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Influence of meteorological phenomena on worldwide aircraft accidents, 1967–2010

J. Mazon,[a,b]* J. I. Rojas,[b,c] M. Lozano,[b] D. Pino,[a,b,d] X. Prats[b,c] and M. M. Miglietta[e]

[a] *Department of Physics, Universitat Politècnica de Catalunya, Barcelona, Spain*
[b] *Escola d'Enginyeria de Telecomunicació i Aeronàutica de Castelldefels, Universitat Politècnica de Catalunya, Castelldefels, Spain*
[c] *Division of Aerospace Engineering, Department of Physics, Universitat Politècnica de Catalunya, Castelldefels, Spain*
[d] *Institute of Space Studies of Catalonia, Barcelona, Spain*
[e] *Instituto di Scienze dell'Atmosfera e del Clima – Consoglio Nazionale delle Richerche (ISAC-CNR), Lecce, Italy*

ABSTRACT: Based on the information available in databases from relevant national and international organizations from 1967 to 2010, an Aviation Weather Accidents Database (AWAD) was built. According to the AWAD, the weather is the primary cause in a growing percentage of annual aircraft accidents: from about 40% in 1967 to almost 50% in 2010. While the absolute number of fatalities and injured people due to aircraft accidents has decreased significantly, the percentage of fatalities and injured people in accidents attributed to the weather shows a slight increase in the studied period. The influence of turbulence, clear air turbulence, wind shear, low visibility, rain, icing, snow and storms on aircraft accidents was analysed, considering the different phases of flight, the meteorological seasons of the year and the spatial distribution over four zones of the Earth. These zones were defined following meteorological and climatological criteria, instead of using the typical political criteria. A major part of the accidents and accidents attributed to the weather occur in latitudes between 12° and 38° in both hemispheres. It is concluded that actions aimed at reducing the risk associated with low visibility, rain and turbulence, in this order, should have priority to achieve the most significant improvements in air transport safety.

KEY WORDS accident; aircraft; weather; air transport; fatality; flight phase; geographical location; meteorological phenomena

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1. Introduction

The weather has always been an important factor in aviation safety since the dawn of the air transport industry. To mitigate the safety risks associated with weather hazards in the different phases of flight, state-of-the-art aircraft incorporate a variety of systems and sensors, including de-icing systems and weather radars. These airborne systems, in combination with other systems (e.g. global navigation satellite systems, instrument landing systems) and services (e.g. the provision of frequently updated, accurate weather forecasts), have allowed a significant and continued reduction in the ratio of accidents and incidents *per* number of aircraft operations. Thanks to this, according to the International Civil Aviation Organization (ICAO) (2009), aviation has become the first ultra-safe system in transport history.

Despite all the safety improvements, the weather is still today a major cause of aviation accidents and incidents. Namely, according to statistics from the US Federal Aviation Administration (FAA), the weather was the primary cause of 23% of all aviation accidents in the United States in 2012. In addition, the weather has been responsible for an increasing percentage of flight delays over the last decades, up to, for instance, approximately 70% of the delays in the US National Airspace System (NAS) in 2012. Moreover, the total economic impact of the weather in 2013 was estimated in US$3 billion, including the costs of property damage, injuries to people, delays and associated increases in aircraft operating costs (FAA, 2013).

The meteorological phenomena and atmospheric conditions that are hazards with the potential of causing aircraft accidents are well known. However, to the authors' knowledge, there are only a few studies aimed at establishing the relative contributions of the various meteorological phenomena to weather-related aircraft accidents, while considering also the phases of flight. On the one hand, Luers and Haines (1983) studied the effects of heavy rain on aircraft, and described how this meteor was responsible for several aircraft accidents. On the other, Rasmussen *et al.* (2000) analysed five take-off accidents attributed to inappropriate de-icing and low visibility associated with heavy snowfall.

Furthermore, to the authors' knowledge, there has been no previous investigation about the spatial and seasonal distribution of this type of accident considering the world total air traffic. The studies on the influence of weather on aircraft accidents are limited so far to national or regional scales. For instance, Pike (1988) analysed the damage to aircraft and injuries to people in the United Kingdom between 1977 and 1986. In total, 1926 accidents were studied, 432 of which (i.e. 22.4%) were related to the weather. From 1967 to 1976, there were 1776 accidents concerning all powered aircraft in the UK Register, 173 of which (i.e. 9.7%) were related to the weather. Shao *et al.* (2013) examined the factors involved in aircraft accidents in Taiwan from 1985 to 2011, including weather conditions during take-off, landing and ground operations.

Additionally, several authors have analysed the relationship between aviation and weather under a meteorological perspective. Ágústsson and Ólafsson (2014) studied a case of severe tur-

* Correspondence: J. Mazon, Department of Physics, Universitat Politècnica de Catalunya, 5 Esteve Terrades Street, Building C3, Office 105, 08860 Castelldefels, Barcelona, Spain. E-mail: jordi.mazon@upc.edu

