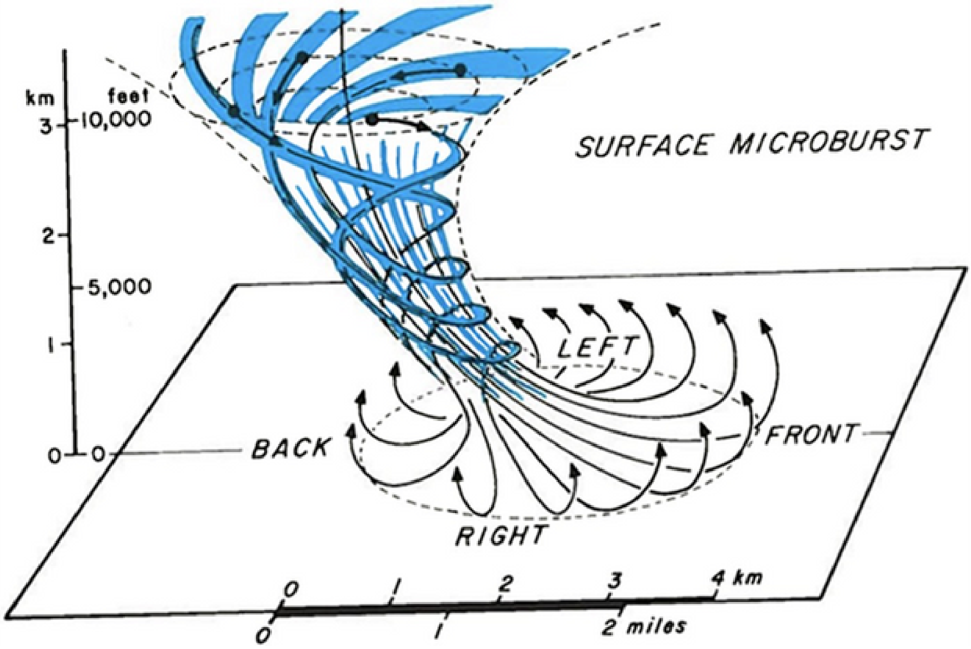

Figure 2: Schematic view of the airflow associated with a microburst. In this case, the downdraft is rotating prior to spreading out horizontally upon striking Earth's surface (Fujita 1985). Adapted from McCarthy 2022)

Airborne measurements for turbulence studies can be done using pilot weather reports (PIREPs) and aircraft in-situ measurements. PIREPs have been widely used for aviation applications because of their wide coverage in space and time. (Boeing Jeppesen Comp, 2014). But subjective judgment of turbulence assessment can lead to an uncertainty I the turbulence intensity, timing, and location. Therefore, the use of in situ airborne data has been used o obtain more accurate observations (Kim et al 2010). The indicators of turbulence severity the are the Vertical Acceleration (VA) , Derived Equivalent Vertical Gust velocity (DEVG) (Gill et al 202014), and Eddy Dissipation Rate (EDR) (Sharman and Pearson 2017; Gill 2014; Cornman et al 1995). The commonly used VA indicator is called as RMS-g (Root Mean Square of vertical acceleration divided by 1-g) (Michael et al 2018). This method cannot reflect the objective turbulence severity; therefore, using airspeed and aircraft mass an improved DEVG still cannot represent turbulence occurring in the atmosphere satisfactorily (Gill 2014). To remove these deficiencies, the new EDR estimation algorithm that uses measured vertical wind speed, and/or aircraft vertical acceleration provide an objective and aircraft-independent indication of turbulence intensity. Lately, acceleration-based in situ EDR estimation with flight data was suggested by Gao et al (2020) ad that can improve in-flight EDR estimation.

Wind is the contributing factor of weather-related accidents occurred between 2003 and 2007 (Figure 3), with 1149 citations almost half of the contributing factor citations in the accidents studied). FAA (2010) study clearly indicated that wind was the one of the most important factor in the aircraft accidents but fatality can be much higher in low visibility conditions. Wind is a 3D movement of air currents across the Earth’s surface as a result of pressure differentials, temperature changes, elevation differences, and the Coriolis force. The largest number of wind citations is given in part 91 operations. There were 1,047 wind citations in part 91 compared to 53.4 percent of all part 91 (FAA 2014) weather-related citations.

