UNIVERSITY OF NAIROBI

IMPACTS OF WEATHER ON AVIATION DELAYS AND DIVERSIONS AT JOMO KENYATTA INTERNATIONAL AIRPORT, KENYA

BY

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A Dissertation submitted in Partial Fulfillment for the Award of the Degree of Master of Science in Aviation Meteorology of the University of Nairobi

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Declaration

I declare that this dissertation is my original work and has not been submitted elsewhere for examination, award of a degree or publication. Where my own work or that of others has been used, it has been appropriately cited and acknowledged in accordance with University of Nairobi regulations.

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Dedication

This work is dedicated to my uncle Ouhoumoudou Mahamadou, current Niger Prime Minister and, my big brother and superior Mohamed Moussa, current General Director of the Agency for Aerial Navigation Safety in Africa and Madagascar. It is a privilege to work under your direction. Saying thank you is not enough to express how grateful I am for your supports over the years. And everything I've accomplished so far is thanks to you. Your words of encouragement and kindness have been invaluable to me and have kept me sane as I pursued deadlines in my studies at University of Nairobi, Kenya. I can't thank you enough for all the help you have bestowed me.

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At the end of this work, I would like to thank Almighty God for having given me the courage, patience and health to complete this modest work.

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Abstract

Adverse weather is the main cause of the disruptions to operations at Jomo Kenyatta International Airport (JKIA), Kenya. In order to assess the potential implementation of a weather impact index on aviation delays at JKIA, meteorological data composed of Meteorological Aviation Reports (METARs and SPECIs) and Terminal Aerodrome Forecast (TAFs) were used in this study, and the data was gathered from KMD and JKIA. The decoding of the METAR and SPECI messages made it possible to identify the weather phenomena (causing aviation delays). The times, dates, months and year of each occurrence of aircraft delay or diversion made it easy to find the METAR or SPECI and TAF messages that were associated with the incident. The aviation weather-related delay and diversion data was gathered from KCAA. The study categorized the weather elements that occurred at JKIA from years 2000 to 2009 and examined the type of adverse weather that impacts the aviation operations in term of departure delay, arrival delay and diversion of aircraft. The need for a simplifying hypothesis for the analysis of incidents of delays and diversions led the study to operate a method of ranking the weather categories adopted. This hierarchy is important insofar as it makes it possible to assign a specific category in the specific case where several categories are coded in the same message associated with an aircraft delay or diversion.

The temporal analysis in this study is composed of the annual, monthly analysis and the analysis of the 4 daily times which reflect the intensity of the airport operations that is a function of the capacity of the airport.

In order to assess the Terminal Aerodrome Forecast (TAF), a TAF assessment technique was adopted. The evaluation of the TAF consists, for each unit of delay or diversion, in using the METAR which is the actual meteorological situation observed to test the accuracy of the TAF. The considered TAF is the one at least 6 hours before since this time is more than enough to allow good flight planning. ICAO regulation from Annex 3 for operationally desirable accuracy of forecasts is used for visibility, cloud amount and cloud height verification in this study.

From the analysis of METARS, delay and diversion incidents, and, delay and diversion durations, it was found that the highest contributors are fog/mist, thunderstorm and low level clouds, followed by rain not originating from convective clouds and wind causing runway change.

From the examination of the accuracy of the Terminal Aerodrome Forecasts (TAFs) that were associated with the delays and diversions, it was found that when the percentage of TAF accuracy is high (above 65%), decrease in delay and diversion incidents begins. Also when the percentage of TAF accuracy is beyond 67% to reach 73%, the number of delay and diversion incidents decreases and drops sharply to a small number. Therefore, improving the forecast accuracy at JKIA results in enhancing the aviation safety, in passenger satisfaction, in improving the airport capacity and in allowing an orderly flow, in avoiding and reducing the delays and diversions with effect to improve the finances of the airlines operating at JKIA. When the percentage of TAF accuracy is low (48%), the delay and diversion incidents is very high. Any slight increase in TAF accuracy from 48% until 65% leads to a slight decrease in combined-delay/diversion incidents. Therefore, a deterioration in TAF accuracy at JKIA results in decreasing the aviation safety, in reducing the airport capacity, in passenger inconvenience, in increasing the delay and diversion incidents with effect of income loss (due to additional costs) to the airlines operating at JKIA. The study reveals the relevance of International Civil Aviation Organization (ICAO) regulations which require 80% of forecasts to be successful. It was found that adverse weather will generate delays and diversions at JKIA despite the accuracy of a TAF, however an improved planning can reduce the duration and impact of delays. A weather impact index system for in-flight delay/diversion and combined-delay/diversion models were designed to assess weather-related risks and that can be used in estimating and planning for JKIA delays. Recommendations for delay reductions are made. Case studies show the validity of applying the developed index models in operations and its usefulness in planning and management, and therefore being proactive in aviation operations.

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List of Acronyms

ACC	: Area Control Centre
ADM	: Aeronautical Decision-Making
AMC	: Airport Management Centre
ATC	: Air Traffic Control
ATFM	: Air Traffic Flow Management
ATM	: Air Traffic Management
CANSO	: Civil Air Navigation Services Organization
CB	: Cumulonimbus Cloud
CHIRPS	: Climate Hazards Group InfraRed Precipitation with Stations
FAA	: Federal Aviation Administration
FIR	: Flight Information Region
FUAs	: Flexible use of airspaces
GAT	: General Air Traffic
ICAO	: International Civil Aviation Organization
ILS	: Instrument Landing System
JKIA	: Jomo Kenyatta International Airport
KAA	: Kenya Airports Authority
KCAA	: Kenya Civil Aviation Authority
KMD	: Kenya Meteorological Department
MAE	: Mean Absolute Error
METAR	: Meteorological Aerodrome Report
NTSB	: National Transportation Safety Board (USA)
OAT	: Operational Air Traffic
RMSE	: Root Mean Square Error
RPAS	: Remotely piloted aircraft system
RVR	: Runway Visual Range

SARPs : standards and recommended practices

SPECI : Special Weather Report

TAF : Terminal Aerodrome Forecast

TCU : Towering Cumulus Cloud

TMIs : Traffic Management Initiatives

TRMM : Tropical Rainfall Measuring Mission

UAV : Unmanned aerial vehicle

UNISDR : United Nations (UN) International Strategy for Disaster Reduction

UTM : Unmanned aircraft system traffic management

VFR : Visual Flight Rules

WITI : Weather Impact Traffic Index

Definition of Technical Aviation Terms

The following defined operational terms have been used in this study for the purpose of assessing the impact of weather on aviation operations at Jomo Kenyatta International Airport:

Aircraft Accident – It is defined as an occurrence connected to the operation of an aircraft that takes place between the time someone boards the aircraft for a flight and the time everyone has disembarked, and in which someone dies, sustains a major injury, or sustains significant damage to the aircraft.

Aircraft Incident – An event connected to an aircraft operation—other than an accident—that has an impact on or has the potential to have an impact on operational safety. For this dissertation, it will represent these; **Flight delays, flight diversions, flight go-arounds/ over shoots** and **flight cancellations.**

Aircraft Movement- A take-off (aircraft departure) or a landing (aircraft arrival) is recorded and defined as one aircraft movement (CASA, 2014).
Airport Capacity - Airport capacity is defined as the number of air operations that the airport and the supporting air traffic control (ATC) system can accommodate in a unit of time, such as an hour (Heritage, 1982).

ATS – Air Traffic Service.

Combined delay/diversion: refers to a set of impact where the elements are departure delay, arrival delay and diversion.