bulence, caused by orography, affecting an aircraft when flying over the southeastern coast of Iceland. They used numerical simulations to describe a down-slope windstorm at the ground associated with an amplified lee waves and rotor aloft. Strong shear turbulence was simulated at the interface of the lee wave and the rotor, which produced severe turbulence. Based on this simulation, they pointed out the need to provide pilots and forecasters fine-scale products from simulations over complex terrain in order to improve the information about hazards. Bech *et al.* (2007) studied an outbreak of at least five tornadoes over the Barcelona region on 7 September 2005, two of them seriously affecting the international airport at Barcelona, of which one was classified as F2 on the Fujita scale. Air traffic was disrupted and the airport closed for an hour. These tornadoes crossed one of the runaways, seriously damaging some hangars. A couple of empty commercial aircraft were moved, and some others on landing and taking off experienced strong wind shear associated with the thunderstorm. In total, there were 42 cancellations and 162 delays longer than an hour. Chan *et al.* (2012) studied an F0 tornado crossing Hong Kong International Airport on the evening of 20 May 2002. Based on this study, they applied an algorithm for detection based on Doppler velocity difference. Matsangouras and Nastos (2010) analysed a tornado event on 27 July 2002 at Athens International Airport which caused injuries to a woman as a consequence of the shift of a parked aircraft during the disembarkation procedure, and several areas of damage to the airport's facilities. Kaplan *et al.* (2005) analysed 44 cases of aviation accidents caused by turbulence, categorized as a function of the location, altitude, hour and turbulence environment (clear air turbulence (CAT), convection, near mountain) and linked to reanalysis by the National Centers for Environmental Prediction (NCEP). These authors found a prevalence of severe aviation accidents caused by turbulence during the entrance of the polar or subtropical jet stream at the synoptic scale, associated with flow curvature located upstream within this jet entrance region. In most of the analysed cases, convection was detected closer than 100 km to the place of the accident; additionally, upward vertical motions, low vorticity and an increase of wind shear in time were observed. Keller *et al.* (2015), using recorded data and numerical simulations, studied the meteorological conditions during the accident of a Boeing 737 during the take-off phase at Denver International Airport on 20 December 2008. The accident occurred due to a significant crosswind while the aircraft was accelerating. They found that the intermittent gust, which created a severe crosswind over the runaways, was associated with undulations in a train of lee waves in the mid-troposphere in a stable layer above the airport, creating descending strong winds towards the surface. Kim and Chun (2016) used observational data recorded by some flights of Korean Air Lines to obtain the derived equivalent vertical gust velocity as a turbulence indicator. They found an average of one turbulence *per* flight and *per* 10 h of navigation, mainly following the jet stream. Most of the events associated with turbulence were related to shear instability. Finally, Tighe (2015) studied the meteorological conditions for an incident that occurred on the night of 2 January 2014 during one approach phase to Cork Airport (Ireland). On that day sea salt aerosol accretion on the windscreen of the plane reduced the visibility to dangerously low levels for landing.

The objective of the present paper is to integrate in one database the information about worldwide aircraft accidents between 1967 and 2010 available in databases from relevant national and international organizations. On the other hand, based on these data, the contribution of several meteorological phenomena to aircraft accidents is analysed in depth. In particular, the influence of turbulence, CAT, low visibility (caused by fog, heavy rain or snowfall), rain, icing, snow and storms (see Appendix A) is analysed. This analysis considers the different phases of flight (i.e. take-off, climb, cruise, descent and landing, as described in Appendix B), the meteorological seasons of the year, and the spatial distribution over four zones of the Earth. These zones are defined following meteorological and climatological criteria instead of using the typical political criteria for classification of the location of the accident (i.e. the classification considering the country where the accident occurred).

2. Methodology

The ICAO states that an accident is:

> an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which:
>
> 1. a person is fatally or seriously injured (except when the injuries are from natural causes, self-inflicted or inflicted by other persons, or when the injuries are to stowaways hiding outside the areas normally available to the passengers and crew);
> 2. the aircraft sustains damage or structural failure (except for engine failure or damage, when the damage is limited to the engine, its cowlings or accessories; or for damage limited to propellers, wing tips, antennas, tires, brakes, fairings, small dents or puncture holes in the aircraft skin), or
> 3. the aircraft is missing or is completely inaccessible.

On the other hand, an incident is

> an occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation. (ICAO, 2001, p. 10)

In the analyses as part of the present investigation, only accidents are considered.

A database named the Aviation Weather Accidents Database (AWAD) was created *ad hoc* for this investigation, containing information about worldwide aircraft accidents from 1967 to 2010 for which the primary cause has been established to be the weather. Aircraft accidents are generally caused by a chain and/or combination of multiple factors. The final contribution of each factor to the occurrence of the accident is quantified in the corresponding accident investigation. Notwithstanding this, for simplicity, aircraft accidents for which the investigation established that the primary cause was the weather are hereafter termed 'weather-caused accidents'.

The AWAD was built from information in databases gathered from several national and international organizations (from now on named 'primary databases'). Namely, the databases from the ICAO were used, i.e. the Accident/Incident Data Reporting (ADREP) system (ICAO, 2013), the FAA (2013), the US National Transportation Safety Board (NTSB) (2013), the Civil Aviation Authority (CAA) of New Zealand (2013) and

Transport Canada (TC) (2013). Furthermore, the information obtained from these organizations was cross-checked with that available in the websites of the Aviation Safety Network (ASN) (2013), AirSafe (2013), AirDisaster (2013), the Cabin Safety Research Technical Group (CSRTG) (2013) and the Aircraft Crashes Record Office (ACRO) (2013).

Despite the rigorousness of all these organizations in reporting accidents in their records, the information related to a given accident is not always totally coincident, i.e. it is not uncommon to observe discrepancies in, for instance, the reported number of fatalities or injured people, or even the causes of the accident. It was decided that the AWAD would include only those accidents for which the same information is reported in all the primary databases; in particular, the type of aircraft, the date and location of the accident, the number of passengers, the number of fatalities and injured people, the flight phase, the atmospheric conditions, and the causes of the accident. This is necessary to ensure the quality and veracity of the information in the AWAD. An unfortunate consequence is that the number of weather-caused accidents included in the AWAD and considered in this research is less than the actual number of weather-caused accidents, since some of these may have been excluded due to discrepancies in the reported information in one or more primary databases. In addition, the following criteria were established with the purpose of analysing only accidents involving commercial civil aviation aircraft: only flights under instrument flight rules (IFR) of turbine-engined, fixed-wing aircraft, with a maximum certificated take-off mass over 2250 kg (ICAO, 2001) and 19 passenger seats or more were considered. Hence, finally, 1099 weather-caused accidents from 2686 aircraft accidents reported in the primary databases were analysed in the present work. In any case, the studied sample is large enough so that the analysis features sufficient statistical validity.

For all the primary databases, the data records begin in 1967, the year in which the amendment to ICAO Annex 13 to the Chicago Convention entitled ‘Communication Procedures for Sending Aircraft Accident Notification’ became effective and applicable. Therefore, the data records in the AWAD also begin in 1967. Particularly, these records contain information such as, *inter alia*, the number of fatalities and injured people, the flight phase, the meteorological season and, the date and location of the accident.

An important innovation and distinctive feature is that while the primary databases refer simply to the day, month, year and country in which the accident occurred, in the AWAD the date and location are referenced following meteorological criteria to facilitate a better understanding of the influence of the weather. Namely, to classify the location of the accident, four climate zones were defined based on the position of the Ferrel, Hadley and Polar cells in the General Atmospheric Circulation. Table 1 shows these defined zones.