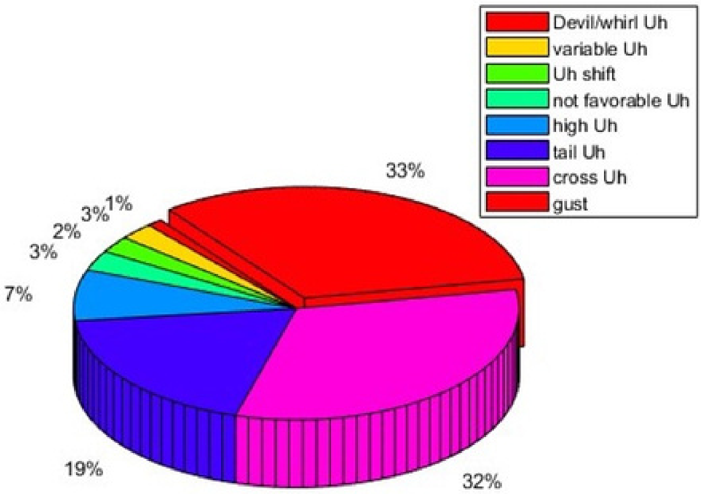

Figure 3: Wind Citations 2003–2007 based on NTSB Aviation Accident and Incident Database (AAID). Wind related 51.7%, other weather related are 48.36% that was part of 2223 citations.

The large number of wind citations occurred during the takeoff or landing phase of flight under the various weather conditions (NTSB 2020). Turbulence is the fluctuations of wind speed in 3D flow. Accidents citing turbulence is found to be a contributing 4th factor in 114 citations (see figure 1). The majority of the 114 citations was found in part 121 operations with 42 turbulence citations (65.6%). Windshear is a sudden in wind speed in the same various directions over a given time-period. Its occurrence can be related to topography, storm systems, jet streams as well as downbursts. An encounter with windshear can create conditions to maintain the control of an aircraft. Some airports have low-level windshear alert systems to warn pilots for the windshear. Thirty-seven weather-related citations in the study (1.7 %) were attributed to windshear. The 1.7% (37 items), and 1.8% (35 items) of weather-related accidents are part of 1960 citations in part 91 citations. The only two citations are in part 135 operations.

The air carrier accidents between 1983 and 2017 (NTSB, 2020) suggested that fatal injuries are in decrease. The accidents due to weather conditions is approximately 25%, and high impact weather conditions still play an important role in aviation accidents. Although fatal injuries are decreasing, flight planning due to weather conditions still lead to very high financial losses to commercial travel companies (Gultepe et al 2009).

Approximately 23,000 aircraft operated by more than 2,000 airlines carry more than 2.2 billion passengers annually at the 3,750 airports in the world (www.oagaviation.com) (Brasseur and Gupta 2023). Mostly flights are done at cruise altitudes between 8 and 13 km. Aircraft engines usually emit carbon dioxide (CO2), water vapor (H2O), nitrogen oxides (NOx), sulfur oxides (SOx), hydrocarbons (HC), and soot particles. The impact of aviation on climate (Moon et al 2022), the microphysical, dynamical, and optical properties of contrails should be studied. The scavenging of chemical compounds by ice particles from the atmospheric layers, including the role of heterogeneous chemistry (aerosol and ice phase) need to be further studied and details can be found in Brasseur and Gupta (2016) and Lee et al (2009).

In the next sections, high impact weather conditions on aviation operations will be summarized, and then it will be followed up by future challenges and expectations.

5. Visibility and Ceiling

Visibility is the one of the major meteorological parameters that affects aviation operations severely. Based on the NTBS analysis, Vis effects on the aircraft related delays are about 30-35% of times and its fatality is #1 compared to other weather-related accidents (Gultepe et al 2019b; 2007). Therefore, its prediction and measurements are very important for aviation planning and developing algorithms. Table 1 shows the visibility and ceiling criteria used in visibility predictions.

Table 2: FAA Report # Weather Decision-Making Guide v. 1.1 Aug 06

Category	Ceiling height (Ch) [ft]	Condition	Visibility (Vis) [miles]
VFR	Ch>3000	And	Vis>5 miles
Marginal VFR	1000< Ch <3000	And/Or	3<Vis<5
IFR	500< Ch <1000	And/Or	1<Vis<3
LIFR	Ch<500	And/Or	Vis<1

A study of NTSB statistics (Kulesa 2002) indicated that ceiling and visibility were cited as contributing factors in 24 percent of all general aviation accidents between 1989 and early 1997.They were also cited as contributing factors in 37 percent of commuter/air taxi accidents during the same period. Low ceiling and poor visibility accidents occur generally when pilots are not properly trained or ready for flying an aircraft not equipped with sensors properly that they are not used for the control, or controlled flight into terrain. National Transportation Safety Board (NTSB) reports that weather is in fact a primary contributing factor (~23%) of all aviation accidents (Kulesa 2002). A study of FAA (2010) based on the NTBS data archive suggested that at least 18% of weather-related accidents due to low Vis and ceiling conditions (Fig. 4). Figure 4 summarizes 2223 weather related accident citations that are related to various low Vis conditions. Visibility and ceiling are also very critical delays of aircraft taking off and landing. Figure 3 suggests that delay hours in the National Airspace System for January 2001 to July 2002 peaked at 50,000 hours per month in August 2001, and declined to less than 15,000 per month for the months following September 11. Again, it exceeded 30,000 per month in the summer of 2002. Weather delays comprise the majority of delays in all seasons and fog and low visibility are the most important critical parameters.