Cross winds – These are winds which blow across the runway at an angle.

Ground Delay Program-A Ground Delay Program is an air traffic flow management (ATFM) mechanism used to decrease the rate of in-coming flights into an airport when it is projected that arrival demand will exceed the airport capacity (Ball&Lulli, 2004).

In-flight delay/diversion: refers to a set of impact where the elements are arrival delay and diversion.

Instrument Landing System (ILS) - An ILS is a ground-based system that provides landing guidance to aircraft approaching and landing on a runway. The system uses a combination of radio signals and high-intensity lighting to enable safe landing during poor meteorological conditions, such as low cloud ceilings and reduced visibility.

METAR (Meteorological Aerodrome Report) - A METAR is a coded weather observation used for aviation purposes. The observation will be conducted, and the METAR globally disseminated on each main hour, and on each every half hour at major aerodromes. A METAR is a standardized report, and is regulated by ICAO. Each report contains specific weather variables namely wind speed and direction, cloud type, height and amount, horizontal visibility, vertical visibility when appropriate, temperature, dew point temperature, atmospheric pressure, precipitation and other weather, and any other information deemed relevant at the observation time.

Tail winds – These are winds blowing in the direction of travel of a vehicle or aircraft; winds blowing from behind

Visibility – This is the distance one can see as determined by light and weather conditions.

Source: (ICAA, 2005)

1. INTRODUCTION

1.1 Background of the Study

Atmosphere and meteorology play an essential role in aviation industry with its associated socio-economic impacts by the fact that pilots and airplanes can't operate and fly in a vacuum in order to get lift and propulsion. Furthermore, the differential heating of the earth's surface, the tilt and rotation of the earth, the inhomogeneity of topography on the earth's surface, the ocean-land distribution and the revolution of the earth around the sun give rise to dynamic and thermodynamic forcings in the atmosphere which in turn generate weather spatially and temporally from micro-scales to macro-scales. The generated weather can be fair or active, and the active weather can become severe due to some feedback processes.

Numerous studies have attested that both civil and military aviation operations are severely impacted by weather conditions (e.g., Cook *et al*. 2009, Rudra *et al*. 2015; Gultepe *et al*. 2014, 2017). The impact of atmospheric processes on aviation has been recognized since the 1900s. For example, Dines (1917) stated that ''thus it appears that the demand of the airman on the meteorologist is that he shall be able to forecast wind and fog, and to less extent clouds, on the route, the airman is proposing to follow.'' Presently, his comments on aviation-related parameters such as wind speed and visibility are still valid. Good examples are shown in Figure 1. a,b,c,d (Gultepe *et al*., May 2019).

These severe weather are often the source of the most dangerous phenomena for air navigation. They are most often associated with thunderstorms, heavy precipitation, downburst, gust fronts etc whose consequences can be fatal for an aircraft, especially during the critical phases of takeoff and landing.

A Review of High Impact Weather for Aviation Meteorology (Gultepe *et al*., May 2019)

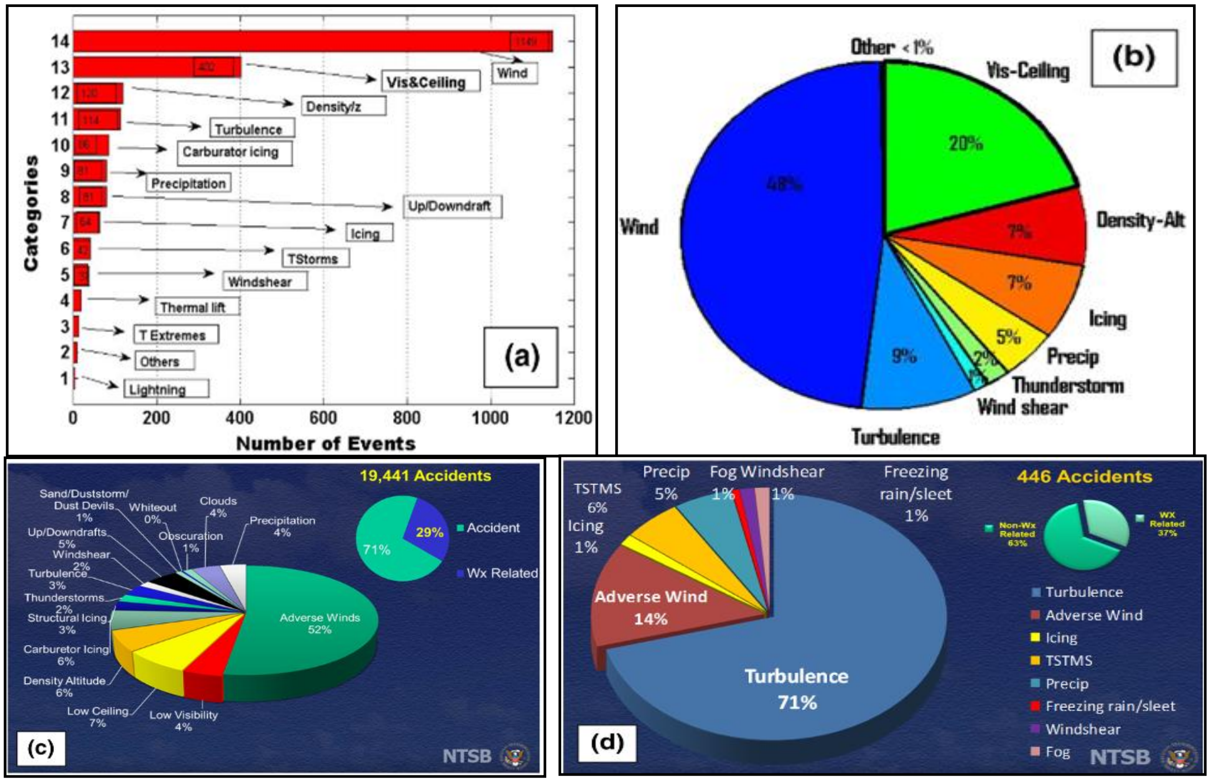


Figure 1: (a) Statistics for aircraft related accidents related to meteorological parameters from 1994 to 2000: actual numbers of accidents; b: Statistics for aircraft related accidents related to meteorological parameters from 1994 to 2000: probabilistic distributions in pie chart; c, d -Weather as cause/factor during all accidents for the period of 2000–2011. The NTSB (National Transportation Safety Board) based statistics which resulted in 19,441

Theoretical Reminders of Weather Hazards on Aviation:

Across the world, many aviation accidents and ATS irregularities are attributable to weather phenomena. The importance of weather in aviation can be explained by its effects on aircraft performance with the serious consequences it can have on flight safety. Therefore, the understanding of basic weather theories by examining the causes and the effects of the most encountered phenomena which are of concern to aviation operations at JKIA airport are essential for pilots to achieve better anticipation and to make sound decisions during flight planning after receiving weather briefings. These major weather phenomena which afflict aviation are described below.

Convective currents

In the air, convective currents refer to localized vertical air movements, both ascending and descending. By the principle of conservation of mass, for every rising current, there is a compensating downward current; thus animating the atmosphere horizontally and vertically, and whose intensity sets the shearing potential. In final approach, it is predominant that upward currents tend to cause the aircraft to overshoot the runway, while downward currents tend to undershoot the runway (Figure 2).