Table 1. Range of latitudes for the four zones.

Zone	Latitude range (°)	Main features
1	±12	Wind convergence area, deep convection
2	12–38	Subsidence, high-pressure areas
3	38–64	Large-scale polar fronts, low-pressure areas
4	64–90 (Pole)	Polar regions

In particular, Zone 1 is the equatorial area, i.e. a latitude within ±12°, where prevailing winds from the north and the south converge, causing strong vertical air currents and deep convections in the atmosphere. Zone 2 corresponds to latitudes between 12° and 38° in both hemispheres, characterized by persistent high pressures, where subsidence dominates at low altitudes. Zone 3 corresponds to latitudes between 38° and 64° in both hemispheres, characterized by low pressures and large-scale synoptic fronts. Finally, Zone 4 corresponds to high latitudes (between 64° and the respective Pole in both hemispheres). To classify the date of the accident, the meteorological seasons corresponding to the Northern Hemisphere were used, i.e. spring corresponds to March–May (autumn in the Southern Hemisphere), and the following three consecutive months correspond to summer (winter in the Southern Hemisphere), and so on.

3. Results and discussion

The information in the AWAD about worldwide aircraft accidents for which the primary cause has been established to be the weather was analysed from different perspectives: (1) to identify trends in the period 1967–2010; (2) to determine the effect of various meteorological phenomena depending on the flight phase; and (3) to establish the spatial and seasonal distribution of aircraft accidents following meteorological criteria.

3.1. Trends related to weather-caused accidents, 1967–2010

One of the most relevant observations derived from the data in the AWAD is the evolution of the worldwide annual total number of accidents and the annual number of weather-caused accidents from 1967 to 2010, which are shown in Figure 1, together with the annual percentage of the latter number with respect to the former. The linear regressions of the data in Figure 1 indicate that all these numbers have grown in the studied period (in part due to the relatively large number of accidents that occurred in 2001, 2003, 2005 and 2007). Aviation safety thinking and safety reliability have evolved significantly in this period, spanning across three different eras: the technical era (before 1969), the human era (1970–1995) and the era of organization (from 1996 to the present day). This way, air transport has evolved from a fragile system to a safe one, and ultimately to an ultra-safe system, in less than a century (ICAO, 2009). The safety standards required by the ICAO for the air transport industry have been kept constant over the last decades below one catastrophic event *per* 10 million cycles (ICAO, 2009), while the worldwide air traffic (i.e. the absolute number of flights) has increased dramatically. Hence, consequently, it is normal to expect the annual absolute number of accidents to increase, and this is exactly what has occurred over the years (Figure 1). Remarkably, the annual absolute number of weather-caused accidents has increased comparatively faster (i.e. the percentage of annual weather-caused accidents has increased noticeably from 1967 to 2010, from about 40% to almost 50%, as shown in Figure 1).

Figure 2 shows the annual number of fatalities and injured people corresponding to all aircraft accidents worldwide, and to weather-caused accidents only, in the period 1967–2010. In both cases, the linear regressions of the data show a progressive decrease in the number of fatalities and injured people in the last decades. However, the decrease in the number of fatalities and injured people associated with weather-caused accidents is comparatively less significant. Therefore, the percentage of the contribution of weather-caused accidents shows a slight increase.

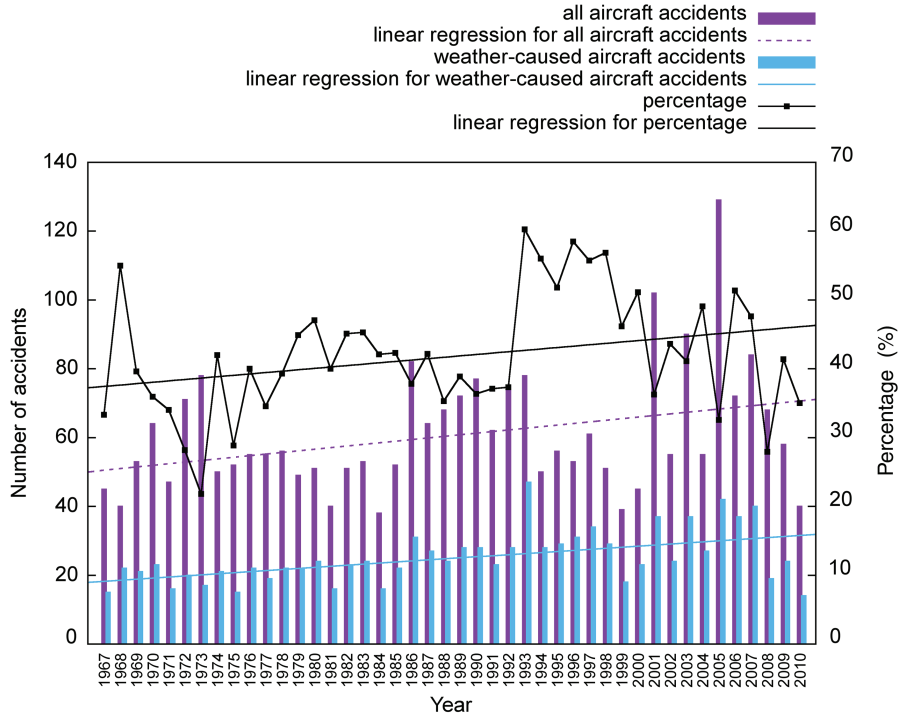

Figure 1. Worldwide annual numbers of aircraft accidents and weather-caused aircraft accidents, 1967–2010, and the percentage of the latter number with respect to the former. [Colour figure can be viewed at wileyonlinelibrary.com].