Visibility can be reduced due to aerosols, dust, moisture, fog and cloud droplets and ice crystals, as well as precipitation size particles (Gultepe et al 2015; Rasmussen et al 1999; Gultepe and Milbrandt 2010). There are various fog types that can be classified thermodynamically as warm fog, cold fog, and mixed-phase fog (See Gultepe et al 2017a,b; 2019). Based on its occurrence reason, fog types can be listed in many ways such as radiation fog, frontal fog, precipitation fog, upslope fog, valley fog or cold pool fog, advection fog, steam fog, ice fog, and freezing fog. All these fog types need a nuclei population and cooling mechanism for the nucleation. Fog is defined as Vis<1 km based on aviation perspective. When Vis is between 1 and 2 km due to droplets is called mist. If no droplets involved, low visibility condition is called as haze and forms due to aerosols and dust particles in which Vis is more than 2 km (Gultepe et al 2016).

Figure 5 shows the visibility related particles and hydrometeors that affect Vis significantly. This figure suggests that fog, clouds, and ceiling are mot critical meteorological events that lead to aviation related accidents under the low Vis conditions.

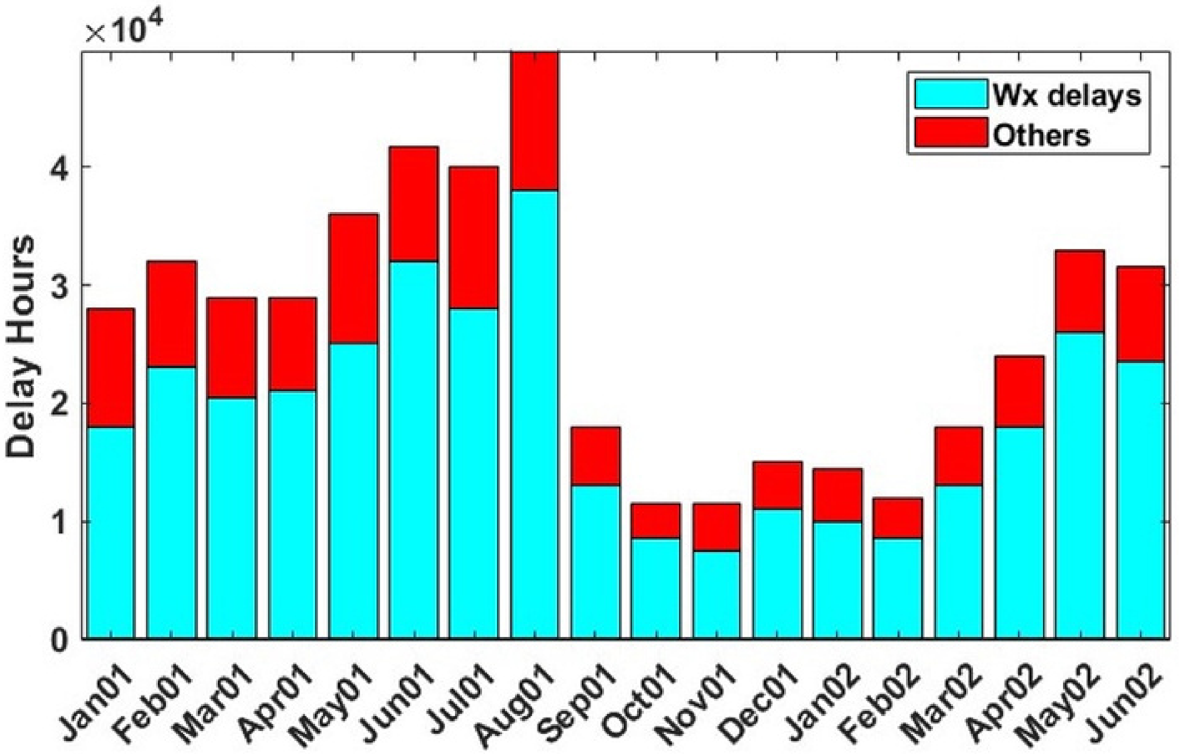

Figure 4: Delay hours in the National Airspace System for January 2001 to July 2002. See text for details on this figure (adapted from Kulesa 2002)