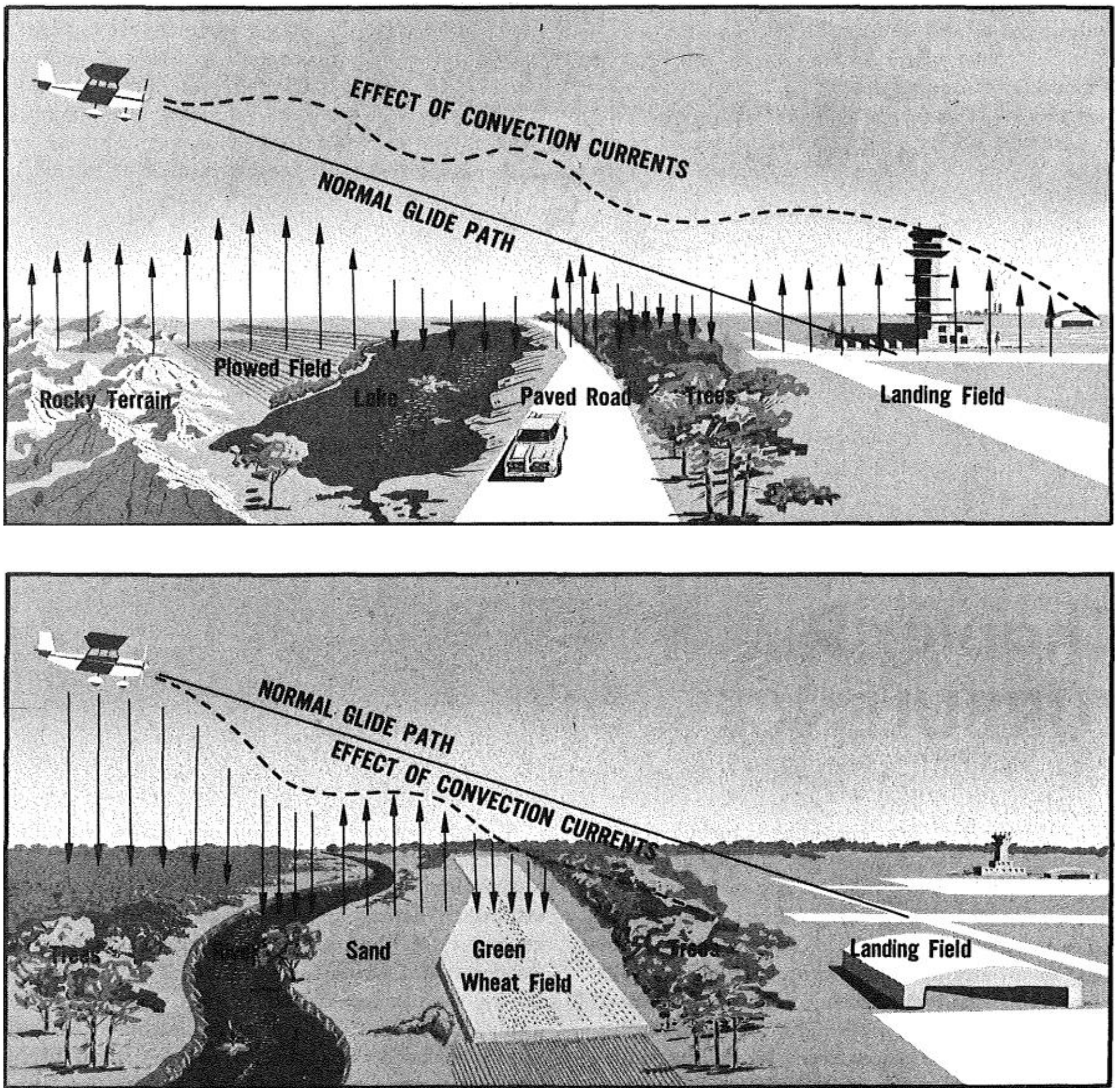


Figure 2: Effect of convective currents on final approach. Predominantly upward currents (top) tend to cause the aircraft to overshoot. Predominantly downward currents (bottom) tend to cause the craft to undershoot (Aviation weather for pilots, FAA)

Small planes can be sensitive to wind shifts accompanying rising thermals close to the ground. In most cases, these convective currents can be avoided by flying at higher altitudes, even above cumulus cloud layers (Figure 3).

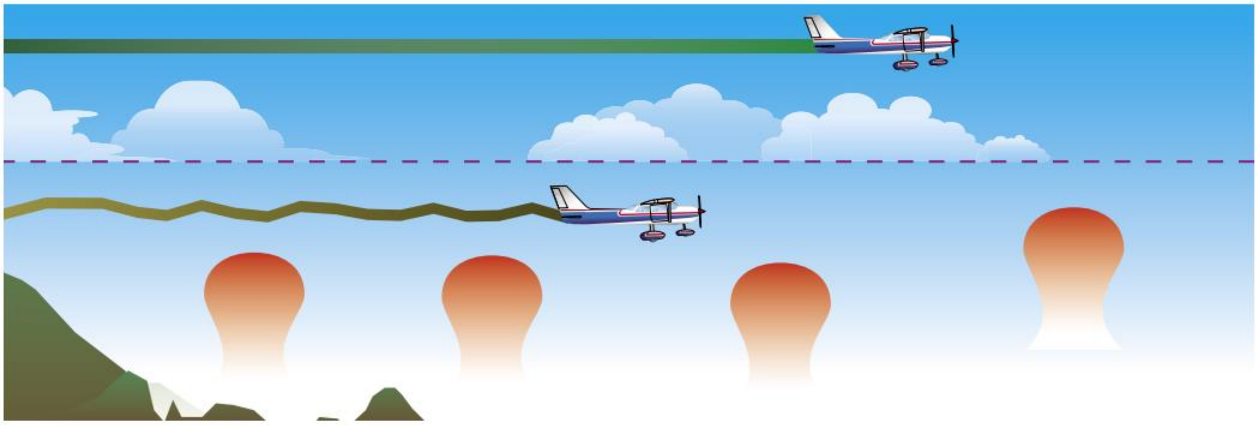


Figure 3: Schematic illustration of convective turbulence avoidance (Aviation Handbook, FAA)

Typically, convective currents are most active on warm summer afternoons when winds are light. Several processes can provide certain air parcels with sufficient momentum to trigger convective instability. If it is heated by an external heat source, the air expands, becomes lighter than its environment and rises spontaneously: this is called “free convection” or even “natural convection”. The air can also rise when it encounters a relief, a mountainous barrier, the surface of a warm or cold front, or even if it is in a region of convergence of the surface winds or under a region of divergence of the high winds. In these cases, the origin of the initial uplift is dynamic in nature and acts by transforming horizontal movement into vertical movement: this is called “forced convection”.

Free convection is frequently observed on sunny days, when solar radiation easily passes through the atmosphere and warms the earth's surface abundantly. They can also be observed at night when cold air hits a warmer surface. If the warming and humidity of the air are insufficient, there are no clouds, but one can nevertheless guess the position of the ascending currents, or "thermals", by observing the birds or the gliders which take advantage of their presence to stay in the air, sometimes for several hours. These updrafts most often have a diameter of a few hundred meters and vertical speeds of around two meters per second. Depending on the situation, their summit can rise up to one or two kilometers in height. If the air is humid enough to reach its saturation level during the ascent, small cumulus clouds are observed at the top of the thermals. Water condensation enhances convection by warming the rising air. The top of the cumulus are then moved to a higher altitude. Below 0°C, freezing releases additional heat and may be sufficient to further increase the vertical development of the clouds formed.