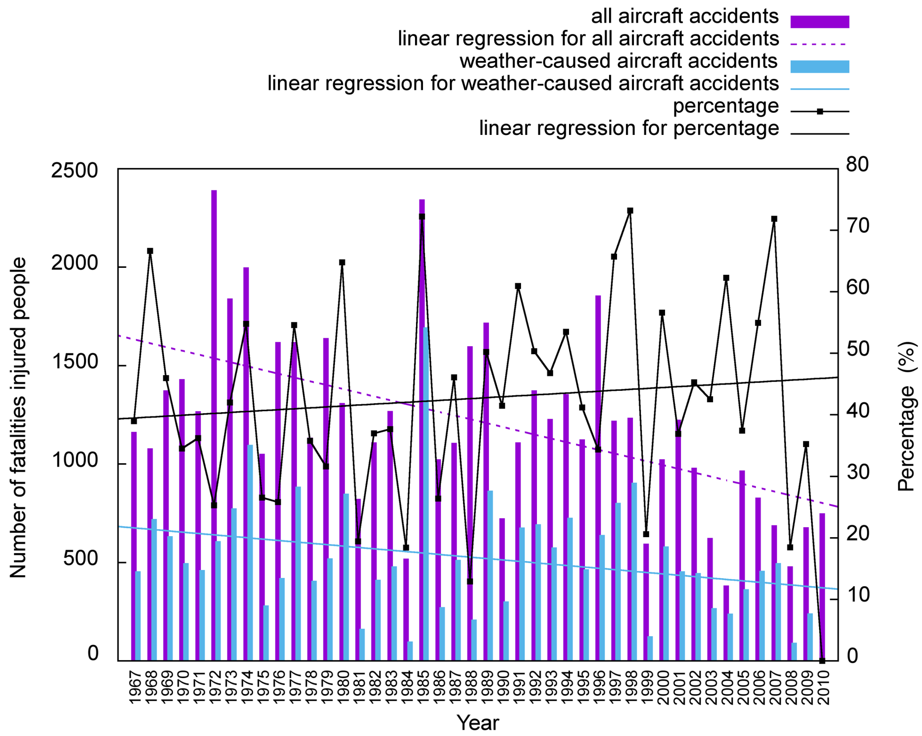

Figure 2. Total number of annual fatalities and injured people in all aircraft accidents worldwide, and in weather-caused accidents only, 1967–2010, and the percentage of the latter number with respect to the former. [Colour figure can be viewed at wileyonlinelibrary.com].

Thus, from Figures 1 and 2, it seems that the aviation safety improvements conducted between 1967 and 2010 have had a smaller effect on weather-caused aircraft accidents compared with other accidents, i.e. the number of weather-caused accidents and the associated fatalities and injured people, have been less sensitive to those improvements.

3.2. Distribution of weather-caused aircraft accidents according to the flight phase in which the accident occurred

Aircraft operate in all layers of the troposphere, from the lowest levels (take-off and landing) and medium levels (climb and descent), to the highest levels (cruise). This section analyses

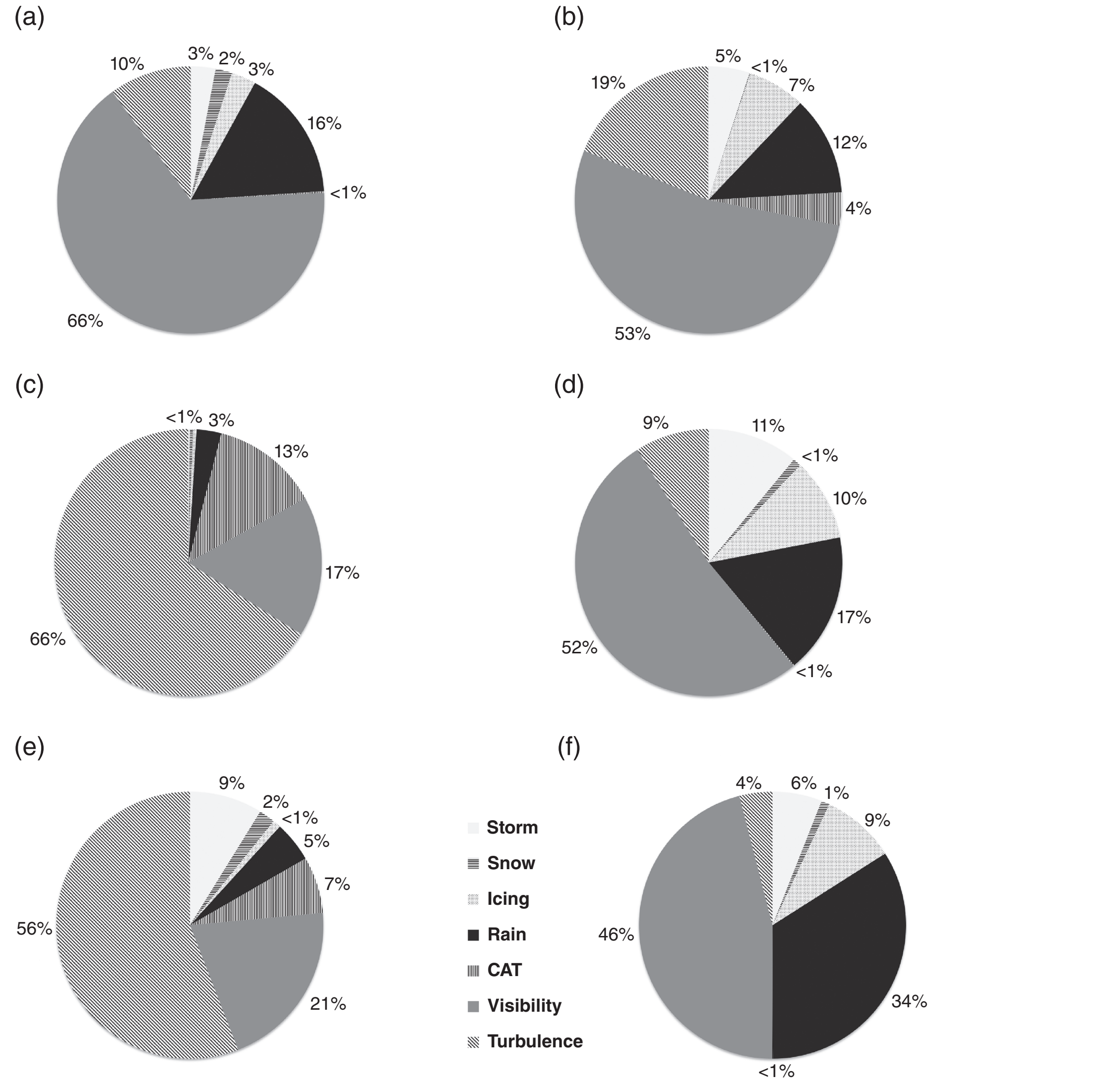

Figure 3. Relative contributions of meteorological phenomena (turbulence, low visibility, clear air turbulence (CAT), rain, icing, snow and storms) to worldwide weather-caused aircraft accidents, 1967–2010, for various flight phases: (a) take-off, (b) climb, (c) cruise, (d) approach, (e) descent and (f) landing.

