Annals of MIRCE Science

"MIRCE Science is a theory of the motion of working systems through MIRCE Space resulting from any functionability actions whatsoever, used for Management of In-service, Reliability, Cost & Effectiveness."

Dr J. Knezevic, Founder, 1999

MIRCE Science: Clear Air Turbulence as a Mechanism of the Motion of Aircraft through MIRCE Space

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Abstract

MIRCE Science is a theory of the motion of a working system through working process, resulting from any imposing natural and human action whatsoever. Clear air turbulence is a unique natural action that occurs when turbulent masses of air moving at different speeds collide without visual clues, often blindsiding pilots as result. This form of turbulence could be dangerous for passengers and crew who are moving around the cabin when it occurs or sitting without their seatbelts fastened. Hence, the main objective of this paper is to understand the physical mechanisms that generate the occurrences of clear air turbulence and assesses their impacts the motion of an aircraft through MIRCE Space. The available methods for dealing with this imposing functionability action in respect to the provision of safety and protection are also addressed in the paper.

Key words: MIRCE Science, working process, clear air turbulence, functionability performance

Citation: Knezevic, J., MIRCE Science: Clear Air Turbulence as a Mechanism of the Motion of Aircraft through MIRCE Space. Annals of MIRCE Science. MSA2024-12-9. MIRCE Science, Exeter, UK, 2024.

Published: 9 December 2024

MIRCE Science unique identifier: MSA2024-12-9

1. Introduction

Aviation is an important mode of transportation process that enables people and cargo to be moved quickly and efficiently across long distances. However, the imposing meteorological actions, like: thunderstorms, icing, turbulence, fog and so forth make significant impacts on the aviation working process and performance.

On 22nd May 2024 Singapore Airlines B777, was flying from London Heathrow to Singapore Changi Airport, with 211 passengers and 18 crew members on board. When it reached Thai airspace an unexpected severe turbulence developed causing severe injuries to 7 passengers, 32 passengers and crew had moderate injuries (16 of which were transported to the hospital) and 14 were treated at the airport. Regretfully one elderly passenger died[1]. The damage to the interior of the aircraft was substantial according to the passengers that confirmed that “overhead bins were dented and ceiling panels where oxygen masks drop from were broken as people's heads went straight through”. Although the full investigation of this accident will be performed by relevant aviation authorities, the aviation specialist accepted that the cause was Clear Air Turbulence (CAT).

The last accident caused by CAT with fatalities took place in March 1966. The BOAC B606 was on a scheduled flight service from Tokyo to Hong Kong. While the flight 911 “treated” their 113 passengers to a close-up view of Mount Fuji, the disaster struck violently and without warning. Extreme air turbulence in the wake of the volcano ripped the Boeing 707 apart in midair, sending it spiralling downward toward the world’s most iconic mountain in full view of hundreds of witnesses. None of the 124 people on board survived the catastrophic plunge from 16,000 feet.

Turbulence, resulting from atmospheric disturbances and variations in wind speed and direction, could be highly dangerous for aviation. It can occur in various forms, such as: thermal turbulence, orographic turbulence and CAT. [1]

The National Transportation Safety Board in the USA (NTSB) analysis of CAT concluded that between 2009 and 2022 over 163 passengers sustained severe injuries from turbulence onboard commercial flights. The majority of those injured were flight attendants who were working in the cabin when the events occurred. A brief description of several CAT related events are given in appendix A.

According to Delta Air Lines and NASA, up to two-thirds of flights deviate from the most fuel-efficient altitude due to turbulence. Each of these deviations adds 41 minutes, on average, to the duration of the flight. Consequently, fuel is wasted, up to 600×10^6 litres annually, which contributes 1.5×10^6 tonnes of unnecessary CO_2 emissions to climate change (equivalent to the annual emissions of 324,000 cars). Thus, airlines should start thinking about how to manage the increased turbulence, as it costs the aviation industry $150–500 million annually in the USA alone[2].

The main objective of this paper is to investigate the clear air turbulences, as a mechanism of the motion of an aircraft through MIRCE Space, which compels additional flying hours for delivering the transportation function required.

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[1] https://simpleflying.com/severe-turbulence-singapore-airlines-london-flight-causes-fatality-injuries/
[2] https://www.nationalgeographic.com/travel/article/what-is-turbulence-explained

The available methods for dealing with this imposing natural action in respect to the provision of safety and protection of aircraft are also addressed in the paper, as every additional minute spent travelling through turbulence increases structural damage to the aircraft and increases the probability of injuries to passengers and crew members.