Effect of Obstructions on Wind

With respect to flight level of an aircraft, there are some conditions that can cause various weather phenomena in the lower layers. A combination of strong surface winds and prevailing wind obstacles situated downstream of the approach or departure path (such as tall buildings, low hills or high tree curtains) can create localized areas of low-level wind shear. The effect of obstacles on the prevailing wind depends on the wind speed and its orientation relative to the obstacle. This type of wind shear is most often very localized around small aerodromes and is of particular concern to pilots of light aircraft. On aerodromes where the runways are close (figure N˚4) to large buildings, strong surface winds can create wind shear, by friction effects: a strong wind increases mechanical turbulence thus producing a transfer of momentum throughout the brewed layer.

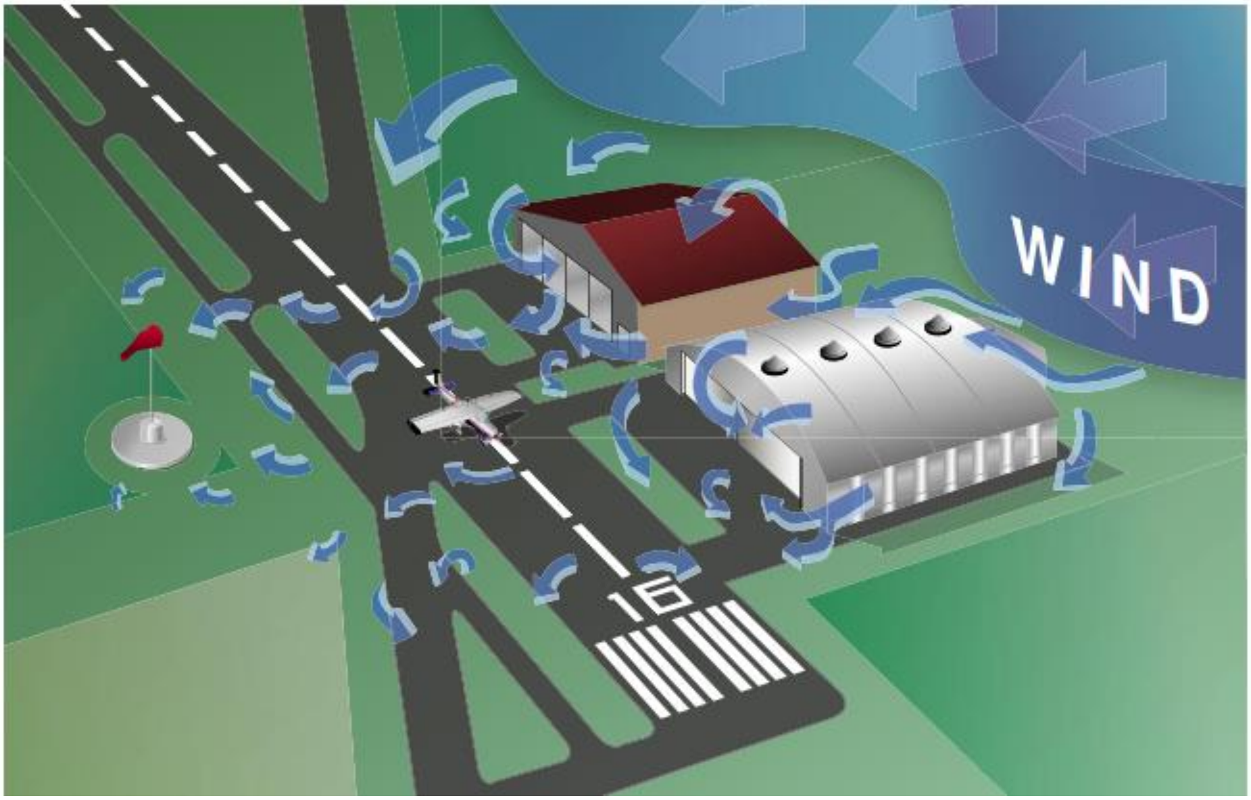


Figure 4: Schematic illustrations of turbulence caused by manmade obstructions (Aviation Handbook, FAA)

Sometimes aerodromes are literally embedded in large coniferous forests or coconut plantations, and the runway is actually in a tree tunnel. Even if the tree line is beyond the runway strip and therefore does not constitute an obstacle for planes, as the height of the forest or the canopy of the plantations can reach 30m, it is frequent that there is little, if any, connection between the surface wind blowing along the runway and the prevailing wind blowing over the green canopy.

For runways built in a narrow valley or along a chain of hills, the obstacle is of such extent that it can affect the wind circulation in the low layers over a large region (Figure N˚5). When the wind is strong when crossing a mountain range, a series of standing waves occurs on the leeward side, associated with whirls (Figure 6).

Figure 5: Schematic illustration of turbulence in mountainous regions (Aviation Handbook, FAA)

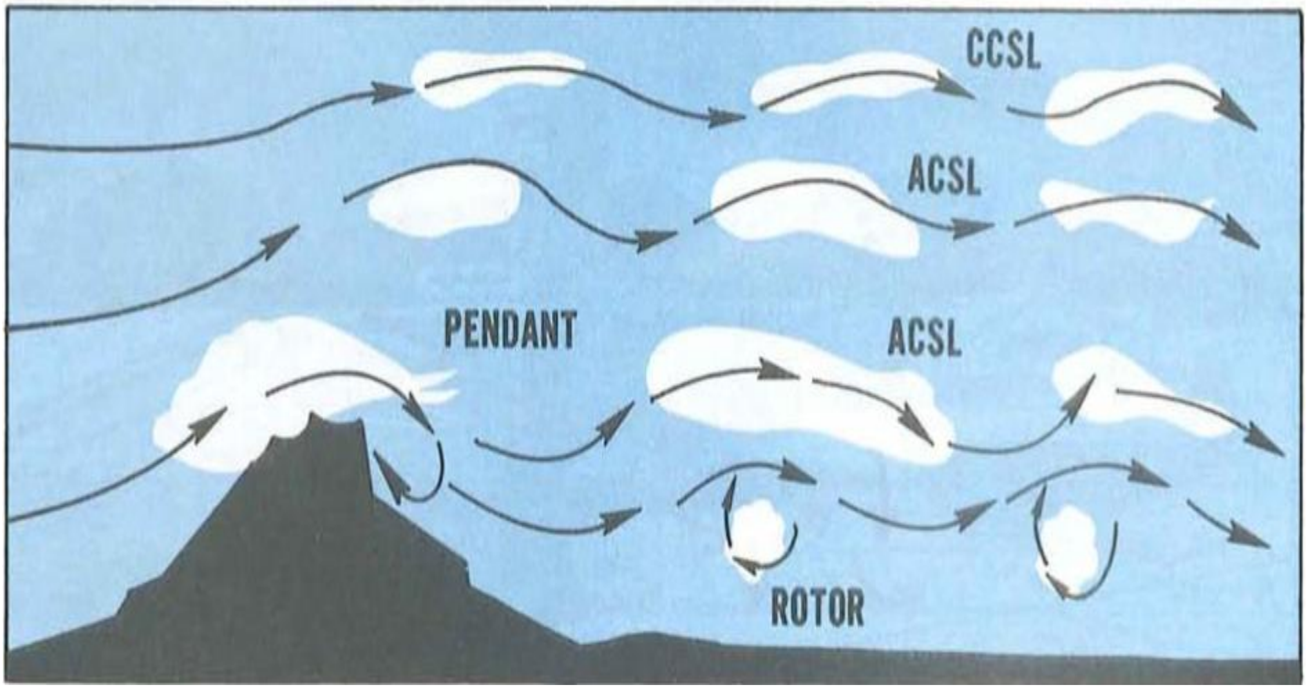


Figure 6: Schematic cross section of a mountain wave. Note the standing wave pattern downwind from the mountain. Note also the rotary circulation blow the wave crests. When the air contains sufficient moisture, characteristic clouds form (Aviation weather for pilots)

Low level wind shear

The expression wind shear is stated as follows: change in wind speed and / or direction in space, updrafts and downdrafts included. It follows that any atmospheric phenomenon or any physical obstacle to the circulation of air which produces a change in the direction and / or the speed of the wind effectively causes shearing. Wind shear is always present in the atmosphere, its presence can be visible to an observer by observing the movement of the layers of clouds at different levels, in different directions, the plumes of sheared smoke evolving in different directions, at different heights from the frontal limit of dust or sand storms which rises like a wall, or the trees which bend in all directions under the sudden gusts of a squall-line. All these phenomena testify to the universal presence of wind shear and the phenomena that generate it in the atmosphere.