Visibility prediction based on the NWP models is critical to evaluate the inflight and terminal flight operations. For this reason, visibility in NWP models is obtained in 2 ways; 1) using bulk parameterizations based on 1) predicted Nd and LWC using microphysical parameterization (MP) (Gultepe et al 2006b; 2019c) and correspondingly Ni and IWC), or 2) using MP schemes that assumes PSDs for fog/cloud droplets and precipitation (see Gultepe et al 2017b). What important in these calculations is that nucleation processes are not well known; therefore, Nd and Ni cannot be parametrized accurately (DeMott et al. 2003). Usually, single moment and double moment MP schemes are used for Nd (Ni) and LWC (IWC) (Gultepe et al 2017b,c) but Nd is not a direct prognostic variable.

In the PSD models, gamma size distribution type is used extensively in MP algorithms; then, these MP products are used obtain Vis. In fact, both Nd or Ni are still not predicted directly but obtained using thermodynamical parameters such T and RH as well as assumed aerosol number concentrations as well as chemical composition type (Mazoyer et al 2017). The most commonly used Vis calculation types are Stoelinga and Warner (1989) for clouds and precipitation; and for fog are Gultepe et al (2007b). Later suggested that Nd (or Ni) should be included in the parameterizations, not only LWC (or IWC) as suggested by Stoelinga and Warner (1989). Overall, there are other MP Vis parameterizations suggested by (Song et al 2019; Long et al 2021) but these represent some variations of Gultepe et al (2007) . Except the work of Gultepe et al (2007), Kunkel (1984), Song et al (2019), and Wagh et al 2022, there are also other parametrizations that utilize RHw and dew point temperature depression (Boudala et al 2012) but they are not based on microphysical information; therefore, their usage is limited.

NWP models have various resolutions from 10s of km down to m scales because of this grid area is not always filled up with fog or cloud droplets; therefore, threshold of RHw for fog formation changes. In fact Ta-Td difference if close to zero it means RHw~100%. This is true for saturation of air and fog formation but doesn’t tell fog intensity e.g., Vis. Over marine environments, 95% of RHw can indicate the fog formation because salt particles’ hygroscopicity is usually high. This suggests that un-physical use of T-Td difference may not work for Vis prediction but its existence with yes/no criteria. Another issue is that at the same volume with a fixed RHw and LWC, you can get various Nd values that play a critical role in Vis estimation (Gultepe et al 2007; 2009).

It is found by earlier studies that Vis and cloud-based ceiling can be responsible for 16-17% of the weather related aviation accidents (NTBS 2014; 2020; Figure 6a; Gultepe et al 2019b). One of the difficulties to obtain Vis prediction accurately is to use MP assumptions related to nucleation parameterizations. Fog variability as a function of time and space scales also create difficulties timely predicting low Vis location.

Of course, developing space technologies such as using satellite (Gultepe et al 2007; 2021b) and radar-based observations can improve the Vis prediction and monitoring that can be used in integrated weather systems. Lately, AI techniques based on both observations and model predictions are being used and suggested that these AI based techniques improved Vis predictions (Gultepe et al 2023).