the influence of meteorological phenomena in weather-caused aircraft accidents depending on the flight phase. Particularly, Figure 3 shows, for each of the flight phases, the relative contributions of various meteorological phenomena to weather-caused aircraft accidents worldwide between 1967 and 2010. For instance, it shows that turbulence has a significant impact in those flight phases at medium and high levels of the troposphere. Namely, it is responsible for around 19, 66 and 57% of the weather-caused accidents in the climb, cruise and descent phases respectively; while in the phases at low levels, it is responsible for significantly fewer of the accidents (10, 9 and 3% for the take-off, approach and landing phases respectively).

In the primary databases, CAT is considered separately from other types of turbulence, and so it is in the AWAD. CAT is characteristic of high flight levels near the upper limit of the troposphere, but it is responsible for much fewer weather-caused accidents compared with turbulence: only 4, 13 and 7% of this type of accidents in the climb, cruise and descent phases respectively (as expected, CAT has no impact at low levels, i.e. during take-off and landing). CAT has not any influence on the take-off, approach and landing phases. The reason for these low contributions is that CAT can often be avoided because, on the one hand, pilots inform of CAT encounters by means of pilot reports of turbulence (PIREP), and, on the other, because there are operational methods for CAT forecasting, such as Graphical Turbulence Guidance (GTG), which currently flight dispatchers can use when preparing the flight plans of commercial aviation aircraft, aside from other more advanced methods under development (Sharman *et al.*, 2006; McCann *et al.*, 2012).

Low visibility (caused by fog, heavy rain or snowfall) is a major factor in weather-caused accidents, especially in those flight phases for which the terrain is much closer to the aircraft, or the aircraft flies in more congested air spaces such as the vicinity of aerodromes. In particular, low visibility is majorly responsible for around 67, 53, 52, 21 and 46% of the weather-caused accidents in the take-off, climb, approach, descent and landing phases respectively.

Rain is also more likely to affect aircraft flying at low levels of the troposphere. In particular, it is the second major cause of weather-caused accidents in the landing phase, with around 34%, while for the take-off, climb, approach and descent phases the influence drops to around 16, 12, 17, 11 and 5% respectively.

As regards weather-caused accidents in the cruise phase, the influence of rain is minimal (only around 3%).

Storms (including lightning and heavy winds) have a rather testimonial impact in the take-off and cruise phases: only 3 and 0.5% of the weather-caused accidents are attributed to storms in these phases respectively. On the other hand, the percentage of weather-caused accidents associated with storms is roughly uniform for the other flight phases (between 5 and 7%). An explanation might be that severe storms are often associated with cumulonimbus, which can be found practically in any layer of the troposphere, and consequently aircraft are exposed to this hazard in all flight phases. In general, the contributions of storms to weather-caused accidents are low, probably because storms are reported by weather forecasting services and other affected aircraft, and can be detected by airborne weather radars. Thus, aircraft can often dodge storms. Another reason is that aircraft respond generally very well to lightning impacts, which most of the time do not cause high-severity damage on the airframe or the avionics. The particularly low contribution of storms to weather-caused accidents in the landing phase is likely thanks to the fact that aircraft are diverted to alternative airports if a severe storm is affecting the destination airport. The even lower impact of storms in the take-off phase is probably because flight departure is often conveniently delayed if a potentially dangerous storm is affecting the aerodrome of origin.

Icing usually affects aircraft flying at medium and high levels of the troposphere because supercooled water drops can form ice on parts of the aircraft at the low temperatures typical of these levels (that can be as low as −60 °C), a process that could ultimately cause an accident. Nowadays, the effects of icing have been greatly reduced thanks to de-icing systems in use and the fact that icing areas are thoroughly reported. Thus, for instance, this meteor has a marginal contribution to weather-caused accidents in the cruise and descent phases. Unfortunately, its impact on other flight phases still cannot be neglected. In particular, icing is responsible for around 7, 10 and 9% of the weather-caused accidents in the climb, approach and landing phases respectively. The small contribution of icing in the take-off phase (only 3%) is likely thanks to the additional contribution of the de-icing services provided to aircraft on the ground prior to take-off.

Finally, snow has a very low influence in weather-caused accidents in all flight phases: it is responsible for only around 11, 9 and 7% in the approach, descent and landing phases respectively; less in the other phases: around 3 and 5% of the weather-caused accidents in the take-off and climb phases respectively; and less than 1% in the other phases.

To sum up, low visibility is the main contributing factor to weather-caused accidents in all flight phases except cruise and descent, where it is the second major factor after turbulence. Rain is the second major contributing factor in the take-off, approach and landing phases. In the take-off phase, rain (storms) causes 17% (3%) of the weather-caused accidents, while in the landing phase it causes 34% (6%). This suggests that more often take-off is conveniently delayed due to rain and/or storms, thus preventing the aircraft from being exposed to a high level of risk, while conversely landing under rain and/or storms is unfortunately attempted more than it should due to, for example, low fuel level.