Directional wind changes of 180° and speed changes of 50 knots or more are associated with low-level wind shear. Although it can be present at all levels of the atmosphere, it is when it occurs below 500 meters in height (1600 feet) that the phenomenon is of particular importance for aircraft in critical phase of speed and height. during landing and takeoff. During the ascent and approach phases of the flight, the aircraft speed and altitude are very close to the critical values and make the aircraft particularly vulnerable to the effects of wind shear.

The sea breeze is one of the causes of wind shear, very noticeable in the immediate extension of airport runways when they are built on the edge of the sea. Indeed, this shear can only occur at an altitude of 250 to 400 meters where the winds come from the land, while the sea winds arrive at ground level. In this case, the aircraft taking off with the headwind, facing the sea finds itself tailwind, gaining altitude and at a time when its speed is still low. The surface of the sea heats up very little during the day. On the other hand, the earth's surface undergoes variations often greater than 10 °. The air, in contact with the ground, expands and rises. It is then replaced by cooler air coming from the sea: it is the sea breeze (Figure 6).

Thus, during the day, the earth heats up faster than water, which creates a breeze coming from the sea. The sea breeze or day breeze can give a wind of 20 to 30 km / hour (10 to 15 KT), which blows perpendicular to the coast from the sea towards the earth. The sea breeze is much stronger than the land breeze because it can penetrate in the middle of the afternoon up to 48 km inland and develop vertically up to a height of around 360 m above the ground level. During the night, the opposite phenomenon occurs since the land cools by radiation much faster than water: it is the land breeze. The land breeze or night breeze is on the other hand weaker. It blows perpendicular to the coast from land to sea and can give a wind of 10 to 20km / h (5 to 10 KT).

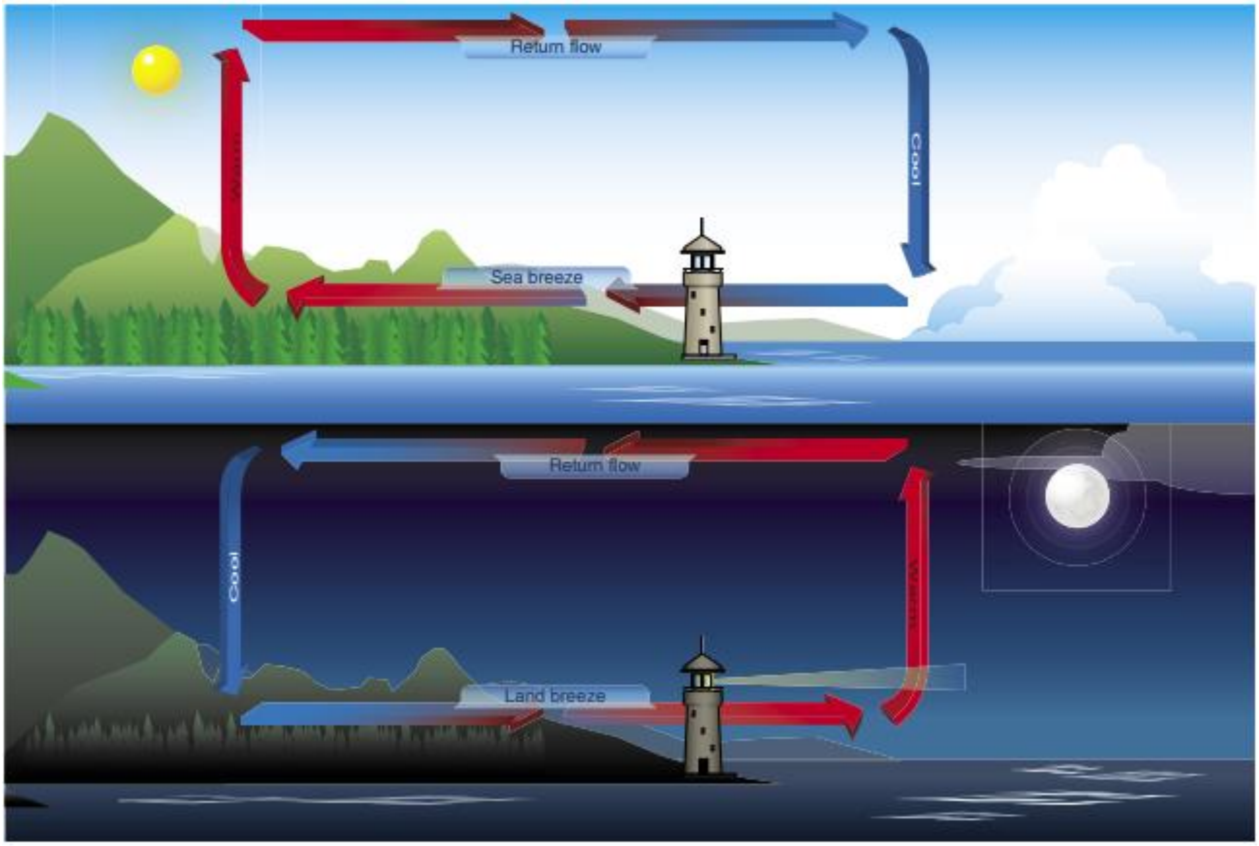


Figure 7: Sea breeze and land breeze wind circulation patterns (Aviation Handbook, FAA)

The front surfaces are transition zones separating air masses of different temperatures, and therefore of different density. When two of these air masses come into contact, an equilibrium is achieved in such a way that the colder and denser air expands in wedge under the warmer and less dense air, the limit between the two air masses forming a slight angle with the horizontal. It's like an air mass adjustment zone, a transition zone. The faster air mass will push the other out of the way. The hottest air is always the one that lifts and rises along the contact surface. It is then that its pressure decreases, it cools and at the same time the water vapor which it contains condenses giving rise to clouds. Naturally, all of these clouds are arranged along the contact surface, called the frontal surface. Fronts are classified according to their displacement and the resulting temperature change where they pass.

A cold front is a front along which cold air replaces hot air on the surface; conversely a warm front is a front along which warm air replaces colder air on the surface. The warm front is tilted forward in the direction of movement of the front, while the cold front is tilted in the opposite direction to this movement. The dynamics of the frontal surfaces want it to have a discontinuity in the wind speed, in particular in the lower layers of the atmosphere.

The frontal surface is therefore, by definition, a zone of wind shear. Consequently, in the case of an aerodrome crossed by fronts, a vertical wind shear through the frontal surface will occur: Over the aerodrome ahead of the warm front, the maximum wind shear zone dropping to ground level as the warm front approaches; and as the cold front passes and behind it, the area of maximum wind shear rising above the aerodrome from ground level after the cold front has passed. Low-level wind shear is commonly associated with passing frontal systems, thunderstorms, and temperature inversions with strong upper level winds (greater than 25 knots).