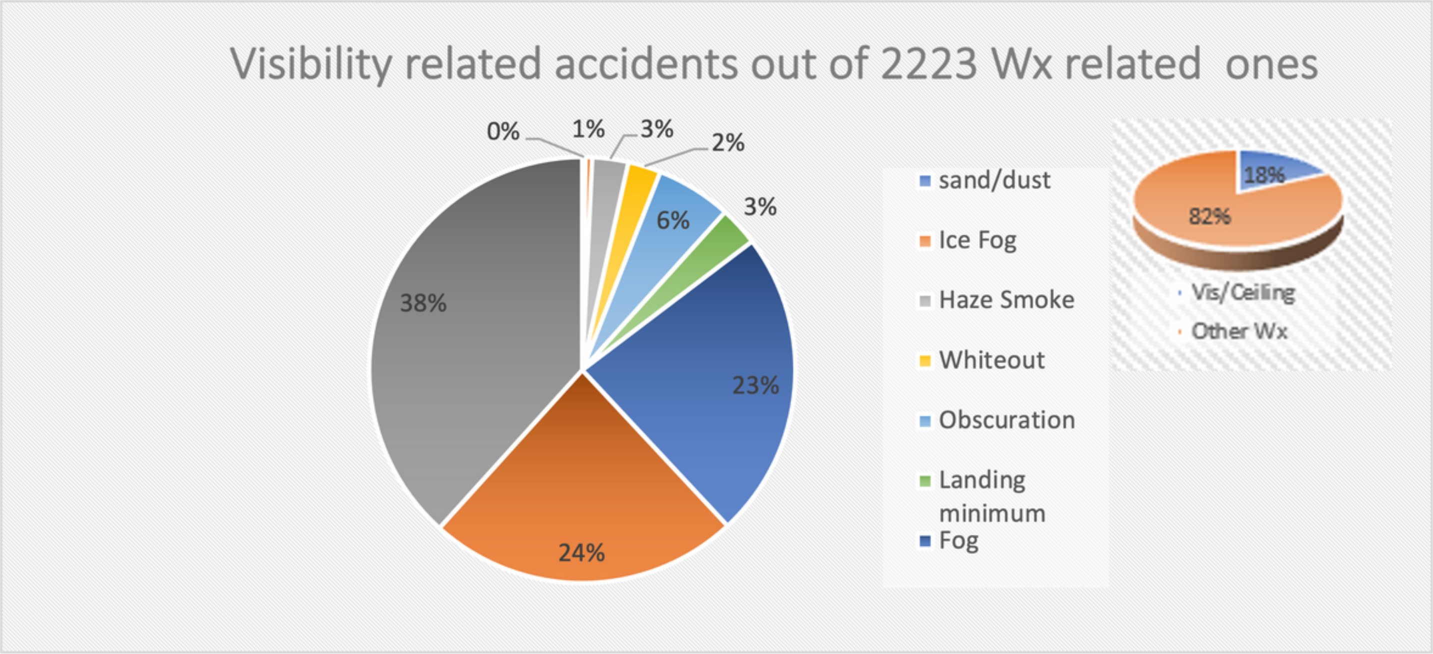

Figure 5: Visibility/ceiling citations for the period of 2003–2007. Adapted from FAA (2010) data source called Aviation Accident and Incident Database (AAID)

It is found by earlier studies that Vis and cloud-based ceiling can be responsible for 16-17% of the weather related aviation accidents (NTBS 2014; 2020; Figure 6a; Gultepe et al 2019b). One of the difficulties to obtain Vis prediction accurately is to use MP assumptions related to nucleation parameterizations. Fog variability as a function of time and space scales also create difficulties timely predicting low Vis location. Of course, developing space technologies such as using satellite (Gultepe et al 2007; 2021b) and radar-based observations can improve the Vis prediction and monitoring that can be used in integrated weather systems. Lately, AI techniques based on both observations and model predictions are being used and suggested that these AI based techniques improved Vis predictions (Gultepe et al 2023).

Overall, low visibility/ceiling was the second largest cause or contributing factor in weather-related accidents, with 402 citations over the 5-year study period and It was the leading weather-related accident category in part 135 operations, with 46 citations. Visibility/ceiling ranked second on the list of causes or contributing factors in part 91 operations and accounted for 350 of 1,960 total weather-related citations (17.8 percent) (Eick 2014, 2022; NTSB 2005, 2020).