2. Brief Overview of MIRCE Science

MIRCE Science is a theory of the motion of working system[3] through a working process compelled by any imposing functionability action whatsoever. The kernel of MIRCE Science is the scientific understanding of the phenomena that generate functionability actions in order for accurate predictions of the expected trajectory to be made by making use of Mirce Functionability Axioms and Equations. [2]

In accordance to MIRCE Science philosophy at any instant of time a working system could be could be in one of the following two states, from functionability point of view:

- Positive Functionability State (PFS), a generic name for a state in which a system is able to deliver measurable function(s)
- Negative Functionability State (NFS), a generic name for a state in which a system in not able to deliver a measurable function(s), from any reason whatsoever.

Being in one of these two functionability states is a physical manifestation of the motion of system functionability through working process. This motion is compelled by any imposing functionability actions, which in MIRCE Science are classified as following:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS,
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

The mechanisms, nature, frequency and complexity of functionability actions, positive and negative, are specific to each system, but the sequential transitions to a corresponding functionability state is common for working processes.

The motion of working system through the functionability states is physically manifested through the occurrences of functionability events which, according to MIRCE Science philosophy, are classified as following:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence during a working process that signifies the transition of a system from a NFS to a PFS,
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence during a working process that signifies the transition of a system from a PFS to a NFS.

[3] Working system is a collection of mutually related resources that is able to deliver a measurable function(s) under given constrains.

Consequently, a working process could be considered as the motion of working system through functionability states through time. The pattern generated forms the functionability trajectory that uniquely determines the functionability performance of the functionability system engaged in a given working process. [2]

Research studies conducted at MIRCE Akademy by staff and students had shown that any serious studies of the mechanisms of the imposing functionability actions have to be based between the following two boundaries [2]:

- the "bottom end" of the physical world that is at the level of interactions between the atoms and molecules of working system engaged, which is in the region of 10^{-10} of a metre.
- the "top end" of the physical world that is within boundaries of the actions within the solar system, which is within a region of around 10^{+10} of a metre.

This range is the minimum sufficient "physical scale" which enables scientific understanding of relationships between physical phenomena that take place in the natural environment and the functionability mechanisms that govern occurrences of functionability events of the given working process.

3. The Earth Atmosphere

The atmosphere of the Earth is a thin spherical shroud containing a mixture of gases that are retained by gravitational attraction. Its highest layer extends up to $10x10^3$ km (exosphere), containing extremely low densities of hydrogen, helium and several heavier molecules. The atoms and molecules are so far apart that they can travel hundreds of kilometres without colliding with one another, no longer behaving like a gas, and finally escaping into space.

The lowest layer of the atmosphere, the one in which humans live, is called the troposphere[4], and it hosts what is commonly known as weather. It extends to about 11 km. The troposphere undergoes vertical air movement, for example, convection, an upward motion of air due to heating. This effect may alter the lapse rate and cause instability. The rising air gets colder. Once the moisture in the air reaches saturation at the dew-point temperature, it condenses on the huge number of aerosols, dust particles, salts, ions, and so forth, which are contained in the air. The resulting movements of clouds, thunderstorms, and precipitation are part of the origin of local weather, making the meteorological prediction of local weather difficult. [3]

Global circulation, however, concerns a more constant meteorological pattern, driven by the overall effects of sun's radiation. Local weather, in a larger geographical area, results from a perturbation – or disturbances – superposed on the basic global pattern. Because of the higher position of the sun in the sky, more energy is delivered by radiation to the equatorial regions. In complicated interactions of pressure and radiation differences occurring at all latitudes, air rises near the equator and flows at high altitudes toward the poles.

[4] The Greek word *tropos* means turning; turbulent air motion results in continual mixing.

Due to the Earth rotation, however, all motions are affected accordingly in respect to the latitude. The force caused by the rotation of the Earth, known as Coriolis[5] force, pushes moving objects out of their straight path. Flows moving away from the equator turn to the east (to the right) in the Northern Hemisphere and westward in the Southern Hemisphere. The law applied to ocean currents as well, and the Gulf Stream is the prime example found north of the equator.

3.1 Aviation portion of the atmosphere

The composition of the air in the aviation portion of the atmosphere, which is approximately up to 11 km above sea level, are gases that include nitrogen, oxygen, argon, carbon dioxide and water vapour, together with solid particles such as dust, sand and carbon (smoke), with traces of other gases such as helium, hydrogen and neon.

