Environmental Factors Affecting Loss of Control In-Flight:

Best Practice for Threat Recognition & Management

1st Edition

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Table of Contents

I. Abstract

In the IATA 2015 Safety Report, less than one tenth of accidents in the period 2011 – 2015 were categorised as Loss of Control Inflight (LOC-I) but approaching a half of all fatal accidents in the period were found to be LOC-I. Environmental threats were identified in a significant proportion of all LOC-I accidents and therefore a strong link can be drawn between environmental factors and fatal accidents. IATA has prepared this guidance material to bring together industry knowledge and identified best practices in a single document. For the purposes of the document the environmental factors to be considered are meteorological phenomena such as convective weather and the associated conditions, turbulence in clear air and turbulence from aircraft wake vortices.

II. Executive Summary

Loss of control seems an unlikely condition in today's modern aircraft, with sophisticated automation and flight control systems, but it continues to feature in accident statistics and is the leading fatal accident category in recent years. As with most commercial aircraft accidents, loss of control almost always involves a sequence of events and a number of contributory factors. Analysis published in the IATA 2015 Safety Report has shown that influences related to the physical operating environment are frequently in that mix of events and factors.

This guidance material provides a summary of the relevant data from the 2015 Safety Report and from the IATA Safety Trend Evaluation, Analysis and Data Exchange System (STEADES) Program, which supports the argument for consolidated guidance. Four case studies illustrate some of the catastrophic outcomes to which environmental factors have contributed.

A short 'refresher' on global meteorology and the more hazardous atmospheric phenomena precedes an analysis of the specific environmental threats that have been found to play a part in loss of control. These include convective turbulence, micro-burst, icing, lightning, the more recently identified threat of high altitude ice crystals, clear air turbulence, mountain wave and from beyond the realm of meteorology, the potential effects of aircraft wake vortices. Because the eventual outcome of an environmental upset is largely dictated by the response of the pilots, human performance in these situations is also examined. There is increasing evidence, for example, that pilots can suffer a period of impaired performance when startled by unexpected aircraft behavior.

The guidance would not be complete without some solutions and under the title 'Mitigations' appear 'Forecasting', 'Avoidance', 'Detection', 'Recognition' and 'Reporting', which combine to offer an enhanced 'Resilience' to environmental threats. Although principally aimed at pilots, these mitigation strategies should be properly understood by operational management, dispatchers and air navigation service providers.

Following the consolidated conclusions are a number of recommendations directed to a variety of audiences, including operators, Air Navigation Service Providers (ANSPs), dispatchers, manufacturers and of course those at the actual environmental interface; the pilots.

III. Aim

The aim of this document is to provide a point of reference for the understanding and mitigation of the risk of LOC-I as a result of the environmental factors encountered in flight.

IV. Reference Data

a) European Aviation Safety Agency (EASA) Safety Information Bulleting (SIB) 2015-13 'Safety Management of Flight Operations in Adverse Convective Weather and the Inter-Tropical Convergence Zone'

b) IATA 2015 Safety Report (data from 2011 – 2015)

c) IATA STEADES Analysis: 'Wake Turbulence'

d) 'Hidden Danger: A Special Report on the Inter Tropical Convergence Zone' by Roger Rapoport

e) US Federal Aviation Administration (FAA) Advisory Circular (AC) 'Thunderstorms'

f) UK Civil Aviation Authority (CAA) Aeronautical Information Circular (AIC) P 056/2010 'The Effect of Thunderstorms and Associated Turbulence on Aircraft Operations'

V. LOC-I Statistics

The data for the statistical analysis in this section pertain to accidents and incidents recorded in the period 2011 – 2015 inclusive. These include accidents to commercial jet and turboprop aircraft but exclude private aviation, business aviation, illegal flights, humanitarian relief, crop-dusting/agricultural flights, security related events (hijacking etc…) and experimental/test flights.

The chart illustrated in Figure 1 below shows all accidents in the period by percentage in each accident category (accident categories are defined in Annex 2 to the IATA 2015 Safety Report); LOC-I accounted for eight percent (8%) of all accidents.

2011–2015 Aircraft Accidents

408 Accidents

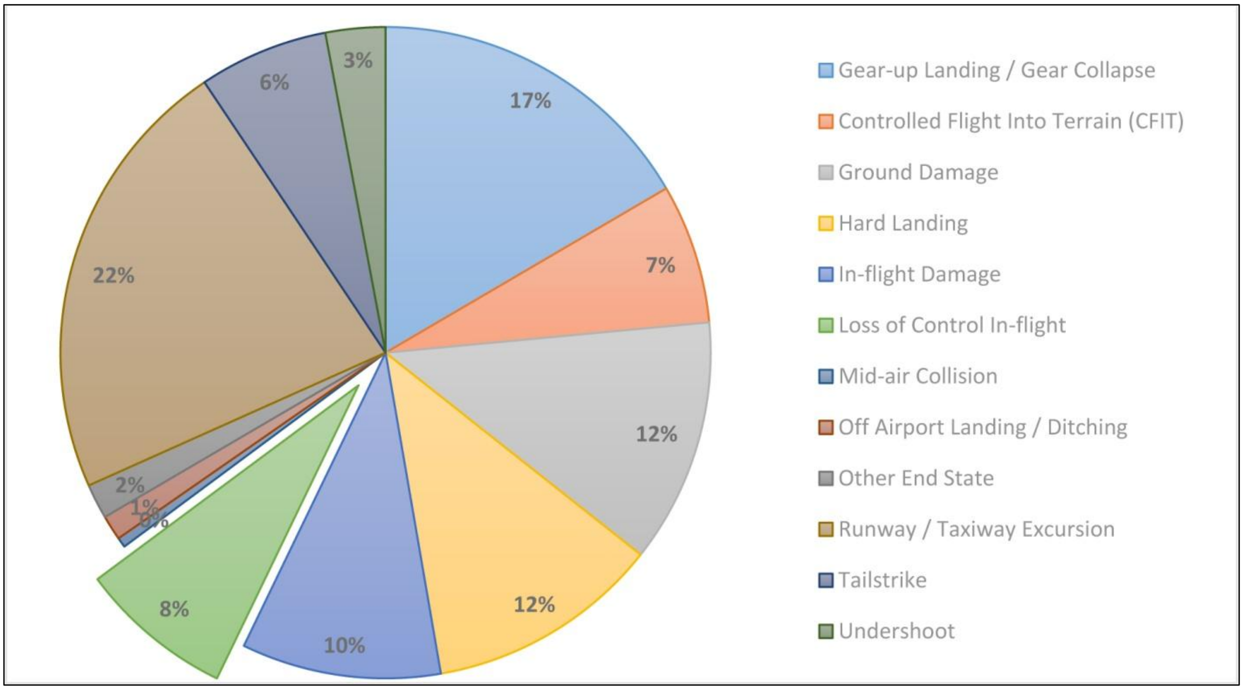

Figure 1. Breakdown per Accident Category

When the 'all accidents' data is filtered to show only fatal accidents in the period, LOC-I accidents can be seen in the chart illustrated in Figure 2 below to account for 45% of all fatal accidents, a far greater percentage than in all accident categories.