Gust fronts create wind shear phenomena that can cause aircraft to crash when landing or taking off. As previously mentioned, a gust front can advance a distance of several kilometers (20 to 40km) in front of a convective system. An aircraft that takes off, lands or flies at low altitude may find itself in an abruptly changing wind field, which can very quickly threaten the aircraft's ability to maintain airborne power. In a few seconds, the wind direction can change by 180 ° and its speed, at this time can be around 100 KT in gusts, creating strong wind shear accompanied by very severe turbulence. This is particularly true during takeoff and landing when the speed of the aircraft is closer to that of stalling and that a back gust can cause the aircraft to stall which may crash due to the proximity of the ground (Figure 7).

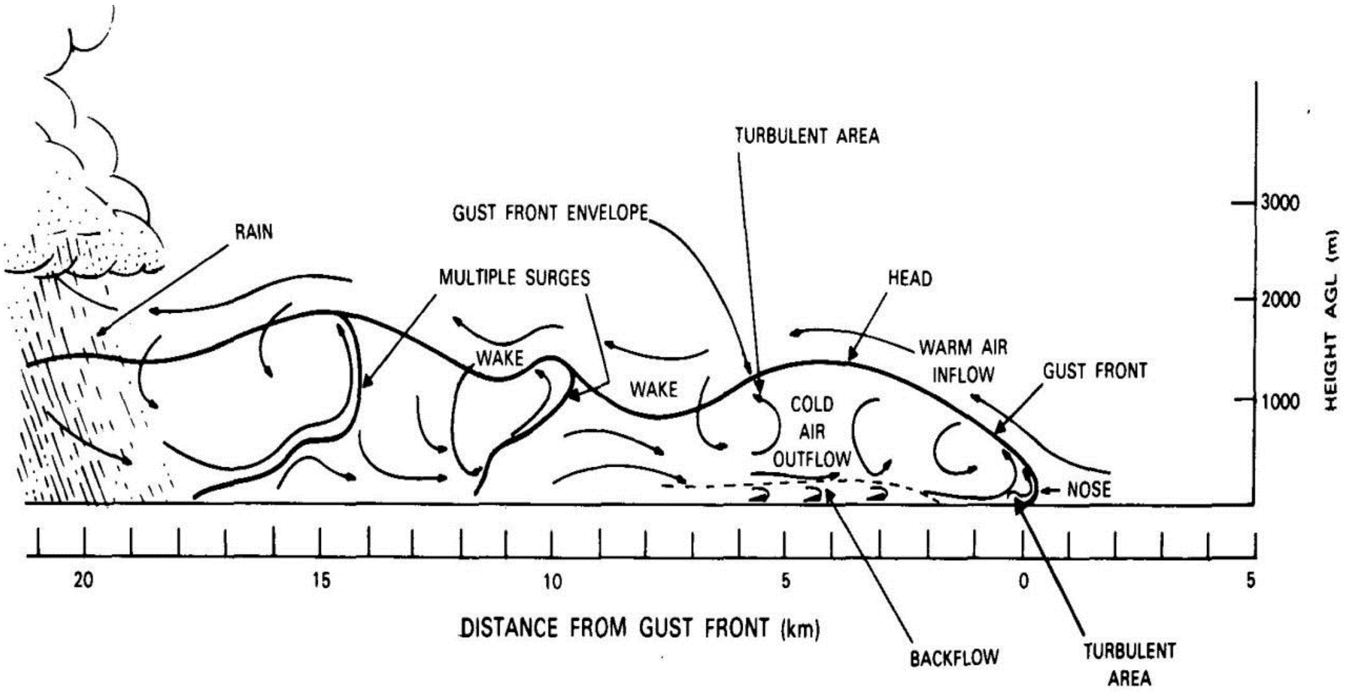


Figure 8: Schematic representation of the vertical structure of a gust front of convective origin. The various movements relate to the gust front. Source: Dina et al (1987)

A microburst (the vertical element is also known as a downburst) is defined as the wind shear coming from with thunderstorms.
Downbursts are very dangerous for airplanes, especially during takeoffs and landings. Indeed, the sudden change in the force of the winds over short distances considerably changes the lift of the aircraft because strong downdrafts penetrate through the base of the cloud and reach very close to ground level before spreading out radially along the ground. In this kind of situation, the aircraft flies close to the ground, at a speed close to that of stalling and in an attitude that is difficult to change.

For example, during a landing, the pilot adjusts his rate of descent to the speed of the surrounding winds but suddenly the gust faces the plane which then picks up speed and then sees its lift increase, The reaction of the pilot is then to reduce the throttle so as not to gain altitude before landing. However, as soon as the aircraft passes the other side of the micro-burst, the aircraft encounters a downdraft followed by a tailwind. the wind changes direction completely and the plane suddenly sees its lift sharply decrease. But at that time, the pilot having reduced the throttles, the reactors only operate at 70% of their maximum power and it is however at this moment that the airplane needs all its power.

In addition, the turbine engine of a jet aircraft takes several seconds to recover 100% of its power. This time interval is enough to make it lose too much altitude which can cause it to crash in front of the runway. And if it is taking off, it can be tackled to the ground just after getting in the air (Figure 9).