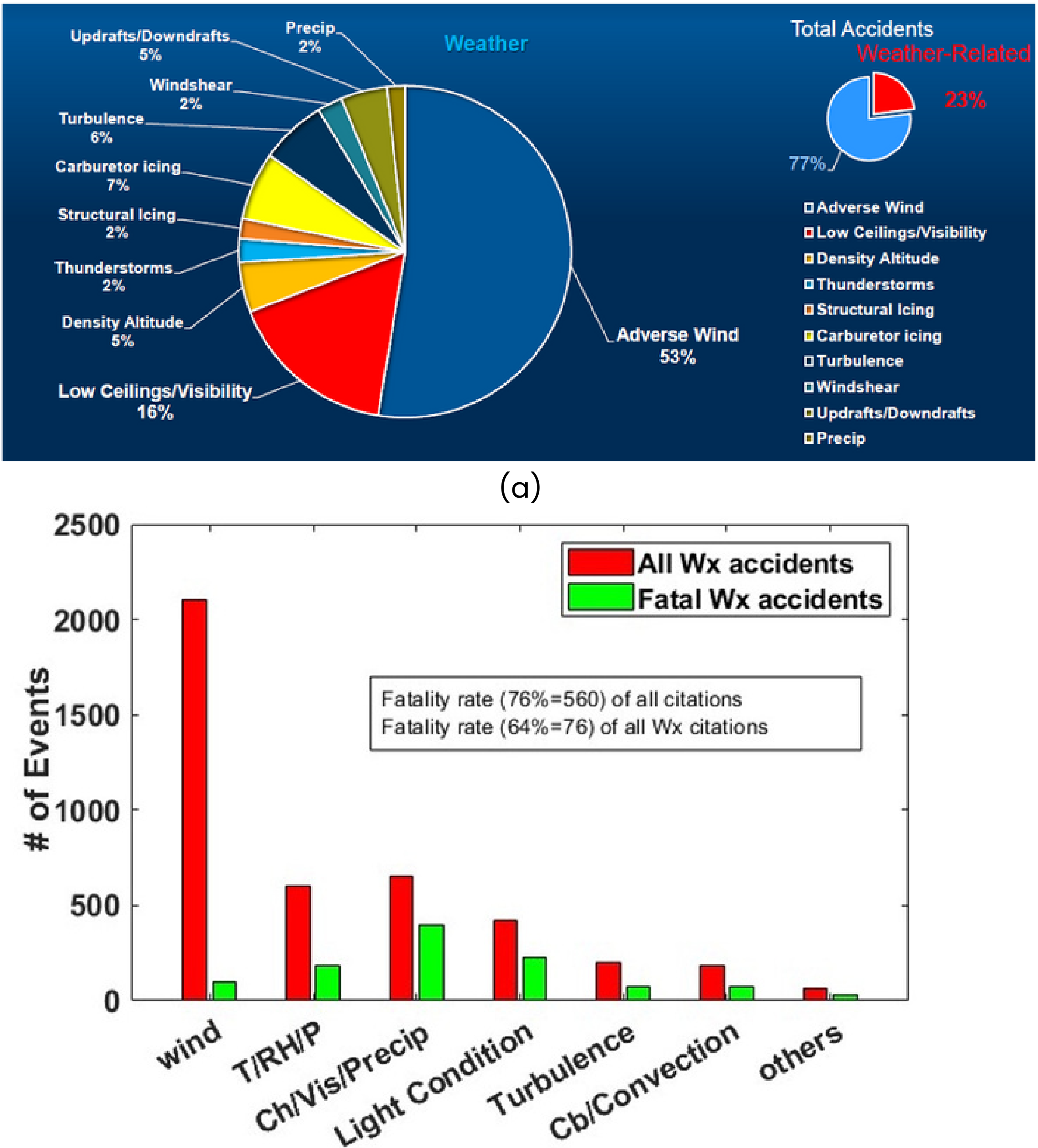

Figure 6 (a) Part 91-Environmental factor accidents covering 2008-2020 time period that is based on NTSB data. It is adapted from Eick (2022), (b) Part 91-Fatal aviation accidents related to weather from 2008-2020 study period that is based on NTSB data. It is adapted from Eick (2022).

Doi: https://doi.org/10.56801/jaoam.v2i1.1

6. Outcome

The current review suggested that weather is an important element of all the aviation accidents (Fig. 6a). Visibility and ceiling, followed by the wind and turbulence, precipitation, and convective activities are critical meteorological events leading to aviation accidents with high fatality numbers. Based on Part 91

covering 2008-2020 incident citations it is found out by Eick et al (2022) that weather related accidents was 23% of all others for which Vis/ceiling was responsible of 16 %, and adverse wind effects were at the rate of 53% (Fig. 6a). Figure 6b shows the fatality rates of weather related accidents at 76% and Vis/ceiling ones in fatality rate was responsible related fatal accidents (Eick et al 2022). Their work suggested that Vis/Ceiling is the number 1 reason in the fatal aviation accidents.

The FAA report by Knecht and Lenz (2010) suggest that the following specific factors constituted a problem for the studied aircraft pilots on weather related issues. Their work provided a list of "usual suspects," with an increase statistical evidence. The factors mentioned their work are:

- Low lighting (dusk or darkness)
- Type of weather encountered:
    a) deteriorating visibility (e.g., lowering ceiling, clouds, fog, rain, rising cloud tops, merging cloud layers)
    b) icing
    c) thunderstorms
    d) turbulence
- Multiple weather factors experienced simultaneously.
- Failure to get a preflight weather briefing, or "briefing" with only a low-grade (non-aviation-oriented) source.
- General deterioration of weather forecast accuracy over time.
- Weather that materialized worse than predicted.

In addition to above, the FAA report (2010; DOT/FAA/AM-10/13) also emphasized the importance of lack of weather-related training and experience for both non-instrument-rated and new instrument rated pilots, Air ambulance missions (particularly helicopter ambulance), and aircraft lacking substantial weather information/handling/avoidance equipment, and non-weather-related, compounding factors such as decision-making factors, time pressure, “get-home-itis”, aircraft equipment problems, fatigue, and distractions can also affect the occurrence of aviation related accidents.