2011–2015 Fatal Aircraft Accidents

68 Accidents, one of which could not be assigned an End State

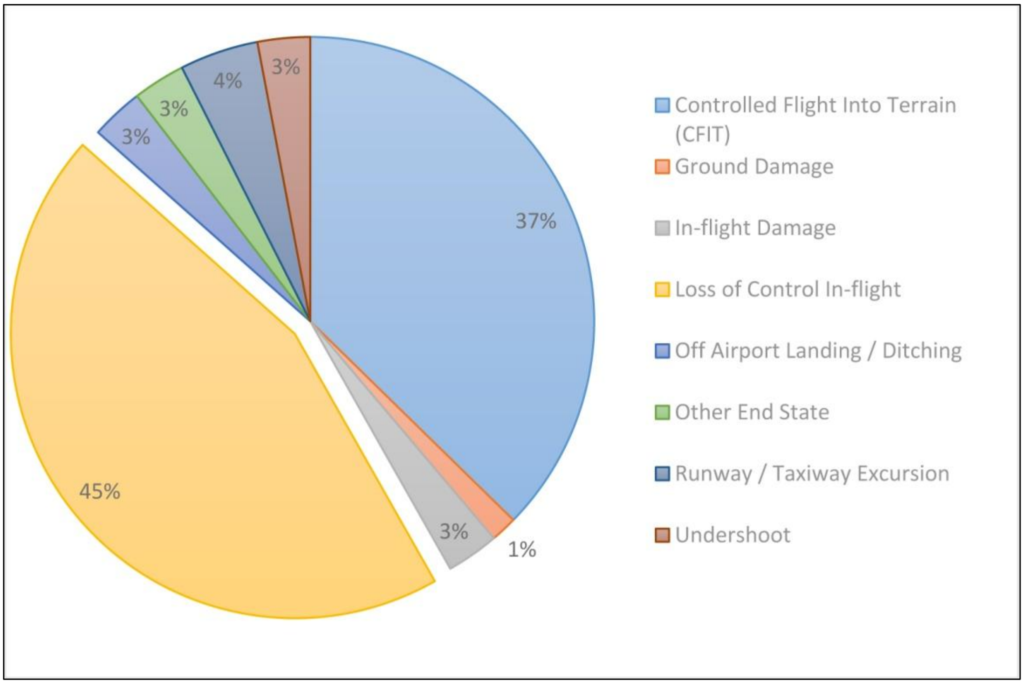

Figure 2. Breakdown per Fatal Accident Category

The background to this disproportionate ratio of LOC-I fatal accidents is illustrated in the figure 3 below; note that the circle size increases as the total number of fatalities sustained in the accident category increases. Whilst Runway/Taxiway Excursion accidents are more frequent than LOC-I by a factor greater than three (3), survivability for passengers and crew in runway excursion accidents is much higher than in LOC-I accidents. Hence substantially more fatalities were attributed to LOC-I in the period 2011 – 2015.

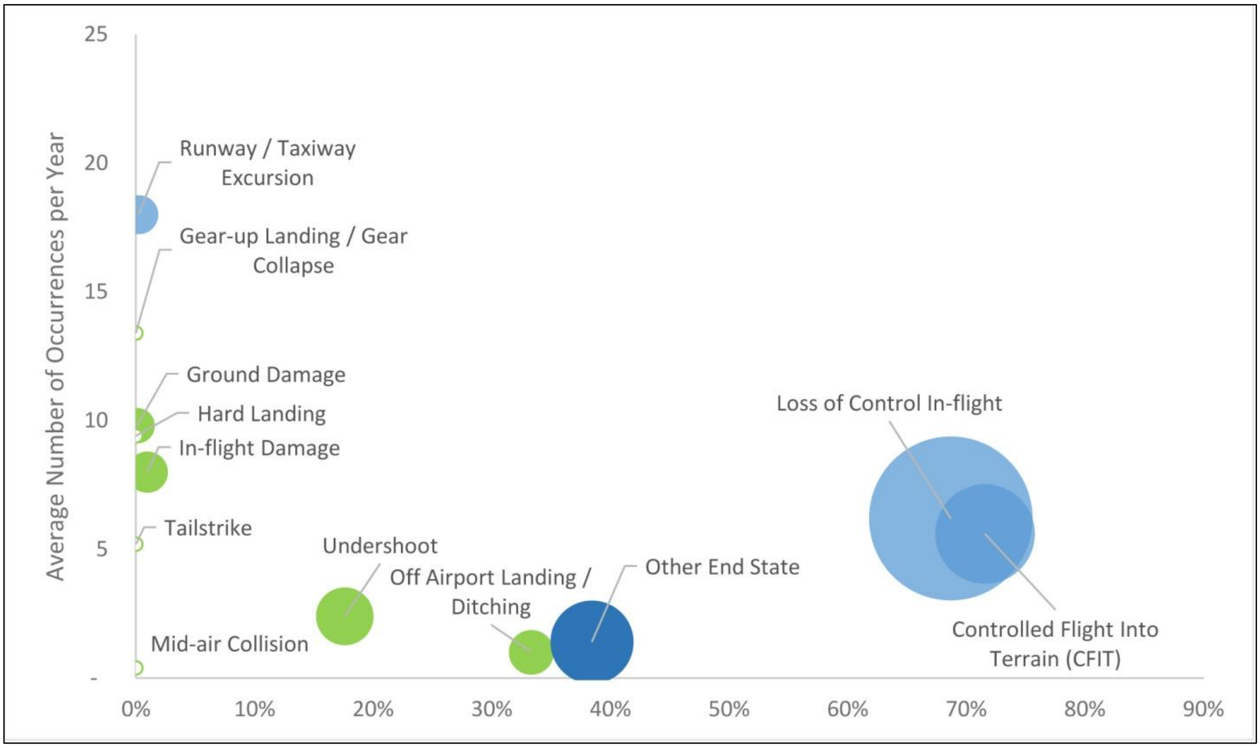

Figure 3. Percent Ratio of All Fatalities by All People Carried (Passenger and Crew)

The IATA Accident Classification Task Force (ACTF) uses specific taxonomy (defined in Annex 2 of the 2015 Safety Report) to categorize the Threats encountered by the crew in each of the accidents. In the terminology of Threat & Error Management (TEM) a Threat is defined as: ‘an event or error that occurs outside the influence of the flight crew, but which requires flight crew attention and management to properly maintain safety margins’. For LOC-I accidents in the period 2011 – 2015 the ACTF identified that 42% encountered meteorological threats (of which 40% included thunderstorms, 40% icing conditions and thirty percent (30%) poor visibility/IMC. The numbers add up to more than 100% because the factors are not mutually exclusive), and thirteen percent (13%) encountered lack of visual reference. These environmental threats were therefore identified in a substantial proportion of the overall number of LOC-I accidents.

The IATA STEADES Database, consisting of air safety reports from numerous contributing operators, recorded almost 4,000 reports of wake turbulence encounter in the period 2010 – 2014. 26% of these encounters were during the approach phase and 22% in cruise, and unsurprisingly it was the heaviest aircraft (A380/B747/B777) which were responsible for creating the vortices in the greatest number of events. In total 155 injuries to passengers and cabin crew were recorded in wake turbulence encounters. When the data is normalized to provide a rate of reports per 1,000 flights, it is apparent that the rate declined over the 5 year period from approximately 0.09 in 2010 to 0.06 in 2014.