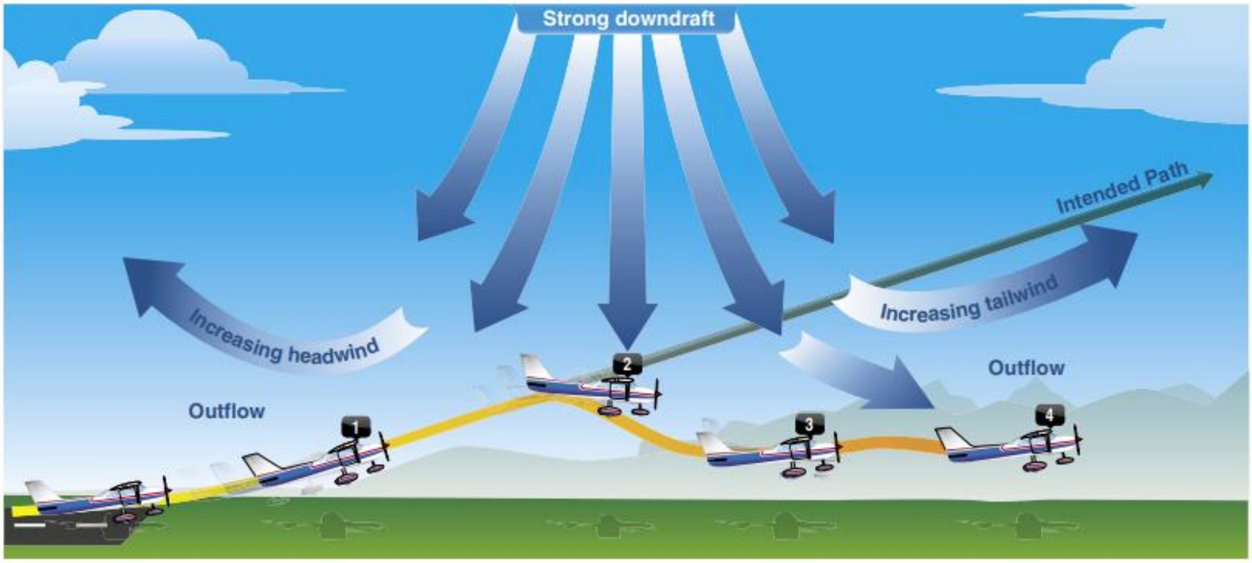
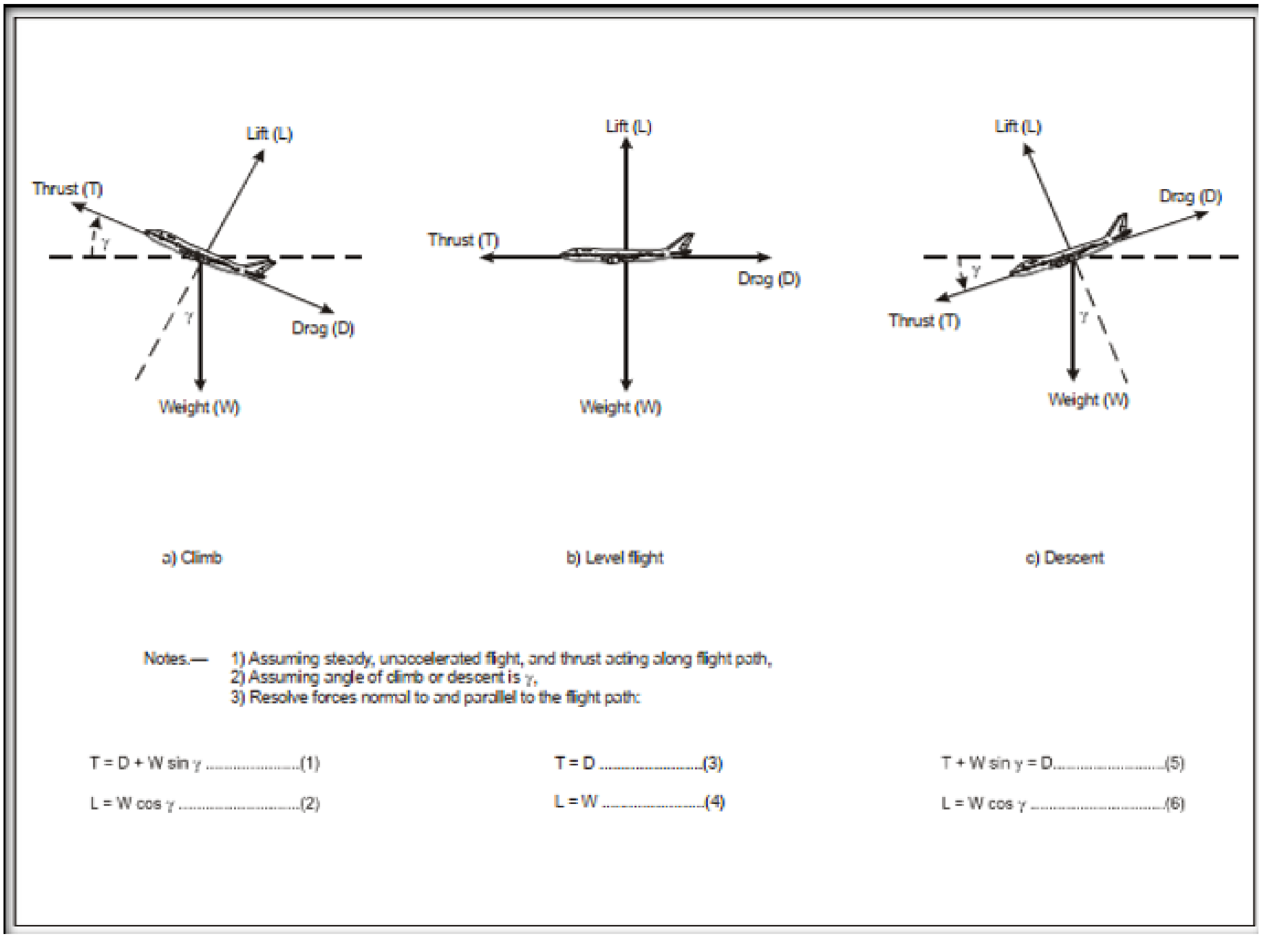


Figure 9: Schematic illustration of the effects of a microburst wind (Aviation Handbook, FAA)

Effect of wind shear on an aircraft

Elementary principle of flight

To understand the influence of wind shear on the behavior of an aircraft, it is first necessary to briefly recall certain basic principles of flight. The main forces acting on an airplane in flight are: the traction of the engine (s) (thrust), the weight of the airplane, the lift and the drag. The longitudinal stability of the aircraft depends on the balance of these forces.



Notes.— 1) Assuming steady, unaccelerated flight, and thrust acting along flight path,
2) Assuming angle of climb or descent is γ,
3) Resolve forces normal to and parallel to the flight path:

$T = D + W \sin \gamma$ ....(1)

$L = W \cos \gamma$ ....(2)

$T = D$ ....(3)

$L = W$ ....(4)

$T + W \sin \gamma = D$..............................(5)

$L = W \cos \gamma$ ....(6)

Figure 10: Forces acting on an airplane in flight (ICAO DOC 9817 AN / 449)

Effects on aircraft airspeed

In stable wind or when the wind horizontal component changes gradually, the wind has no effect on the airspeed, but in the event of wind shear, the horizontal wind (its component relative to the route followed is then the important element, whether it is a headwind during takeoff or landing or a tailwind during flight) is certainly not stable. An airplane exposed to a rapid passage from the headwind to the tailwind cannot, because of its inertia, accelerate or decelerate instantaneously to regain or resume its airspeed, which means that for a short period the airspeed is modified according to the wind change. This transient change in airspeed modifies the lift and drag, upsetting the balance of forces exerted on the aircraft.

Effect of wind shear on the angle of attack

In straight line flight the angle of attack (α) varies according to the plane's airspeed. The relationship between the angle of attack and the airspeed is that: the air hits the leading edge of the wing horizontally (i.e. with a negligible upward or downward vertical component). But if an aircraft is flying in a downdraft or updraft, however, the air is no longer striking the wing horizontally but at a small angle to the horizontal, which depends on the relative magnitudes of the airspeed and the vertical component of the wind (downdraft or updraft).

A change in angle of attack due to a downdraft/updraft is a transient change pending the restoration of the original trimmed angle of attack by the longitudinal stability of the aircraft. A downdraft causes a transient reduction in angle of attack that in turn causes a reduction in lift coefficient and disturbs the equilibrium of the forces acting on the aircraft, thus causing a resultant force acting below the intended flight path. An updraft acts in the opposite sense. A downdraft therefore has the same initial effect on an aircraft as a decreasing headwind or increasing tailwind, and an updraft has the same initial effect as an increasing headwind or decreasing tailwind. However, the downdraft/updraft effect is due to a transient change in angle of attack while the headwind/tailwind effect is due to a transient change in airspeed.