Federal Aviation Administration (FAA 2010) Aviation Safety Information Analysis and Sharing (ASIAS) analysts performed a study of the National Transportation Safety Board (NTSB) Accident and Incident Database to identify aviation accidents in which weather was found to be a major cause or contributing factor (Figure 7). The data was analyzed to find relationships between the type of weather involved and the various factors having the operating rules. ASIAS analysts further broke down the weather-related accidents into their respective operations category to determine which weather factors are the biggest threats to pilots and aircraft based on type of operation. The analysis showed that 14 CFR part 91 operations accounted for the highest percentage of weather-related accidents, followed by 14 CFR parts 135, 121, and 137 operations. They stated that wind was the most common weather factor in part 91 and part 137 operations and the second leading factor in part 121 and 135 operations. Turbulence was identified as the most common weather hazard to part 121 operations, while visibility/ceiling contributed to the most weather-related accidents for part 135 operations. Although it was not easy to show which weather factor affected accidents, their contributions together and interactions can also play an important role.

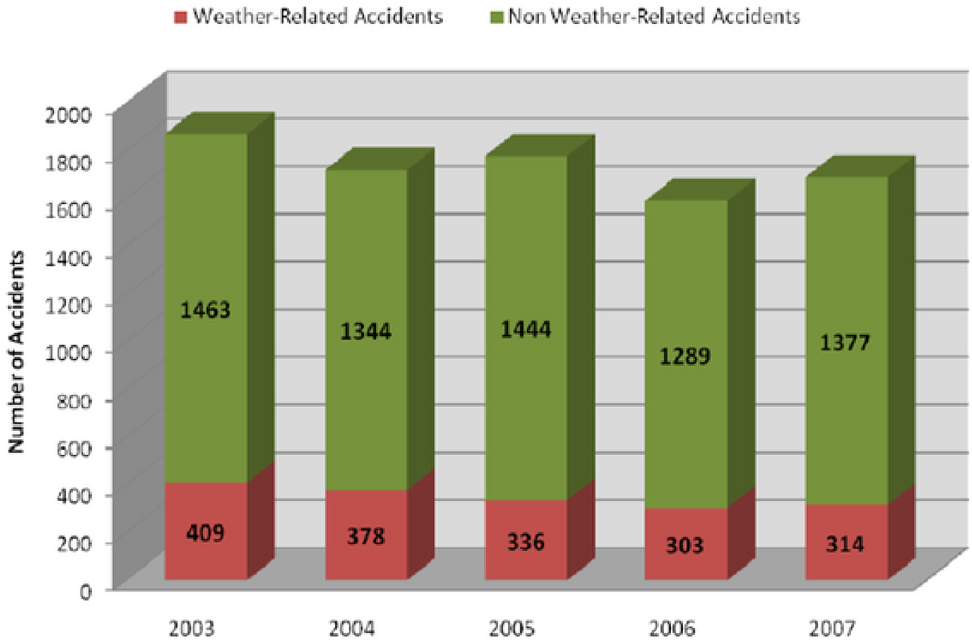

Figure 7: Weather-related versus non-weather-related accidents during 2003–2007 time period based on NTSB Aviation Accident and Incident Database (adapted from FAA 2010).

7. Future Challenges

Aviation operations are strongly affected by the weather type and events including aerosols, dust, fog, clouds, rain and snow, wind, and turbulence and gust, as well as visibility and surface weather conditions while landing and taking off. These all interplay an important role in affecting aircraft operations in the terminal weather or inflight conditions, leading to extensive financial losses to commercial companies as well as human life.

In the future electric vertical take-off and landing (eVTOL) vehicles flights will increase and their interactions with high impact weather events described above will be faced often because of limited flight volumes; therefore, these UAVs should be evaluated under the extreme weather conditions. To integrate eVTOL vehicle operations into airspaces, under IFR and turbulence conditions with minor and more flexible separations are needed compared to those used for conventional aviation (Franciscone and Fernandes, 2023; Mueller 2017).

In addition, collisions with ground obstacles can occur more often due to low visibility conditions (Muller, 2017). In addition to UAVs, helicopters, mostly operate in ClassG airspace that describes the weather minimums for the operations. Instrument Flight Rules (IFR) is used when flights are conducted below the cloud ceiling of 1000 feet and visibility of 3 miles. However, helicopters may also operate in Class G airspace under visual flight rules (VFR) with less than half-mile and 1 mile visibility during the day-time and night time with clear air, respectively (Voogt et al 2020).

Both IFR and VFR used for helicopters are different compared to fixed-wing aircraft. Helicopters generally have lower visibility and cloud base requirements than fixed-wing aircraft. Fog is defined as an instrument meteorological condition (IMC) that requires IFR. The helicopters flying under visual flight rules (VFR) are required to avoid or leave low Vis conditions immediately (Wiggens et al 2012).