VI. Case Studies

Case Study 1: In cruise at Flight Level 350 over the Atlantic Ocean the aircraft entered cloud in the region of the inter-tropical convergence zone (ITCZ – see below). Airspeed indications became erratic, the autopilot and autothrust disconnected and the stall warning activated. The pilots lost control of the aircraft which later crashed into the sea. The investigation concluded that the accident was initiated by large ice crystals obstructing the pitot probes, temporarily rendering the airspeed indications invalid. This condition was known to, but misunderstood by, the industry in general at the time. The loss of airspeed in turn caused the flight control computers to revert to a more basic functionality, in which some flight envelope protections (including the low speed stall protection) were lost, and the autopilot and auto-thrust to disconnect. At the same time the altitude indications reduced by around 300 feet. The startling suddenness of the onset of the warnings, cautions and indication anomalies was considered to be a factor in the pilots' failure to correctly recognise and rectify the situation.

For further information on this case study, please see the following link from BAE:
https://www.bea.aero/fileadmin/documents/docspa/2009/f-cp090601.en/pdf/f-cp090601.en.pdf

Case Study 2: The aircraft took off shortly after a heavy 4-engined aircraft and encountered wake vortex turbulence early in the climb out. The turbulence itself was not catastrophic but the control inputs applied by the pilot flying were so sudden and severe that the ultimate load of the vertical fin was exceeded and it detached. The aircraft became uncontrollable and crashed. It was later identified that the pilot flying had previously undergone training in upset recovery that was not appropriate to the aircraft type involved.

For further information on this case study, please see the following link from NTSB:
http://www.ntsb.gov/investigations/AccidentReports/Reports/AAR0404.pdf

Case Study 3: The aircraft was being flown on an 'acceptance' flight test. During preceding maintenance water had incorrectly been allowed to enter the mechanism of the 'alpha' or angle of attack sensor vane. At altitude the water froze and prevented further movement of the vane, thereby disabling the low speed protections and warnings. When the pilots deliberately entered a low speed regime as part of the test schedule, the aircraft stalled and was not recovered prior to impact with the sea.

For further information on this case study, please see the following link from BAE:
https://www.bea.aero/docspa/2008/d-la081127.en/pdf/d-la081127.en.pdf

Case Study 4: In cruise at FL310 the pilots requested to deviate around weather and subsequently requested a return to the point of departure. The aircraft then began to slow down, before descending rapidly to impact the surface below. The investigation was not complete at the time of writing but it was apparent that both engine pressure ratio (EPR) recordings began to decrease, causing the air speed to reduce. The autopilot gradually increased the angle of attack in order to maintain altitude and eventually the aircraft suffered an aerodynamic stall. The investigation has suggested that engine anti-ice had not been selected on prior to the incident and that engine probe icing was the likely cause of the reduced thrust.

For further information on this case study, please see the following link from BAE:
https://www.bea.aero/docspa/2014/ec-v140724.e1.en/pdf/ec-v140724.e1.en.pdf

Section 1—Meteorology

1.1 Structure of the Atmosphere

For the purposes of this document it is sufficient to consider only that part of the atmosphere which is currently utilised for commercial aviation and which coincidentally is home to virtually all of the relevant meteorological activity – the troposphere, the lower reaches of the stratosphere and the boundary between the two, the tropopause.

1.2 Troposphere

The troposphere is the lowest layer of the atmosphere extending from the Earth's surface to between 20,000 feet and 65,000 feet altitude. The vertical extent of the layer is generally at its lowest at the Poles and highest at the Equator but varies locally with atmospheric pressure and temperature. Approximately 75% of the total mass of the atmosphere is contained within the troposphere, together with virtually all of the entire atmosphere's water vapour. Most of the heat energy in this layer comes from below as terrestrial radiation and conduction, and the temperature generally decreases with altitude in a fairly linear manner. This decrease of temperature with altitude is called the environmental lapse rate (ELR) and averages approximately 2°C per 1,000 feet. Atmospheric pressure also decreases with altitude and although the rate is somewhat exponential throughout the entire atmosphere (greatest rate at lower altitudes), it can be considered to be almost linear within the troposphere. Virtually all of the Earth's weather occurs within the troposphere.

There are six (6) major circulatory 'cells' within the troposphere, three (3) in each hemisphere, which run like belts around the Earth. Strong solar heating in the vicinity of the Equator causes air to warm and rise until it reaches the top of the troposphere, where it begins to flow towards each of the Poles. In sub-tropical latitudes, having cooled, the air tends to sink back towards the surface whereupon it is drawn back towards the Equator to replace the rising air. These are known as the Hadley Cells.

At around 60° of latitude a similar, though much weaker process of heating and rising air occurs and again having risen to the top of the troposphere the air flows towards the Poles, where it descends and is drawn back to temperate latitudes at the surface. These circulations are called the Polar Cells.

In between the Hadley and Polar Cells there exists a reverse circulation, the Ferrel Cells, in which the upper flow is towards the Equator and the surface flow towards the Poles.

1.3 Tropopause

The tropopause is the boundary between the troposphere and the next atmospheric layer above; the stratosphere. It is the surface in the atmosphere at which temperature initially stops decreasing with increasing altitude and remains almost constant. Only the most active of convective weather systems penetrate above the tropopause, due to this significant change in the lapse rate.

1.4 Stratosphere

In the lowest levels of the stratosphere immediately above the tropopause, those which are attainable by commercial aircraft, temperature remains almost constant with increasing altitude and pressure continues to decrease but at a lesser rate than in the troposphere. Very little weather occurs in the stratosphere, especially outside of the tropics.

Section 2—Environmental Phenomena

2.1 Convective Activity

When air is warmed at the Earth's surface it becomes less dense relative to the surrounding atmosphere and will tend to rise. The rising air expands with the decreasing pressure, and its temperature reduces in proportion (Combined Gas Law in which temperature, pressure and volume are directly related). If the air is 'dry' at less than 100% humidity, it will cool at the dry adiabatic lapse rate (DALR) of approximately 3°C per 1,000 feet and if this rate of cooling is greater than the prevailing ELR the air will quickly become colder and more dense than the surrounding atmosphere and the rising effect will cease; this is a 'stable' atmosphere. However, if the rising air is 'saturated' at 100% humidity, or becomes saturated due to the adiabatic cooling, it will cool more slowly with decreasing pressure, at the saturated adiabatic lapse rate (SALR) of approximately 1.5°C per 1,000 feet. Hence as this saturated air rises the temperature differential with the surrounding air may increase with altitude (an 'unstable' atmosphere) and consequently so will the upward force. Only when the rising air encounters a rapidly increasing and stable ELR, or the constant temperature profile at the tropopause, will the differential begin to decrease and with it the convective energy. This is the mechanism which drives convective weather activity.

2.2 Localised Convective Weather

Convective activity can consist of a single 'cell' arising from local surface heating and high humidity, combined with an unstable atmosphere above. The moisture in the rising column condenses into cloud as it cools and then coalesces into water droplets; when it has risen high enough, these freeze into hail and ice crystals. Once these either escape the rising air column or become too heavy for it to support they fall as precipitation, below or close to the base of the convective cloud. The strong thermal ascent and the falling precipitation give rise to fast flowing vertical airstreams – updrafts and downdrafts - which may exist in close lateral proximity to each other. It is a function of this intense motion that leads to the generation of static electricity and lightning. When strong downdrafts encounter the Earth's surface they are deflected outwards in turbulent horizontal flows in phenomena known as micro-bursts. Localised convective weather is generally more frequent in daytime, and especially afternoon, when surface heating peaks but certain local phenomena such as 'lake effect' convection may be more prevalent at night when surface temperature differentials are greater.