The density of gases and solid particles is the greatest near the surface of the Earth due to the weight of the air above. This value decreases with increase of the height. This reduction in density affects the amount of water vapour present in the air and it decreases with the increase of height, so that the lower stratosphere is almost dry.

The most important single property of the atmosphere is its variability, both horizontally and vertically in pressure, regarding the following physical properties:

- Atmospheric pressure, which is defined as the weight of air in the column above unit area of the Earth's surface. It is expressed in millibars, which are equal to 100 N/m^2.
- Temperature, which is the most controlling factor in meteorology. Change in temperature leads to density changes which cause vertical air movement and changes in pressure leading to horizontal air movements and winds.
- Humidity, which represents the amount of water in the air. As the water vapour is completely transparent it has to be measured. The amount of water vapour in a unit of air is called the absolute humidity. Water vapour can change to water droplets, liquid water and to ice. When and how this occurs, and the processes involved is germane to the formation of cloud and fog and to precipitation.
- Wind, which is the sustained movements of air from one place to another. The wind velocity reflects its speed and direction. Wind speed is given in knots.

Visibility is defined as the furthest horizontal distance that a dark object can be seen by an observer with normal eyesight. It is measured in meters at eye level above the ground. Thus, visibility reflects the clarity of air, or how obscured it is. Reasons for obscurity are in two categories; water and ice crystals in the air and solid particles such as dust, sand and smoke.

3.2 The impact of weather on aviation

Weather phenomena have a significant impact on aviation operation, from a safety point of view. Hazards generated by weather embrace a wide range of atmospheric conditions that can affect functionability of the air transportation process.

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[5] Gaspard de Coriolis (1792-1843), a French mathematician, mechanical engineer and scientist, who experimentally calculated the effects and mechanics of the Earth's turning, in 1935 (Paris).

The most common weather hazards are briefly presented below:

- Thunderstorms; a natural phenomenon that are able to generate severe turbulence, strong winds, heavy rain, hail, and lightning strikes. These hazards pose risks to aircraft during takeoff, landing, and en route.
- Wind Shear; a natural phenomenon that is manifested as a sudden change in wind speed and/or direction, which can lead to unstable air conditions. It poses a significant risk during takeoff and landing, as it can cause sudden changes in airspeed and affect aircraft control.
- Fog and Low Visibility; a natural phenomena that reduce visibility and can lead to delays or diversions. In these situations pilots rely heavily on instrument landing systems and other navigation aids for safe operations.
- Snowstorms and Ice; a phenomena which if deposited on aircraft surfaces can affect aerodynamics and increase drag. De-icing procedures are crucial before takeoff and during the flight are applied to prevent affected aircraft performance.
- Turbulence; a natural phenomenon that results from strong air currents and is a common hazard during certain weather conditions. It can cause discomfort to passengers and crew and potentially lead to injuries if not managed properly.

4. Air Turbulence

Turbulence is caused by the relative movement of disturbed air through which an aircraft is flying. Its origin may be thermal or mechanical and it may occur either within or clear of cloud. The absolute severity of turbulence depends directly upon the rate at which the speed or the direction of airflow, or both, is changing[6].

Significant mechanical turbulence occurs from the passage of strong winds over irregular terrain or obstacles. Less severe low level turbulence can also be the result of convection occasioned by surface heating.

Turbulence may also arise from air movements associated with convective activity, especially in or near a thunderstorm or due to the presence of strong temperature gradients near to a Jet Stream.

Very localised, but sometimes severe, Wake Vortex Turbulence may be encountered when following or crossing behind another aircraft. This turbulence is due to wing tip trailing vortices generated by the preceding aircraft; however, this phenomenon is distinctively transient.

Air moving over or around high ground may create turbulence in the lee of the terrain feature. This may produce violent and, for smaller aircraft, potentially uncontrollable effects resulting in pitch and/or roll to extreme positions.
Relative air movements which involve rapid rates of change in wind velocity are described as wind shear and, when severe, they may be sufficient to displace an aircraft abruptly from its intended flight path such that substantial control input is required to compensate. The consequences of such encounters can be particularly dangerous at low altitude where any loss of control may occur sufficiently close to terrain to make

[6] https://skybrary.aero/articles/turbulence

recovery difficult. The extreme down-bursts which occur below the base of cumulonimbus clouds called Microbursts are a classic example of circumstances conducive to Low Level Wind Shear[6].
For the purpose of reporting and forecasting of air turbulence, it is graded on a relative scale, according to its perceived or potential effect on a 'typical' aircraft, as Light, Moderate, Severe and Extreme.