3.3. Spatial and seasonal distribution of worldwide aircraft accidents

This section analyses the spatial and seasonal distribution of worldwide aircraft accidents in the period 1967–2010. First, all these accidents were classified by considering the location where the accident occurred, in correspondence with the four climate zones defined above in Section 2. Figure 4 shows the results of this classification, indicating also the absolute number of weather-caused accidents and the corresponding percentage in relation to the total number of accidents for each of the zones. The results differ noticeably from one zone to another. This is not due only to the varying affectations associated with each zone, but also to the different traffic volumes in each zone. Remarkable is the relatively high percentage of weather-caused accidents for Zone 2 (latitudes between 12° and 38°) and Zone 4 (latitudes between 64° and the respective Pole): 50 and 59%, for a sample size of 1330 and 19 accidents respectively. For Zone 1 (the equatorial area, i.e. latitudes within ±12°) and Zone 3 (latitudes between 38° and 64°), the percentage of weather-caused accidents is smaller (25% and 39%, for a sample size of 800 and 511 accidents respectively). The reason for the latter might be

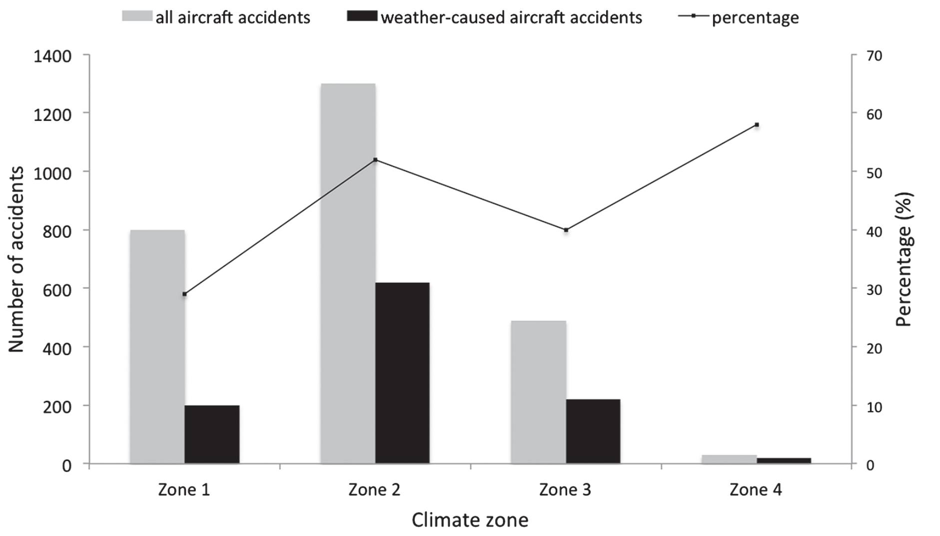

Figure 4. Number of aircraft accidents and weather-caused aircraft accidents, 1967–2010, and the percentage of the latter number with respect to the former, for four climate zones defined in both hemispheres: Zone 1, latitude within ±12°; Zone 2, latitude between 12° and 38°; Zone 3, latitude between 38° and 64°; and Zone 4, latitude between 64° and the respective Pole.

that the meteorological phenomena in Zones 1 and 3 are of lower intensity compared with Zones 2 and 4, and/or that other factors causing accidents (not related to the weather) become comparatively more important in the former zones.

Zones 1 and 2 show the largest number of accidents. The reason is not a higher air traffic volume in these zones, but the fact that in Zones 1 and 2 there is a larger proportion of developing countries where, for instance, aircraft are generally older and the radio-navigation equipment used and airport infrastructures for instrument approach and landing may not be as advanced as in other countries. That is, agents in these developing countries, although compliant with ICAO standards and recommended practices (SARPS), like agents of all ICAO member states, do not usually aim at and achieve target safety standards as far beyond the ICAO SARPS as do agents in developed countries. For example, on the one hand, aircraft from Caribbean airlines have traditionally been involved in a comparatively large proportion of accidents. On the other hand, there is a smaller proportion of aircraft, cabin crew and airports certified for instrument-precision approaches, leading to a greater number of non-precision approaches, and thus low visibility implies a higher level of risk. The figures reported above in Section 1 suggest a lesser relevance of the weather in accidents in developed countries (thus, apparently, the meteorological phenomena entail a lower level of risk there). For instance, the weather was the primary cause of 23% of all aviation accidents in the United States in 2012, and in the United Kingdom it was responsible for 9.7% (in 1967–1976) and 22.43% (in 1977–1986) of the accidents compared with a growing contribution of 40–50% if considering the accidents worldwide, or a contribution of 50% in Zone 2.

Figure 5 shows the relative contributions of the various meteorological phenomena to weather-caused aircraft accidents in each of the four defined climate zones in the period 1967–2010. In Zone 1, low visibility (with 41%), rain (31%) and storms (13%) are responsible for around 85% of the weather-caused accidents. A reason might be that Zone 1 is associated with the Inter-Tropical Convergence Zone (ITCZ). In the ITCZ, prevailing winds from the north and south converge, causing strong vertical air currents and deep convections in the atmosphere, e.g. deep clouds develop forming deep cumulonimbus. These are often associated with severe thunderstorms and heavy rainfall and, consequently, low visibility. Turbulence, probably associated with the cloud dynamics mentioned above, is responsible for around 14% of the weather-caused accidents in this zone. The contributions of CAT, icing and snow are residual (as expected, since in Zone 1 snow is very infrequent).

Zone 2 corresponds to the high-pressure belt, characterized by subsidence, where precipitation is inhibited. Consequently, weather-caused aircraft accidents associated with rain decrease to around 11%, while those associated with turbulence increase to around 30%, probably due to stronger and more frequent low-level turbulence due to a warmer soil. The reason is that clear sky is dominant in Zone 2, such that the intense radiation can heat the surface more significantly. Thus, the consequent horizontal and vertical turbulences are probably behind this increased contribution of turbulence to weather-caused accidents. Moreover, there is a significant increase in weather-caused accidents attributed to snow, reaching around 7%. This meteor is unusual in Zone 2. Therefore, many aerodromes and airports are probably not sufficiently well prepared to manage the effects of this meteor, and thus the level of risk increases significantly when snowing. Storms (mainly formed by deep convection) are associated with around 5% of the weather-caused accidents (the influence of storms in this zone, where clear skies dominate, decreases with respect to Zone 1), while low visibility is associated with around 30%. The contribution of icing is again marginal, as expected.