2.3 Large Area Convective Weather

2.3.1 Frontal Convective Weather

At the frontal surface between air masses of differing temperatures it is common for many convective cells to be present in a line along the front, especially in cold frontal conditions when cold air is advancing over a warm surface and into warmer air. In such cases the convective cells may interact or combine with each other, creating more severe conditions than would be found in a single cell. The convective activity may stretch for long distances along the front in phenomena known as 'squall lines', which in extreme cases can propagate tornadoes.

2.3.2 Inter-tropical Convergence Zone (ITCZ)

As the name suggests the ITCZ is a zone of converging air, where the surface flows of the northern and southern hemisphere Hadley Cells meet near the Equator. A combination of converging air masses, high humidity and strong surface heating gives rise to vigorous convective activity in a wide band that stretches much of the way around the Earth, and with the troposphere at its geographic highest extent in the same regions, the opportunity for vertical cloud growth is substantial. With the changing seasons, the ITCZ migrates to the north and south throughout the year – to a greater extent over large land masses than over the oceans due to the wider fluctuations in surface temperatures. Pilots can encounter vigorous convective activity stretching for hundreds of miles in all directions within the ITCZ.

2.3.3 Monsoon

To the north and south of the ITCZ blow the 'trade winds', the surface flows of the Hadley Cells which feed air into the ITCZ. In certain parts of the world these strong, sustained wind patterns become moisture laden over large oceans, before they encounter land masses heated by the tropical sun. The combined heat and humidity are sufficient to supply season-long periods of prolonged heavy rain, together with widespread convective activity often embedded in more stable cloud masses. These are the 'monsoons'.

2.3.4 Tropical Revolving Storms

Tropical revolving storms, known variously as 'hurricanes', 'cyclones' or 'typhoons', are born out of intense areas of low atmospheric pressure in the tropical latitudes, formed over a warm ocean surface most frequently in late summer. Fed by the warmth and moisture of the sea these storms suck in strong winds at the surface, which are turned by the effect of Coriolis to create a rotating mass of unstable rising air. It is worth noting that these storms rotate in opposite directions in each hemisphere. From the central 'eye' of the storm, lines of convective cells embedded in more stable clouds radiate out in arcs to the periphery. Once these storms encounter land and the moisture supply is cut off, they usually decay rapidly into large areas of cloud and rain.

2.4 Jet Streams

High altitude jet streams occur in the upper reaches of the troposphere close to the tropopause, at the boundaries between the Hadley and Ferrel Cells (sub-tropical jet streams) and the Ferrel and Polar Cells (polar jet streams). They are principally thermal winds generated by the temperature differential between the air masses in the adjacent circulatory cells but instead of flowing from one cell to the other, they are turned by Coriolis to flow along the cell boundaries. Jet streams can extend to hundreds and even thousands of miles in length and their paths weave up and down across latitudes. The polar jet stream tends to be stronger than the sub-tropical stream and can reach speeds in excess of 200 knots.

2.5 Orographic Effects

2.5.1 Mountain Wave

Mountain Waves – winds in the lower atmosphere are affected by friction with the Earth's surface creating a 'boundary layer' of slower moving air. More significantly long, high mountain ranges can induce a substantial wave effect downwind when strong winds blow from close to perpendicular to the range and the air mass at the peaks is relatively stable. The wave can extend several thousand feet above the peaks and oscillations may continue for hundreds of miles downwind. Vertical airspeeds within the waves may reach 2,000 feet per minute. The 'crests' of the mountain waves can sometimes be identified by lens shaped 'lenticular' clouds.

2.5.2 Rotors

Rotors – level with or below the mountain peaks on the downwind side, a rotating cylinder of air can develop below the crests of the mountain waves. These are often characterised by the appearance of lines of rotor cloud.

Please see the following link on Rotor cloud:
https://www.youtube.com/watch?v=_roxFGsfzto

2.6 Geographical Distribution

2.6.1 Localized convective weather

Localized convective weather – this can occur almost anywhere that there is sufficient humidity and heat in the lower atmosphere and the requisite atmospheric instability (ELR lower than SALR) in the troposphere above.

Please see the following link on Localized Convective Weather:
https://www.youtube.com/watch?v=84LZscIE-sM

2.6.2 Frontal convective weather

Frontal convective weather – these conditions are prevalent wherever air masses of differing temperatures meet but the most vigorous activity tends to be associated with plunges of cold polar air spreading across relatively warm land masses and into warmer air. For this reason the greatest exposure is over the northern hemisphere continents.

2.6.3 Inter-tropical Convergence Zone (ITCZ)

ITCZ – whilst the ITCZ is primarily oriented to the Equator it moves north and south with the seasons, reflecting the latitudes of greatest solar heating and the convergence of the Hadley cells. Because land surface temperatures vary more dramatically with the seasons than ocean temperatures the migration of the ITCZ is more marked over large land masses, where it may reach as far as 30° of latitude.

2.6.4 Monsoon

Monsoon – the effects of monsoon are mostly associated with East Africa, the south part of the Indian sub-Continent, Indonesia, Indo China and northern Australia during the southern hemisphere summer (north east monsoon) and with the entire Indian sub-Continent and most of South East Asia during the northern hemisphere summer (south west monsoon).

2.6.5 Tropical revolving storms

Tropical revolving storms – as the name implies these occur in the regions of the tropics, over large oceans during the hemisphere late summer period. The most frequent and violent storms affect East Asia and the islands of the eastern Pacific Ocean, with the Caribbean, Gulf of Mexico and eastern seaboard of the US a close second. Other prone areas include Central America, Southeast Asia, the eastern Indian sub-Continent, the islands of the southern Indian Ocean and the southern Pacific Ocean, and the north of Australia.

Please see the following link on Tropical revolving Storms:
https://www.youtube.com/watch?v=IPHJcuXh4aw

2.6.6 Jet streams

Jet streams – like the ITCZ the principal latitudes of the jet streams migrate north and south with the seasons but the meandering nature of their paths makes it difficult to generalise on geographical locations. However, the polar jet stream averages around the 60° latitudes and the sub-tropical jet stream around 30° - jet streams would rarely be present close to the ITCZ or to the Poles at the altitudes of commercial aviation.

Please see the following link on Jet streams:
https://www.youtube.com/watch?v=C_HiBj0teRY

2.6.7 Mountain waves

Mountain waves – these are associated with the downwind side of long, high mountain ranges such as the Alps, the Rockies and the Andes and may extend several thousand feet above the peaks of the mountains and hundreds of miles downwind.

Please see the following link on Mountain waves:
https://www.youtube.com/watch?v=juGLWnvJaQc

2.7 Wake Vortices

All fixed wing aircraft create wake vortices to some degree, as a function of the generation of lift on the wings. Higher pressure air below the wing tends to flow outwards and at the wingtip begins a rotational movement towards the lower pressure above the wing. As the wing is always moving forward the rotational flow is left behind as a helical motion in free air. The effect of ‘downwash’ at the wing trailing edge also induces a downward tendency to the vortices. The intensity of motion within the vortices depends upon a number of factors including aircraft speed and wing shape but because lift is inextricably linked to aircraft weight, heavier aircraft generate stronger wake vortices. The lifespan of the vortices is also affected by several different conditions but the longest durations of approximately three (3) minutes can be anticipated in still air or very light winds lower down and in the thinner atmosphere at high altitude.