- Light turbulence is the least severe, with slight, erratic changes in attitude and/or altitude.
- Moderate turbulence is similar to light turbulence, but of greater intensity - variations in speed as well as altitude and attitude may occur but the aircraft remains in control all the time.
- Severe turbulence is characterised by large, abrupt changes in attitude and altitude with large variations in airspeed. There may be brief periods where effective control of the aircraft is impossible. Loose objects may move around the cabin and damage to aircraft structures may occur.
- Extreme turbulence is capable of causing structural damage and resulting directly in prolonged, possibly terminal, loss of control of the aircraft.

In-flight turbulence assessment is essentially subjective. Routine encounters involve light or moderate turbulence, although to inexperienced passengers (or pilots), especially in small aircraft, these conditions may seem to be severe.

The perception of turbulence severity experienced by an aircraft depends not only on the strength of the air disturbance but also on the size of the aircraft - moderate turbulence in a large aircraft may appear severe in a small aircraft. Therefore, pilot reports of turbulence should mention the aircraft type to aid assessment of the relevance to other pilots in, or approaching, the same area.

5. Clear Air Turbulence

Clear-air turbulence is a common and hazardous form of turbulence for aircraft to encounter. It is invisible from the cockpit and undetectable by satellites and on-board weather radar. The International Civil Aviation Organisation (ICAO) defines it as turbulence generated in clear air, in regions without clouds, which is invisible to the naked eye.

The U.S. Federal Aviation Administration (FAA) defines CAT as “sudden severe turbulence occurring in cloudless regions that causes violent buffeting of aircraft”. CAT is higher altitude turbulence (normally above 15,000 ft) particularly between the core of a jet stream and the surrounding air. This includes turbulence in cirrus clouds, within and in the vicinity of standing lenticular clouds and, in some cases, in clear air in the vicinity of thunderstorms. The thunderstorms can generate CAT that extends 20 miles or more from the edge of an anvil cloud. This type of turbulence is sometimes referred to as Convectively Induced Turbulence (CIT).

5.1 Common causes and sources of CAT

Clear-air turbulence is generated by Kelvin–Helmholtz shear instabilities, which may be initiated by gravity waves in an otherwise stable shear flow. The spontaneous emission of gravity waves from balanced flow had historically been regarded as an unimportant source of atmospheric gravity waves. However, research led by Williams [3] showed that balanced flow spontaneously generates gravity waves at a much larger rate than previously thought – decaying to zero slowly (linearly) with the Rossby number[7], rather than exponentially. This evidence was obtained by analysing a novel laboratory experiment using a sophisticated flow visualisation technique, which allowed the spontaneous-emission process to be studied in unprecedented detail. These findings suggested that the spontaneous emission of atmospheric gravity waves could be an important, but previously unrecognised, source of clear-air turbulence.

The main four physical phenomena that cause clear air turbulence are briefly described below. Thus:

- **Jet Stream:** A narrow, fast moving current of air, normally close to the Tropopause and generated as a result of the temperature gradient between air masses. Although not all jet streams have CAT associated with them, there can be significant vertical and horizontal Wind Shear on the edges of the jet stream giving rise to sometimes severe clear air turbulence. Any CAT is strongest on the cold side of the jet stream where the wind shear is greatest. In the vicinity of a jet stream, CAT can be encountered anywhere from 7,000 feet below to about 3,000 feet above the tropopause. Because the strong vertical and horizontal wind shear occurs over short distances, this jet stream related CAT tends to be shallow and patchy so a descent or climb of as little as 2,000 feet is often enough to exit the turbulence.

- **Terrain:** High ground disturbs the horizontal flow of air over it, causing turbulence. The severity of the turbulence depends on the strength of the air flow, the roughness of the terrain, the rate of change and curvature of contours, and the elevation of the high ground above surrounding terrain.

- **Cumulonimbus (Cb)**: A heavy and dense cloud of considerable vertical extent in the form of a mountain or huge tower, often associated with heavy precipitation, lightning and thunder. The mature Cumulonimbus cloud has a distinctive flat, anvil shaped top with cells that have strong vertical currents. Aircraft passing within 20 nautical miles horizontally, or less than 5,000 feet above the top, of a Cb may encounter CAT.