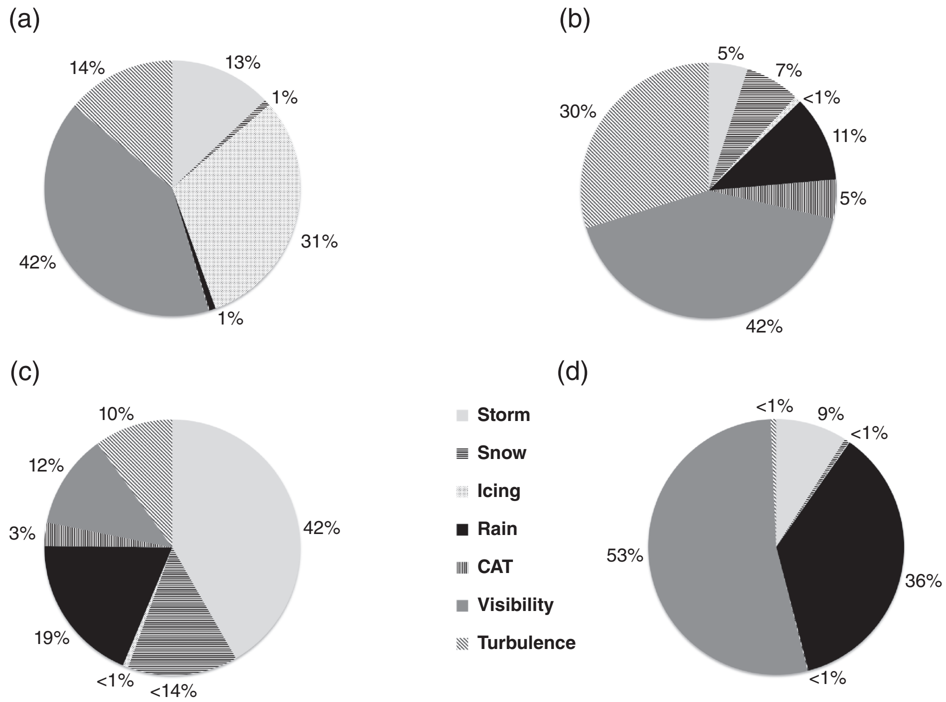

Figure 5. Relative contributions of meteorological phenomena (turbulence, low visibility, clear air turbulence (CAT), rain, icing, snow and storms) to worldwide weather-caused aircraft accidents, 1967–2010, for four climate zones defined in both hemispheres: (a) Zone 1, latitude within ±12°; (b) Zone 2, latitude between 12° and 38°; (c) Zone 3, latitude between 38° and 64°; and (d) Zone 4, latitude between 64° and the respective Pole.

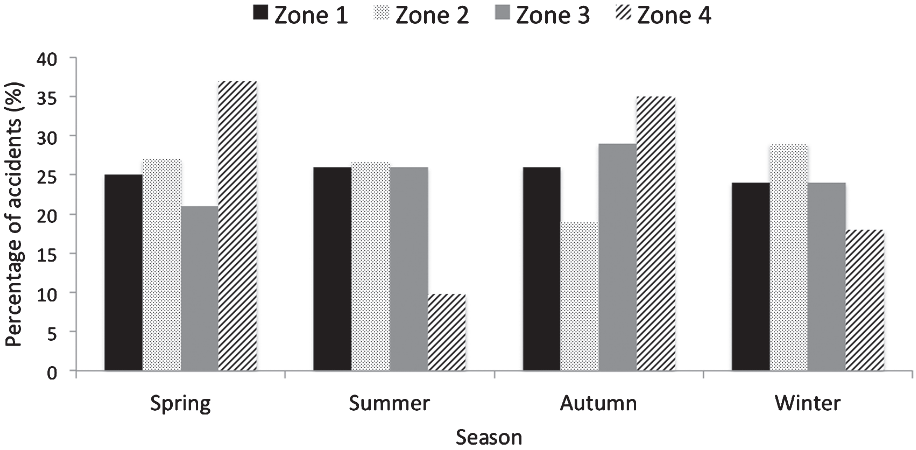

Figure 6. Percentage of weather-caused aircraft accidents in each meteorological season (referenced to the Northern Hemisphere), 1967–2010, for four climate zones defined in both hemispheres: (1) Zone 1, latitude within ±12°; (2) Zone 2, latitude between 12° and 38°; (3) Zone 3, latitude between 38° and 64°; and (4) Zone 4, latitude between 64° and the respective Pole.

Zone 3 corresponds to mid-latitudes, characterized by low-pressure systems and large-scale synoptic fronts. In this zone, rain and snow are responsible for around 19 and 14% of the weather-caused aircraft accidents respectively, while low visibility and turbulence are responsible for around 12 and 10% respectively. The contributions of CAT and icing are again marginal. Finally, storms are the most significant factor, accounting for around 42% of the weather-caused accidents in this region. The high relevance of storms is due to the prevalence of large-scale synoptic fronts.

Focusing now on Zone 4, which corresponds to the highest latitudes, low visibility and rain are responsible for around 53 and 36% of the weather-caused aircraft accidents respectively. Note that snow must be a frequent meteor affecting many aerodromes in Zone 4, but surprisingly, it has a very small contribution (compared with, for example, Zone 2) and icing has never been reported as the primary cause of any accident. This is probably due to the thorough *ad-hoc* safety systems that must be implemented in aerodromes in Zone 4 and the aircraft that operate there, so frequently affected by snow and icing, and due to the low number of operations in this zone, especially in winter and mostly in the Northern Hemisphere). Finally, the contributions of turbulence and CAT are residual.

To sum up, in all zones but Zone 3, low visibility (caused by fog, heavy rain or snowfall) is the main contributing factor to weather-caused accidents, having a similar relative contribution, namely, being responsible for around 41–53% of weather-caused accidents in these zones. Rain is the second major contributing factor in all zones but Zone 2, being responsible for around 19–36% of weather-caused accidents in these zones. Therefore, from a global perspective and considering the findings above in Section 3.2, efforts devoted to improve or further implement procedures and technologies that reduce the risk associated with low visibility and rain should have priority. Moreover, it would seem appropriate also to act to reduce the risk associated with turbulence, particularly for flights in Zone 2. The reasons are the significant contribution of turbulence to accidents in Zone 2, the very large number of accidents occurring in this zone, and the fact that turbulence is the main contributing factor to weather-caused accidents in the cruise and descent phases.