Section 3—Environmental Threats

Having explored the hazardous environmental factors present in the commercial aviation environment, the following section identifies the individual environmental threats that these phenomena present.

3.1 Convective Turbulence

By its nature convective activity is characterised by rapidly rising masses of air and the high volumes of falling precipitation, coupled with increased air density due to cooling aloft, can create equally rapid downwards air currents inside and around a convective cloud. Because of the low viscosity of air these updrafts and downdrafts can exist in close lateral proximity, leading to sharp changes in vertical motion. An aircraft encountering these 'shears' may sustain severe jolts, disturbances in attitude, sudden gains or losses of altitude and potentially structural damage. If unexpected, or in the worst cases even if the encounter has been anticipated, these effects can be startling and debilitating in terms of situational awareness, pilot performance and decision making. Some LOC-I accidents have included structural damage to the aircraft prior to impact but there is evidence that this is more likely to be sustained during attempts to recover from an attitude/airspeed upset in manual flight, rather than from the turbulence encounter itself. In most cases it is recommended to leave the autopilot engaged.

3.2 Micro-burst

Strong downdrafts within or close to convective activity may eventually reach the surface. These fast moving shafts of cold, dense air, sometimes accompanied by heavy precipitation, meet the ground and spread out horizontally in all directions, creating strong dense winds which overwhelm the prevailing flow. The outward burst of wind may be led by a rolling gust front of very turbulent air. The associated windshear, turbulence and downdrafts can severely degrade aircraft performance and disturb aircraft attitude and flight path.

Please see the following link on Micro-burst:
http://digg.com/video/wet-microburst-video

3.3 Lightning

Aircraft are built to sustain lightning strikes, using bonding and static discharge systems to dissipate electrical charges with minimal damage. However, occasionally severe lightning strikes have damaged or disrupted critical aircraft systems, reducing overall capability and increasing cockpit workload. The sudden and dramatic nature of a lightning strike can again startle pilots and the brightness of the flash may degrade night vision. Damage from lightning strikes may be hard to see but even potential strikes should be reported to maintenance so that the appropriate inspections and checks are carried out.

3.4 Icing

Large convective clouds contain massive volumes of super-cooled water droplets, in liquid form but below 0°C. When the surfaces of an aircraft impinge upon these droplets they are prone to freeze instantly and adhere to the airframe. Airframe icing, if not overcome by anti-icing systems, can lead to loss of lift and increase in weight, with an associated deterioration in aircraft performance. Icing in engine intakes may disrupt the engine gas path, reducing available thrust and potentially leading to flame-out. Probes and sensors which provide vital air data to the aircraft systems may also be affected by icing, leading to system failures and loss of automation. Significant icing can also occur when aircraft are on the ground; pilots and maintenance personnel must be vigilant for ice, frost and snow contamination during pre-flight inspections. If icing is observed the appropriate de-icing and anti-icing procedures must be followed to protect the aircraft prior to departure.

3.5 High Altitude Ice Crystals

Only recently identified as a threat to commercial aviation, small ice crystals have been found to exist in and around the upper reaches of large convective clouds. Satellite based research has identified the highest risk to be downwind of large areas of convective clouds, particularly in the tropics. High altitude ice crystals have been identified as the cause of several engine ‘roll-back’ events, which inevitably affected the aircraft’s flight path and increased cockpit workload. Whilst these very cold crystals will not adhere to the airframe or engine inlets as with conventional icing, it is thought that they partially melt in the high temperatures of the engine core and thereafter build up on internal engine parts[1]. There is also a risk of pitot probes becoming blocked with high volumes of ice crystals, which can overwhelm the anti-icing systems.

3.6 Precipitation

Modern turbine engines are designed to sustain high volumes of water ingestion from flight through heavy rain but in very powerful convective clouds the updrafts can overpower gravity, causing very high concentrations of water droplets to accumulate at some levels. This can be sufficient to impair engine efficiency or even cause a flame out. Hail, common in large convective clouds and growing up to several centimetres across, can cause substantial damage to leading edges, radomes and external sensors, especially when combined with high aircraft penetration speeds. Hail encounters generate significant noise in the cockpit which can be disturbing and distracting for pilots.

3.7 Threats in Clear Air

3.7.1 Clear Air Turbulence (CAT)

Generally associated with high altitude jet streams, CAT is the turbulent interaction of the fast moving air streams with the slower moving air surrounding them. Because of the low viscosity of air, especially at high altitude, the velocity gradient at the margins of a jet stream can be very steep and the resulting turbulence

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[1] source Boeing AERO (http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_07/article_03_1.html)

may be severe. CAT may be encountered anywhere in or close to a jet stream but the strongest effects are most common on the polar and lower margins of the strongest flow rather than inside the main core of the jet stream. CAT can be forecast with some accuracy but cannot easily be detected in flight, so encounters may be sudden and unpredicted. The turbulence may cause significant disturbances in attitude, flight path and speed and encounters can be prolonged if the flight path is parallel to the jet stream.

3.7.2 Mountain Waves

The strong and sustained vertical motion of air between the peaks and troughs of the waves can test the margins of aircraft performance in altitude keeping and challenge pilots and automation in maintaining the desired flight path and airspeed. The sharp changes in air motion in rotors below the waves and to the lee of the mountains can disturb aircraft attitude and cause sudden changes in airspeed.

3.7.3 Wake Vortices

A small aircraft encountering wake vortices from a much larger aircraft may find its flight path dramatically disrupted to the point that control is lost. Larger aircraft may well sustain some sharp and sudden disturbances but are more likely to be able to maintain safe flight. However, automation may not be able to cope in the short term and the autopilot may well disengage during an encounter, leaving the pilots to fly manually in an unanticipated and unfamiliar situation. Data from IATA STEADES identified that the greatest risk of wake vortex encounters in cruise exists approximately 1,000 feet below and 10 – 20 nautical miles behind heavy aircraft types and that a number of injuries to passengers and crew have been sustained in these encounters. Vortex encounters are also reported during arrivals, approaches and departures, especially at busy airfields where controllers may apply minimum longitudinal separations to maintain capacity. Reports included significant bank angle disturbances, autopilot disconnection, aircraft system warnings, TCAS alerts, stick shaker activations and even a few engine stalls. In most wake vortex encounters the magnitude of the deviations and the time-span of the disturbances are sufficiently small that the initial undesired aircraft states are recoverable by pilot control inputs. It is only if these are inputs unduly delayed or incorrect that an unrecoverable LOC-I condition may develop.

3.8 Human Performance Factors

Ultimately the outcome of any encounter with environmental threats is dependent upon the performance of the pilots in managing the disturbances or system degradations that ensue. This may be as simple as monitoring the automation to ensure that flight path and airspeed are correctly maintained or as complex as promptly and accurately recovering from an unusual aircraft attitude in cloud. Pilots would seldom seek to encounter significant environmental threats so such encounters will tend to be unexpected and potentially quite sudden in onset – there is increasing evidence that the ‘startle’ effect can seriously degrade performance for some time after the event and lead to impaired judgement and erroneous decision making. It is widely accepted that the heavy reliance upon automation in modern flight operations has eroded manual flying skills but these may be required at short notice and in challenging conditions to avoid a potential LOC-I situation. There are also physiological factors which may affect performance in turbulence such as disturbances to vision, manual dexterity and even fatigue in prolonged encounters.