- **Cyclogenesis:** The process of cyclone development associated with the development of extra-tropical cyclone and intensification. It is initiated by a disturbance occurring along a stationary or very slow-moving front between cold and warm air. This disturbance distorts the front into the wavelike configuration.

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7 A dimensionless number relating the ratio of inertial to Coriolis forces for a given flow of a rotating fluid. Explicitly, the Rossby number is $R_o=U/fL$, where U is the velocity scale, f is the Coriolis parameter and L is the horizontal length scale. This number plays a fundamental role in defining the regime of large-scale geophysical fluid dynamics.

5.2 Observation and prediction of CAT

According to figures from the National Transportation Safety Board (NTSB), the flight crew had no warning in about 28% of turbulence-related accidents from 2009 to 2018 (see Appendix A).

Although turbulence can occur almost anywhere and at any height, some areas are known for being more susceptible. After an analysis of around 150,000 different flight routes, the turbulence prediction website Turbli found that the journey between Santiago, Chile and Viru Viru International airport in Bolivia to be the most bumpy, while the route between Almaty, Kazakhstan, and the capital of Kyrgyzstan, Bishkek, came in second on the list, which was released last year. Nashville, Tennessee to Raleigh/Durham in North Carolina was ranked as the North American route with the highest average turbulence.

5.3 Current "nowcasting" of turbulences

Existing weather forecasts models cannot predict turbulence at airplane-sized scales, and pilots frequently misreport turbulent locations by many dozens of miles. Hence, since 2005 the National Centre for Atmospheric Research (NCAR) in USA is currently developing more precise turbulence tools, named "nowcasting[8]". An algorithm currently installed on around 1,000 commercial airliners analyzes information from onboard sensors to characterise each plane's movement at any given moment. Using data on forward velocity, wind speed, air pressure, roll angle, and other factors, the algorithm generates a local atmospheric turbulence level, which is fed back into a national system every minute. Used in conjunction with national weather forecasts and models, the tool annotates forecasts with real-time conditions, which in turn helps to strengthen weather prediction models.

Meteorologists better understand the atmosphere now, and their computing ability has meant it is possible to provide better descriptions of turbulence. As, by its very nature, turbulence is so chaotic it requires a lot of computer power to be used in order to see what is actually happening.

Over 12,000 Delta Airlines pilots currently use tablets loaded with the tool to check conditions along their flight paths. In addition to the domestic planes currently equipped with the algorithm, international carriers including Qantas, Air France and Lufthansa will also join in. Also, Boeing has begun to offer the algorithm as a purchase option for new aircraft.

5.4 Future expectations of CAT

A study by researchers from Reading University, UK, reported that severe turbulence had increased by 55% in the past four decades due to the impact of climate change. [4] The report, published in June 2023, found that at an average point over the North Atlantic, which is one of the world's busiest flight routes, total yearly duration of severe turbulence had risen by 55% between 1979 and 2020.

[8] The World Meteorological Organisation defines nowcasting as forecasting with local detail, by any method, over a period from the present to six hours ahead, including a detailed description of the present weather.

Williams' analysis [7] predicted that clear-air turbulence would increase significantly across the world in the coming decades. Typically, on a transatlantic flight, currently it is expected around 10 minutes of turbulence, while in a few decades this may increase to 20 minutes or to half an hour. Hence, the seat belt sign will be switched on a lot more, unfortunately for passengers, but for their and crew's safety.

6. CAT Mitigating Risks and Enhancing Safety Actions

As severe turbulence encounters have caused injuries to passengers and cabin crew the best practices, applying recommended techniques and procedures are developed to reduce the probability of risk of injuries. [6]

To ensure the safe motion of aircraft through the working process, the following measures are taken to address weather-related risks, namely:

- Weather Monitoring and Reporting: Air traffic control closely monitors weather conditions and shares critical information with pilots, which helps them to make informed decisions regarding flight routes, altitudes. [6]
- Technology and Tools: Advanced weather radar systems, satellite imagery and predictive models assist in detecting and tracking weather systems. These tools aid in better forecasting and provide real-time information to enhance safety. [5]
- Awareness: SIGMET[9] charts give forecasts of the location and level of clear air turbulence. Information on local terrain induced CAT may be contained in appropriate Aeronautical Information Publications. In addition, Electronic Flight Bag (EFP) applications provide pilots with tools that gather information on reported and forecast turbulence. An example is the Turbulence Aware platform from the International Air Transport Association (IATA). [5]
- Training and Education: Pilots and air traffic controllers undergo comprehensive training on aviation weather. They learn to interpret weather data, understand weather-related risks, and make informed decisions accordingly. [6]
- Pre-flight crew communication: Captains should brief flight attendants on expected timing and duration of forecast turbulence for incoming flights.
- In-flight crew communication: When pilots become aware of impending turbulence, they should let cabin crew know as quickly as possible. This can be done via interphone or through a public address announcement. If time is critical, a warning can be signalled by multiple chimes and/or flashing the seat belt signs.
- Suspension of Cabin Service: Obviously the serving of hot drinks and meals during turbulent conditions puts both cabin crew and passengers at risk. [6]
- External flight crew collaboration: Effective collaboration between pilots, air traffic controllers, and meteorological experts is crucial to address weather-related challenges. Clear and concise communication ensures that the latest weather information reaches all stakeholders. [5]

[9] SIGMET stands for Significant Meteorological Information, and affect all aircraft related to the more severe weather conditions, which usually valid for 4 hours.

7. Conclusion

Clear air turbulence is one of the meteorological hazards that present significant problems to flight safety. While technology and advanced meteorological information have contributed to improved weather forecasting and risk management, it remains ever present and requires constant attention. Thus, the main objective of this paper was to understand physical mechanisms that generate the occurrences of clear air turbulence and assesses their impacts on the motion of aircraft through MIRCE Space and consequential impact to functionability trajectory generated.

The available methods for dealing with this imposing functionability action in respect to the provision of aviation safety and protection are also addressed in the paper. In essence, the effective collaboration between meteorologists, pilots, air traffic controllers and airport authorities is crucial to ensure the safety of aviation operations. Through ongoing research, advancements in technology and continuous training, aviation can strive to minimize the risks posed by meteorological hazards and maintain the highest levels of safety.

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Appendix A: Observe Clear Air Turbulence generated functionability events

- On 25th February 2015, a Boeing 737-800 encountered severe clear air turbulence as it crossed the Pyrenees en-route, south southwest of Toulouse France. Due to serious injuries sustained by two cabin crew the flight was divert to Bordeaux.
- On 5th December 2021, an Airbus A350-900 in vicinity Cayenne French Guiana encountered a very brief episode of unexpected CAT. Not having had prior warning, the senior cabin crew member fell and was seriously injured.
- On 16th January 2022, an Airbus A320 near Okayama Japan was in cruise when experienced, very briefly, CAT. Despite being secured in a seat, one passenger sustained a serious injury resulting in hospitalisation with a broken rib.
- On 17th January 2021, a Boeing 777-300 which had just begun descent into Beirut encountered unexpected moderate to severe clear air turbulence which resulted in one major and several minor injuries to unsecured occupants including cabin crew.
- On 17th January 2021, a Boeing 777-300, en-route north northwest of Tanegashima Japan, encountered unexpected moderate to severe CAT just as begun descent into Beirut. It resulted in one major and several minor injuries to unsecured occupants including cabin crew.
- On 28th May 2021, a Boeing 767-300, encountered unexpected moderate to severe CAT while climbing over central South Korea. A serious injury occurred to one of the cabin crew who was unable to return to her crew seat and secure herself due to short notice that turbulence risk would increase from moderate to severe.
- On 10th July 2019 an Airbus A380-800, en-route to Bay of Bengal India in the cruise at night encountered severe CAT approximately 13 hours into the 17 hour flight. 27 occupants were injured as a result, one seriously. The detailed

Investigation concluded that the turbulence had occurred in clear air in the vicinity of a significant area of convective turbulence and a jet stream

- On 13th February 2019, a Boeing 737-800, en-route over the southern Adriatic Sea unexpectedly encountered severe CAT resulting in injuries of two unsecured cabin crew and some unsecured passengers, which were thrown against the cabin structure and sustained minor injuries.
- On 2nd February 2020, an Airbus A380, en-route to Wyoming, USA, in the cruise encountered unforecast CAT with the seatbelt signs off and one unsecured passenger in a standard toilet compartment sustained a serious injury as a result.
- On 21st August 2019, an Airbus A340-600, en-route, northern Turkey, encountered sudden-onset moderate to severe CAT resulted in a serious passenger injury