Figure 6 shows the distribution of weather-caused accidents depending on both the location and the meteorological season in which the accident occurred. Zone 1 shows a uniform distribution, i.e. there is approximately the same number of weather-caused accidents in each season (around 25%). This is likely because in Zone 1 the weather shows no significant differences throughout the seasons, other than perhaps being more rainfall in the rainy season compared with the dry season. Zone 2 shows a similar percentage of weather-caused accidents in spring and summer (around 26%), slightly more in winter (around 28%), and significantly less in autumn (around 19%). For Zone 3, autumn shows the largest percentage of weather-caused accidents (around 28%), while spring shows the lowest (around 21%), and summer and winter show a similar percentage (around 25%). Finally, for Zone 4, 36% of the weather-caused accidents occur in spring and another 36% in autumn, while only 9% occur in summer and 18% in winter. This may be due to the large differences in the climate between seasons in Zone 4. However, the number of accidents in Zone 4 is so small (19 accidents only) that these conclusions are not statistically significant.

4. Conclusions

A database (Aviation Weather Accidents Database: AWAD) was created based on the reports about aircraft accidents from relevant organizations from 1967 to 2010. The information in the AWAD was analysed statistically. The results show that the weather is the primary cause in a growing percentage of annual accidents (from about 40% in 1967 to almost 50% in 2010). While the absolute number of fatalities and injured people due to aircraft accidents has decreased significantly, the percentage of fatalities and injured people associated with accidents attributed to the weather shows a slight increase. From a study of the contribution to these accidents by each meteorological phenomenon in the different flight phases, the following conclusions are drawn:

- low visibility is the main factor in weather-caused accidents in all flight phases but cruise and descent, where it is the second major factor after turbulence;
- rain is the second major factor in weather-caused accidents in the take-off and landing phases, i.e. it has a large influence on close-to-ground operations;

- it appears that take-off is often conveniently delayed due to rain and/or storms, while landing under rain and/or storms is attempted more than it should be;
- turbulence and CAT are especially relevant at medium and high flight levels, and
- storms, snow and icing have a rather testimonial impact in most phases.

The location of accidents was classified based on four zones defined following meteorological and climatological criteria. From the study of the contribution of each meteorological phenomenon in these zones, and a consideration of the meteorological season in which the accident occurred, the following conclusions are drawn:

- in the equatorial and polar zones, low visibility and rain are by far the phenomena responsible for more aircraft accidents attributed to the weather;
- the ITCZ, characterized by strong vertical air currents and deep convection, is in the equatorial zone. This explains the significant impact of low visibility, rain, storms and turbulence in this zone;
- in the polar zones, the weather is responsible for around 60% of accidents;
- a major part of the accidents and weather-caused accidents occur in latitudes between 12° and 38° in both hemispheres (a high-pressure belt where subsidence dominates at low altitudes). Low visibility and turbulence are the major contributing factors to weather-caused accidents in this zone. Surprisingly, snow is responsible for a much larger percentage of weather-caused accidents in this zone compared with the polar zones;
- in regions with latitudes between 38° and 64° in both hemispheres, where low-pressure systems and large-scale synoptic fronts are usual, storms and rain are the main contributing phenomena to weather-caused accidents, and
- in all but the polar zones, the weather-caused accidents can be considered as uniformly distributed in the various meteorological seasons.

Summarizing, the weather has a major impact on the safety of the air transport industry and, apparently, the aviation safety improvements made between 1967 and 2010 have had a smaller effect on weather-caused aircraft accidents (and the associated fatalities and injured people) compared with other accidents. To achieve the most significant improvements in air transport safety, it appears that actions aimed at reducing the risk associated with low visibility, rain and turbulence, in this order, should have priority.

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Appendices

Appendix A: Occurrence categories

Turbulence refers to in-flight turbulence encounters (ECCAIRS, 2013a):

- includes turbulence encountered by aircraft when operating around or at buildings, structures and objects, and encounters with turbulence in clear air, mountain wave, mechanical and/or cloud-associated turbulence;
- wake vortex encounters are also included, and
- flights into wind shear or thunderstorm-related turbulence are coded as a storm.

Storms refer to a flight into wind shear or a thunderstorm (ECCAIRS, 2013a):

- includes flight into wind shear and/or thunderstorm-related weather, and in-flight events related to hail, events related to lightning strikes and events related to heavy rain (not just in a thunderstorm), and
- icing and turbulence encounters are coded separately (see icing below and turbulence above).

Icing refers to the accumulation of snow, ice, freezing rain or frost on aircraft surfaces that adversely affects aircraft control or performance (ECCAIRS, 2013a):

- includes accumulations that occur in-flight or on the ground;
- carburettor and induction icing events are coded in the fuel-related category;
- windscreen icing that restricts visibility is also covered;
- includes ice accumulation on sensors, antennae and other external surfaces, and
- includes ice accumulation on external surfaces including those directly in front of the engine intakes.

Appendix B: Event phases

Flight phases adopted for classification of aircraft accidents (ECCAIRS, 2013b):

- standing: the phase of flight prior to pushback or taxi, or after arrival, at the gate, ramp, or parking area, while the aircraft is stationary;
- taxi: the phase of flight in which movement of an aircraft on the surface of an aerodrome under its own power occurs, excluding take-off and landing;
- take-off: the phase of flight from the application of take-off power until reaching the first prescribed power reduction, or until reaching the Visual Flight Rules (VFR) pattern or 1000 feet (300 m) above runway end elevation, whichever comes first or the termination (abort) of the take-off;
- climb to cruising level or altitude (or simply ‘climb’, in our analysis): instrument flight rules (IFR): the phase of flight from completion of Initial Climb to arrival at initial assigned cruise altitude;
- cruise: IFR: the phase of flight from the top of climb to cruise altitude, or flight level, to the start of the descent toward the destination aerodrome or landing site;
- normal descent (or simply ‘descent’, in our analysis): IFR: descent from cruise to either Initial Approach Fix (IAF) or VFR pattern entry;
- manoeuvring: an event involving a phase of flight in which planned low-level flight, or attitude, or planned abnormal attitude, or abnormal acceleration occurs;
- approach: IFR: the phase of flight from the outer marker to the point of transition from nose-low to nose-high attitude immediately prior to the flare above the runway, and
- landing: the phase of flight from the point of transition from nose-low to nose-up attitude, immediately before landing

(flare), through touchdown and until aircraft exits landing runway, comes to a stop or when power is applied for take-off in the case of a touch-and-go landing, whichever occurs first.

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