Overall human performance can be improved with awareness and training, and operators should seek to continuously measure and improve the efficacy of training programs in maintaining and enhancing pilots' knowledge of the factors contributory to accidents. Threats will always be present in the global operating environment but the more pilots know about them and how best to recognise, manage and mitigate the risks involved, the more likely it is that hazardous conditions will be avoided and flight path deviations recovered before it is too late. One area that has often been overlooked in pilot training is manual handling at high altitude, where aircraft performance is substantially impaired by low air density and airspeed margins are much reduced.

Section 4—Environmental Factors: Mitigations

4.1 Forecasting

The forecasting of weather in general and the associated conditions that are potentially hazardous to aviation in particular has improved significantly in recent years, with satellite imagery providing a global view and powerful computers able to feed vast quantities of data into complex meteorological models. From a strategic and perhaps climatic perspective this can permit operators to make decisions about the time of day they choose to arrive and depart at a specific airfield to avoid diurnal weather conditions, to manage fatigue by rostering appropriate flight crew compositions to accommodate longer or shorter seasonal flight times or to preclude certain arrival or departure routes which may be exposed to specific environmental threats.

However, because accurate weather forecasting is relatively short term, its greatest benefit is in tactical decision making. In spite of any additional cost in fuel and flight time, dispatchers and pilots would be wise to choose a route that skirts around a revolving storm for example, rather than one that goes straight through it, thereby substantially reducing the risk of an encounter with environmental threats. It might seem attractive to reap the benefit of a favourable jet stream but if that means spending several hours in moderate or severe CAT the best risk management choice would be to fly by another route.

Sometimes it might be impossible to avoid a weather phenomenon in spite of the known threats, when it is as extensive and pervasive as the monsoon or ITCZ for example. In such cases the value of forecasting is in awareness and preparation, allowing pilots to consider in advance the likely threats that will be encountered and the appropriate mitigating strategies to be employed. Will engine anti-icing be required for long periods; can they expect significant deviation around weather; should they carry more fuel to facilitate these defensive measures?

Forecast and anticipated meteorological conditions must also be taken into account in managing aircraft system serviceability. The minimum equipment list (MEL) as it applies to airborne weather radar (AWR), ice detection and anti-icing systems must consider the weather *en-route* when permitting or precluding dispatch.

4.2 Detection

In clear weather and daylight it is quite easy to visually identify isolated convective clouds and at night moonlight and flashes of lightning can assist. Whenever flying in areas of potential or forecast activity pilots can minimise the risk of inadvertent penetration by maintaining a vigilant lookout ahead to the horizon and being especially wary of developing convective cloud ahead, which might subsequently reach the cruising altitude. However, convective activity is often found embedded in large areas of less vigorously active cloud and is hence impossible to see.

For many years the principal aid to the detection of convective activity has been AWR. This generally consists of a laterally scanning antenna mounted inside the nose radome, a processor and a display screen, nowadays often incorporated into the horizontal situation or navigation display. In the cockpit the pilots have controls to switch the system on and off, adjust the displayed range, vary the angle of tilt at which the antenna is scanning and adjust the gain of the radar return signal. The principle of operation relies upon a proportion the transmitted radar energy being reflected back to the antenna by water droplets within a cloud and therefore it is actually a system to detect droplets not turbulence. The strongest convective turbulence is often associated with the boundaries of greater concentrations of large droplets, where updrafts and downdrafts meet so the principle can be reliable but these densely packed droplets can sometimes absorb much of the radar signal energy and effectively conceal further areas of heavy rain and turbulence beyond them.

Within big convective cells, turbulence and sometimes severe turbulence can exist without the presence of droplets. In particular AWR is very poor at detecting ice crystals, which constitute much of the water content in the upper levels of convective clouds and can even be present outside of cloud. Flight in high concentrations of ice crystals is sometimes characterised by St Elmo's fire and an unusual 'tinkling' sound from impact on the windscreen, different from the 'hissing' sound of water droplets.

In order to derive the greatest detection benefit from AWR pilots must actively manipulate the tilt control, searching lower levels for water droplet returns that may hint of ice and turbulence higher up. Some modern AWR systems allow each pilot to select an individual tilt angle, such that the antenna will scan at one angle on the first sweep and a different angle on the next. This allows a better understanding of the structure of the clouds without additional tilt adjustments. Other modern systems use the Doppler principle to detect the vertical motion of water droplets in clouds to provide a more accurate picture of likely downdrafts and turbulence. Care must be taken to avoid confusing ground returns for the presence of bad weather or *vice versa*. The gain control can be used to filter out noise and clutter on the display and to reveal the more significant weather returns but care must be taken not to leave the gain attenuated for long periods.

The most sophisticated 'multi-scan' weather radars automatically scan at a variety of tilt angles and ranges, and then store scan data in a memory from which to create a virtual picture of the weather ahead. They also use internal algorithms to filter out ground returns to present pilots with the clearest and most comprehensive convective weather displays currently available.

Some aircraft are equipped with predictive windshear radar (PWR) but as with AWR it in fact detects raindrops not windshear. The purpose of PWR is to warn pilots of likely turbulence and windshear ahead when at lower altitudes on approach and departure. By detecting and warning of very high concentrations of raindrops PWR gives pilots the opportunity to prepare for potential micro-burst encounters, with strong downdrafts, turbulence and windshear that could compromise aircraft performance and upset the flightpath.

The greatest risk of airframe icing exists in the concentrations of cold and super-cooled water droplets in the lower and mid-levels of convective clouds and hence AWR is useful in warning pilots of areas of likely icing conditions. However, it is to be expected that pilots would already have taken action to avoid significant AWR returns anyway. Most aircraft are equipped with systems to detect icing or potential icing conditions and to alert pilots to use appropriate anti-icing systems (see 4.3 Icing Management below).

AWR provides no assistance in detection of environmental phenomena in clear air – CAT, mountain wave and wake vortices. The first sign of the presence of CAT may be the manifestation of turbulence, which may be sudden and severe, although indications of high wind speeds at altitudes close to the tropopause may well be a precursor. Mountain wave may be apparent from long lines of lenticular cloud running parallel to a mountain range on the downwind side but otherwise the first signs may be unusually high or low thrust settings required to maintain the selected airspeed/Mach number in the upward and downward phases of the waves. Turbulent rotors on the lee side of mountains may also be indicated by linear rotor clouds. Wake vortices offer little opportunity for detection but they can to some extent be predicted when flying close behind a large aircraft on arrival and departure. At cruising altitudes, condensation trails from other aircraft may give some indication of the location and likelihood of wake vortices.

Pilot reports in flight or ‘PIREPS’ offer an opportunity for flight crews to share information on potentially hazardous conditions. This is especially common for reporting CAT at various altitudes and provides following aircraft a form of real-time turbulence detection. Pilots may be able to gain useful situational awareness regarding convective activity by listening to lateral deviation and level change requests made by aircraft ahead. PIREPS are also a vital source of information regarding windshear at low altitude on approach and departure.