Numerical guidance methods for aviation meteorological forecasters can be critical to provide terminal forecasts. Using the numerical weather prediction (NWP) models together with in-situ observations, the terminal aerodrome forecasts (TAFs) and trend-type forecasts (TRENDs) can be used for airports terminal weather applications. These methods continuously can be refined to improve aviation weather forecasts (Jacobs and Maat 2004; Vislocky and Fritsch 1997). An aviation-based application of NOAA’s second-generation medium-range Global Ensemble Forecast System Reforecast (GEFS/R) dataset is being used to study flight rules (Verlinden and Bright 2017). Their study generated a probabilistic prediction system for IFR conditions at major U.S. airports. Their results suggested that the analog approach resulted in skillful probabilistic forecasts of flight conditions.

Ice crystal icing: Ingestion of large amounts of ice crystals by jet engines, known as the ice crystal icing (ICI) hazard, affected more than 150 jet engine power-loss and damage events over last 2 decades (Haggerty et al 2019).

ICI usually occurs near the tropical and mi-latitude convective systems and that may also impact heated inlets used by an aircraft's air data system. The heat within an engine or inlet can prevent ice buildup but analyses of engine power-loss events suggested these conditions to ICI. The CWT testing suggested that ice can accrete inside an aircraft engine. Ice accretion and then ice shedding during flight can adversely affect engine performance and can damage engine components.

Ice crystal icing (ICI) lately resulted in several important field campaigns (Haggarty et al 2019). Lawson et al. (1998) and Mason et al. (2006) suggested that engine power-loss events were attributable to ingestion of high concentrations of small ice crystals into the engine system (Leroy et al 2017). ICI hazards usually occur near cores of deep convective systems with associated cirrus anvils. Flight-level X-band radar reflectivity under this high small ice crystal concentration regions is usually below 20–30 dBZ (Grzych et al 2010) and some heavy precipitation below flight level are also possible. The reports of turbulence are found to be usually light to moderate, and there is no significant ice accretion on airframe that excludes the existence of supercooled liquid water. ICI events can occur over a temperature range of -58° to -3°C having altitudes from 11,000 to 45,000 ft (near the high flight levels) (Bravin et al., 2015).

Overall, the following challenges and future perspectives should be considered to improve aviation operations and reduce the impact of adverse weather conditions on flights:

- Aviation operations are strongly related to weather events and processes; therefore, they should be studied in detail with consideration of weather microphysics, thermodynamics, and dynamics.
- Visibility events change quickly in time and space; because of these conditions, Vis measurements related to PSD should be improved.
- Remote sensing methods for fog, cloud, and wind related parameters should be developed accurately because they affect in-flight and terminal forecasting conditions.

- Cold weather systems such as snowstorms should be studied for physical and dynamical interactions in more detail because ice crystal and snow PSDs as well as snow shapes are not known properly, specifically for IN processes.
- Visibility versus PSD for ice fog and freezing fog can have significant impact on flight operation conditions; therefore, weather events in the northern climatic systems should be studied in depth.
- Low ceilings/visibility conditions are the highest weather cause of fatal weather-related accidents and account for 53% of weather-related fatalities (NTBS 2022). This suggests that low Vis conditions should be predicted accurately.
- Climate change can accelerate turbulence intensity and that can play a very destructive and hazardous flight conditions. This needs to be documented.
- State of art new technologies such as the lidars, radars, satellites, as well as surface and airborne in-situ instrument systems need to be developed to reduce the effect of the adverse weather effect on flight conditions.
- The eVOL and UAS systems will be used more often in the future for aviation operations; therefore, these platforms should be tested for extreme weather conditions in the CWTs.
- When designing and implementing a decision support tool system, using various levels of automation can improve pre-flight and inflight performance, as well as reduce economical losses. This can facilitate and improve information exchange between plots and others (Shimon, 2009).

Most weather accidents occur under Visual Flight Rules (VFR) meteorological conditions (77%) (Capabianco and Lee 2001). Instrument Meteorological Conditions (IMC) are present in only 23% of all accidents however among fatal accidents, IMC conditions are present more than 61%

Overall, this review paper suggests that new technologies and prediction methods representing various time and space scales, and integrated analysis systems such as AI and ML techniques (Gultepe et al 2023; Vorebyava et al 2020; Yulong et al 2019) should be developed to provide safety conditions by reducing prediction uncertainty for aviation communities.

Acknowledgement:

This work was funded by the Grant # N00014-21-1-2296 (Fatima Multidisciplinary University Research Initiative) administered by the Marine Meteorology and Space Program of the Office of Naval Research.

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