Agencies on the ground may also be able to detect the presence of convective weather activity and pass the information to pilots. In addition to ground based weather radar (where available) primary surveillance radar detects precipitation and in particular water droplets in the same way as AWR, and the returns may appear on the controllers’ screens, as long as there is not software in the signal processing to suppress or filter out the weather returns as ‘clutter’. Real time satellite imagery may be available to Dispatchers who can then communicate the developing situation to pilots in flight or even transmit imagery direct to the aircraft. Evolving electronic flight bag (EFB) technology should facilitate the communication of accurate and timely weather information.

4.3 Icing Management

Icing on the ground is managed by three critical functions: inspection; de-icing, and; anti-icing. During cold weather operations with temperatures close to or below 0°C (32°F), especially during precipitation and/or high humidity it is vital that the airframe and engines are inspected for ice and snow accumulations in accordance with the manufacturer’s guidance. Even in warmer ground temperatures, significant icing may have accumulated on the cold airframe during descent. As a general rule, no amount of ice is safe, although some procedures do permit small accumulations in specified areas of the airframe. If icing is observed the aircraft must be de-iced using the relevant Standard Operating Procedure (SOP) and/or the applicable engine ice shedding procedure – after de-icing it is customary for the flight crew to rely on the service provider to ensure that the airframe is free from ice. If further ground icing is a possibility it is essential that the de-icing process includes an anti-icing function in order to protect the aircraft for the time required to taxi to the runway and take-off, after which the aircraft’s airframe ice protection systems may be operated. The duration of anti-ice protection is dictated by the applicable ‘holdover time’ charts and if exceeded the aircraft must return for further protection. Once turbine engines are running in temperatures below approximately 10°C (50°F) and high humidity (visible atmospheric moisture) there is a risk of icing on intakes and cowlings, and engine ice protection systems must be operated. Probe heating must be selected on as specified in the SOPs and thereafter it is usually managed automatically.

In the air pilots must pay heed to the ice detection systems and be vigilant for accumulations of ice in areas visible to them. If airframe icing is detected or suspected in flight, the airframe ice protection systems must be operated in accordance with the SOP. Engine ice protection should generally be operated in the air in the same conditions as on the ground or when icing is suspected but most manufacturers recommend that engine anti-icing is not required in outside air temperatures below minus 40°C (- 40°F).

4.4 Avoidance in Flight

According to the 2015 IATA Safety Report 16% of all LOC-I accidents in the period 2011 – 2015 included an undesired aircraft state (defined in the terminology of TEM as ‘a flight crew induced state that clearly reduces safety margins’) of unnecessary weather penetration.

Historically industry guidance has advised pilots to avoid Cumulonimbus convective cloud by 20 nautical miles laterally, thereby ensuring separation from most of the threats inside and around the cloud. It has also warned against flying over the tops of convective activity, especially when it appears to be building in altitude and intensity, and to avoid the area beneath cloud ‘anvils’ or overhangs where hail, ice and turbulence may be present. Turbulence and precipitation generally extend further on the downwind side of convective cloud and it is generally preferable to fly upwind. Climbing to avoid convective weather also narrows the airspeed range between low speed stall and the maximum speed (V_{MO}/M_{MO}), reducing the margins of aircraft performance within which to manage any flight path disturbance or engine malfunction resulting from encounters with convective weather.

However, experienced pilots know that convective clouds seldom exist in single, easy to avoid units, instead tending to appear in group of cells often at differing stages of development and frequently embedded in more general cloud. In such cases it may be necessary to deviate significantly from the planned track by 100 miles or more in order to maintain separation. In many cases such big deviations may not be permitted by air traffic control due to the proximity of other airways or restricted airspace, or alternatively there may not be sufficient fuel available to facilitate the desired deviation. In large areas such as the ITCZ, convective activity may stretch for hundreds of miles across the aircraft’s track and it may simply be impossible to fly around it.

When it becomes necessary to penetrate an area populated with several convective cells, at an altitude close to or below the cloud tops, pilots may have to abandon the ‘ideal’ separation distance of 20 nautical miles and adopt a different avoidance strategy. AWR uses display intensity or colour to indicate areas of the greatest concentrations of water droplets and with experience pilots learn how to pick their way through a cloud mass, avoiding likely encounters with undesirable turbulence. This becomes a very personal and subjective process, and although guided by general principles of best practice such as to stay upwind, it is by no means 100% effective. It is therefore unsurprising that very little specific guidance exists on how best to manage the transit of convective cloud concentrations, other than procedures for severe turbulence penetration which are unlikely to be appropriate for routine operations. Whenever it is essential or desirable to deviate from the flight plan route, this should be managed in co-ordination with ATC if at all possible.

Proactive avoidance of CAT in flight may be more difficult because it is hard to detect but once it has been encountered or if it is reported by aircraft ahead, pilots may be able to avoid the worst turbulence by requesting a level change. Of course many other aircraft in the area may have the same idea so that traffic congestion and operational constraints may render the desirable levels unavailable. Alternatively there may not be enough fuel remaining to allow prolonged flight at a lower level, or the aircraft may be too heavy to climb. It would be unusual for pilots to attempt to escape an area of CAT by lateral deviation because the affected area can be very wide and the associated turbulence somewhat unpredictable.

Mountain wave is likely to be even more difficult to avoid due to the vast area, both horizontally and vertically, throughout which the effects may be apparent.

Wake vortices on arrival and departure are best avoided by application of the appropriate separation distances, and this lies mainly in the hands of air traffic controllers. However, even when these distances are correctly applied, pilots need to be alert to the possibility of encounters especially in calm or light wind conditions. At cruising altitudes pilots may be able to reduce the risk of wake vortex encounters by flying a lateral offset from the airway centreline, appropriate to the prevailing wind conditions.

Severe airframe, engine and sensor icing is likely to be avoided if the techniques to avoid convective activity are followed but pilots must ensure that anti-icing systems are utilised as directed. In most cases, other than in the most severe icing conditions in convective cloud, the anti-icing systems should keep the aircraft safely free of ice if used in accordance with SOP. However, high altitude ice crystals may be encountered in concentrations dense enough to overwhelm probe and engine anti-icing systems – the best advice to avoid them is to give a wide berth to the downwind side of large areas of convective activity, where ice crystals have been found to congregate.

4.5 Recognition

The transition from normal stable flight to a potential LOC-I event may be gradual or it may be quite sudden but there is a period of transition in all cases. It is this period that allows pilots the opportunity to recognise that all is not well and to intervene to prevent further deviation or recover to stable flight conditions. Two factors are essential in order to ensure that recognition occurs before it is too late.

The first of these factors is effective monitoring. Normal procedures for all aircraft include a requirement for the pilots to monitor critical flight parameters regularly throughout the flight but it has long been understood that humans are not good at routine monitoring over protracted periods of time. A combination of boredom, complacency and distraction can insidiously impair the quality and efficacy of monitoring. The simple reliability of modern aircraft systems and flight automation has the result that for hour after hour, flight after flight, pilots monitor 'nothing' happening and it is easy for them to develop a mind-set that nothing will continue to happen. Pilots have been known to read newspapers or books during flight, watch videos on portable devices or even to fall asleep (inadvertently rather than during authorized controlled rest) instead of executing the routine monitoring duties required by SOP. Hence, if a parameter begins to deviate it may be some time before this is observed and recognised by the pilots. It may be that they have had so little exposure to deviations of this type that they are unable to assimilate what is happening or they may be startled and incapable of an appropriate response.

The second critical factor is a sound knowledge of what 'normal' looks like for any phase of flight. Pilots must know approximately what thrust setting, airspeed and attitude to expect throughout climb, cruise, descent and approach for a variety of aircraft weights and at the full range of altitudes. Only when armed with this knowledge can they expect to quickly recognise an unusual thrust setting in mountain wave for example, or the beginnings of an attitude upset. This may sound obvious but once again the reliability of automation can lead to an erosion of the basic knowledge of flight parameters, because pilots rarely have any need of it. These values are usually available in the aircraft flight manuals but the data presentation can be quite complex. A more simple data set is commonly published in the abnormal procedures for flight with unreliable or erroneous airspeed indications, itself a potential LOC-I precursor.

Analysis in the IATA 2015 Safety Report showed that 25% of LOC-I accidents in the period 2011 – 2015 included an 'undesired aircraft state' of vertical/lateral speed deviation, and 21% included operation outside aircraft limitations. Effective monitoring and a sound knowledge of parameter values may have helped the pilots recognise these undesired states and recover to normal flight. Recurrent training in manual flight at high altitude could also better equip pilots to cope with unexpected loss of automation.

4.6 Reporting

In order for operators individually and the industry collectively to improve knowledge and understanding of LOC-I precursors it is essential that pilots report encounters with adverse weather and any consequent flight parameter deviations or systems malfunctions. Experienced pilots might have encountered the ITCZ for example on hundreds of flights in their careers and may be inclined to regard turbulence as routine. However, many upsets begin with some kind of flight path disturbance and/or system anomaly and the frequency of these non-catastrophic events could provide an indication of risk exposure. Through programs such as IATA STEADES operators can share and learn from each other's experiences.

An effective and comprehensive flight data management (FDM) program can provide operators with valuable data on the frequency and magnitude of flight path disturbances and engine or system anomalies related to environmental effects. Trends in event characteristics, geographical locations and seasonal variations may reveal specific areas of higher risk to be avoided or pilot behaviours that need to be managed through awareness and education. Feedback to pilots based upon reporting and FDM, in accordance with the principles of a safety management system, can enhance operational knowledge and understanding, and inform recurrent training programs. Awareness of individual safety events, local and seasonal trends and aircraft technical failures helps pilots to prepare for operational reality.

4.7 Resilience

Each of the mitigation strategies described above: Forecasting; Detection; Avoidance; Recognition; Reporting, adds another layer of operational resilience to counter the risk of LOC-I accidents resulting from environmental factors. The global operating environment for commercial aviation inevitably holds numerous potential threats and it is only through resilience in depth that we can best defend against them. This multi-layered operational approach does not stop at forecasting, detection and avoidance but accepts that there may be times when pilots will have to actively manage their aircraft's performance from a potentially hazardous flight condition to a normal and safe regime, using their training, technical knowledge and company procedures in a professional and orderly fashion.

Section 5—Conclusions

As an accident category, LOC-I has accounted for numerous fatalities in commercial aviation and environmental factors such as turbulence, icing and wake vortices have been identified as contributory to many of the LOC-I accidents in the period 2011 – 2015. As with all hazards, these environmental factors and their attendant risks must be managed by individual operators as part of a comprehensive safety management system (SMS), and within the state safety program (SSP) of national and supra-national aviation regulators.

Many hazardous environmental phenomena can be accurately forecast and operators have the opportunity to plan flights in order to avoid some of the threats. Once airborne pilots primarily rely upon visual observations and AWR to detect convective activity but this is only effective if the AWR is actively managed in range, tilt and gain. Every effort must be made to avoid the most hazardous areas in and around convective cloud in order to mitigate the risk of LOC-I. Threats in clear air are less easy to detect and pilots must rely on forecasts and pilot reports – CAT is frequently not detected until an actual encounter. Wake vortices can be predicted and pilots can anticipate the likelihood of an encounter in many cases. In all cases the key to a safe outcome is early recognition of any deviation from the flight characteristics of speed, attitude and thrust so that appropriate interventions can be made to prevent an unrecoverable situation from developing.

Reporting, recording and analysis of encounters with environmental precursors, even though they have no lasting impact on the flight, can help to provide the industry with a more accurate understanding of the threats, and from which to develop effective mitigations. Overall, operators and pilots must develop a multi-layered resilience to LOC-I, using all of the resources available to them.

Section 6—Recommendations

6.1 Operators

6.1.1 Recognise within their safety management system (SMS) the full potential for environmental factors to increase the risk of LOC-I;

6.1.2 Identify the hazards of environmental phenomena present within their operating environment and assess the attendant risks;

6.1.3 Promulgate a clear policy with regard to managing the risks of environmental factors, including use of forecasting, defensive flight planning and avoidance in flight;

6.1.4 Ensure that dispatchers and pilots are trained and aware of environmental hazards such as the ITCZ, high altitude ice crystals and wake turbulence, and the best practices for risk mitigation;

6.1.5 Ensure that pilots are aware of the parameters of normal flight in the full range of operating conditions and can quickly recognise deviations;

6.1.6 Ensure that pilots have the necessary training and procedures to manage their aircraft back to normal flight following a disturbance;

6.1.7 Include manual flying where appropriate in simulator training sessions, especially at high altitude, at the edges of the envelope and with abnormal system conditions;

6.1.8 Encourage the reporting of environmental hazards and flight path deviations which did not have a serious outcome;

6.1.9 Use FDM to detect trends and exceedances arising from environmental factors.

6.2 Pilots

6.2.1 Know the flight parameters of air speed, attitude and thrust for 'normal' flight in the full range of operating conditions and altitudes (these can often be found in the procedures for flight with unreliable or erroneous airspeed indications);

6.2.2 Actively monitor flight parameters for deviations from 'normal', especially in areas where environmental threats are forecast or likely;

6.2.3 Be aware of the impact of boredom, fatigue, complacency and distraction upon effective monitoring;

6.2.4 Seek opportunities in simulator sessions to practice manual flying skills in abnormal flight conditions, especially at high altitude;

6.2.5 Know and consistently apply the procedures for use of aircraft anti-icing systems and turbulence penetration;

6.2.6 Be alert to the circumstances when wake vortex encounters are more likely and brief accordingly.

6.3 Dispatchers

6.3.1 Reduce the risk of encounters with environmental hazards by planning flight routes away from forecast and likely locations;

6.3.2 Bring significant environmental phenomena to the attention of pilots as appropriate;

6.3.3 If possible during flights, keep pilots informed of developing environmental phenomena.

6.4 Air Navigation Service Providers

6.4.1 Ensure that air traffic controllers are trained and aware of environmental hazards such as the ITCZ, high altitude ice crystals and wake turbulence, understand likely pilot responses and the best practices for risk mitigation;

6.4.2 Review and manage aircraft separation procedures to reduce the likelihood of wake vortex encounters at all flight phases, while maintaining an appropriate level of operational efficiency and capacity;

6.4.3 Ensure where possible that pilots are notified of likely wake vortex encounters.

6.5 Manufacturers

6.5.1 Ensure that aircraft behaviour characteristics are benign and unchallenging during turbulence encounters;

6.5.2 Develop improvements to flight path ‘protections’ and aircraft protection systems such as anti-icing to maximise tolerance to environmental threats.

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