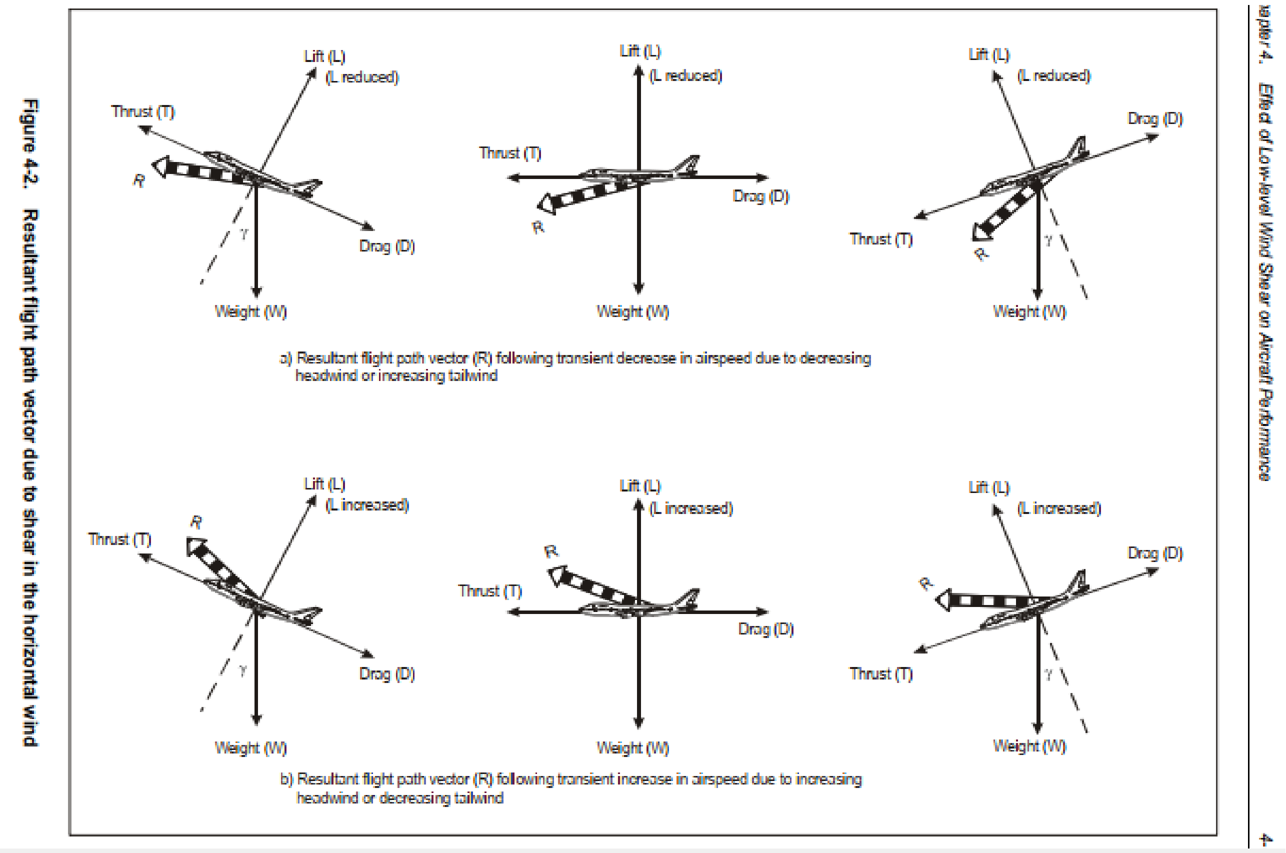


Figure 11: Vector representing the flight path subjected to horizontal wind shear (ICAO DOC 9817 AN / 449)

Cross wind shear effect

The fact that the runways are oriented as much as possible so as to present the weakest transverse component does not mean that the shearing of the transverse component of the wind has no effect on the airplane, because although it does not affect nor the airspeed nor the angle of attack and, therefore, does not change the balance of the airplane in the vertical plane, the shear of the crosswind tends to move the airplane away from its axis of approach.

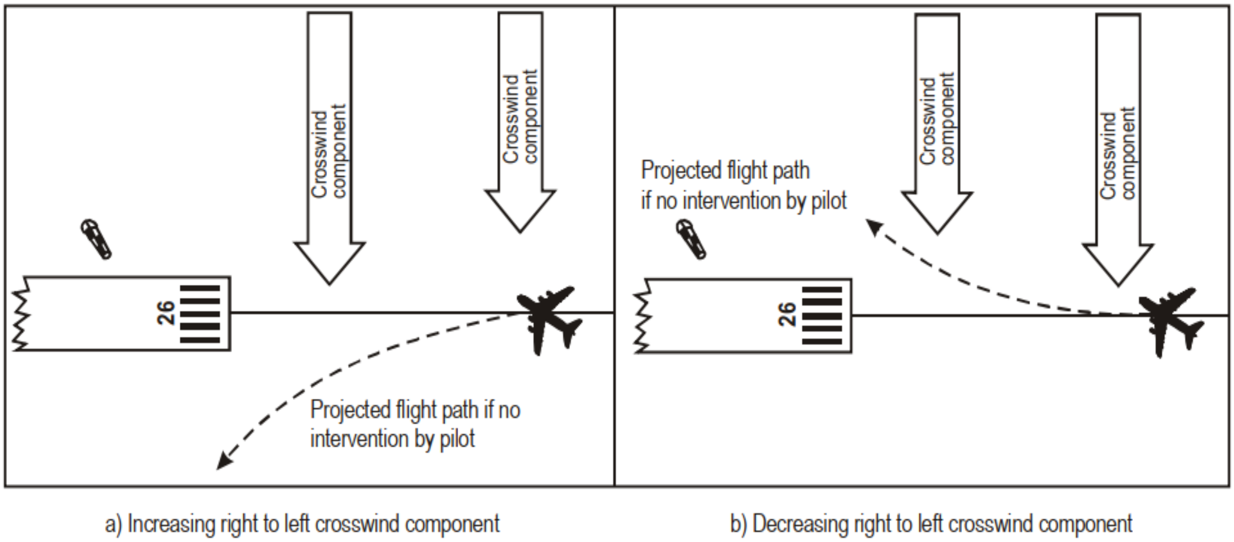
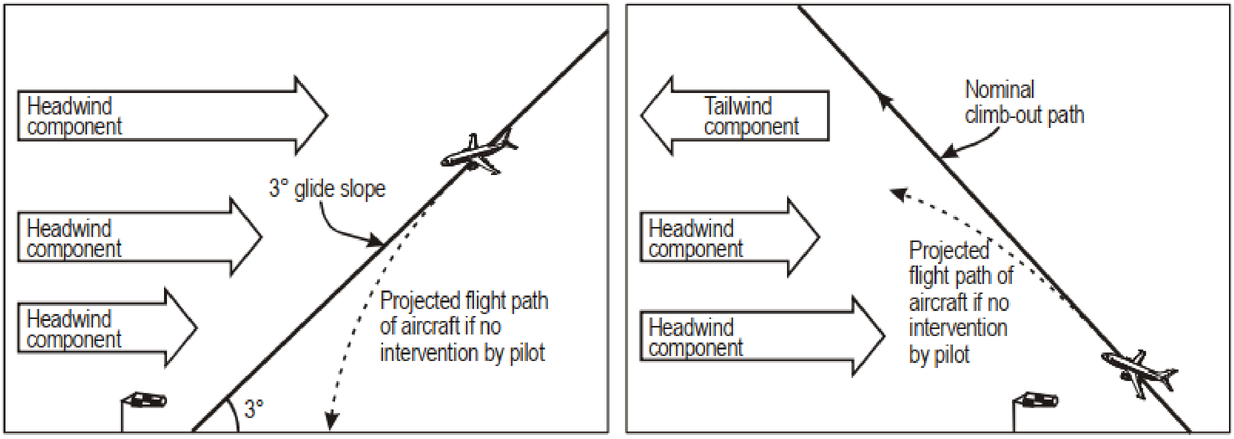


Figure 12:Effect of transverse wind shear on an airplane assuming that the pilot does not intervene (ICAO DOC 9817 AN / 449)

Understanding the behavior of the aircraft in wind shear helps the pilot to understand what is happening and explains the reasons for the recommended technique in the event of involuntary exposure to wind shear.

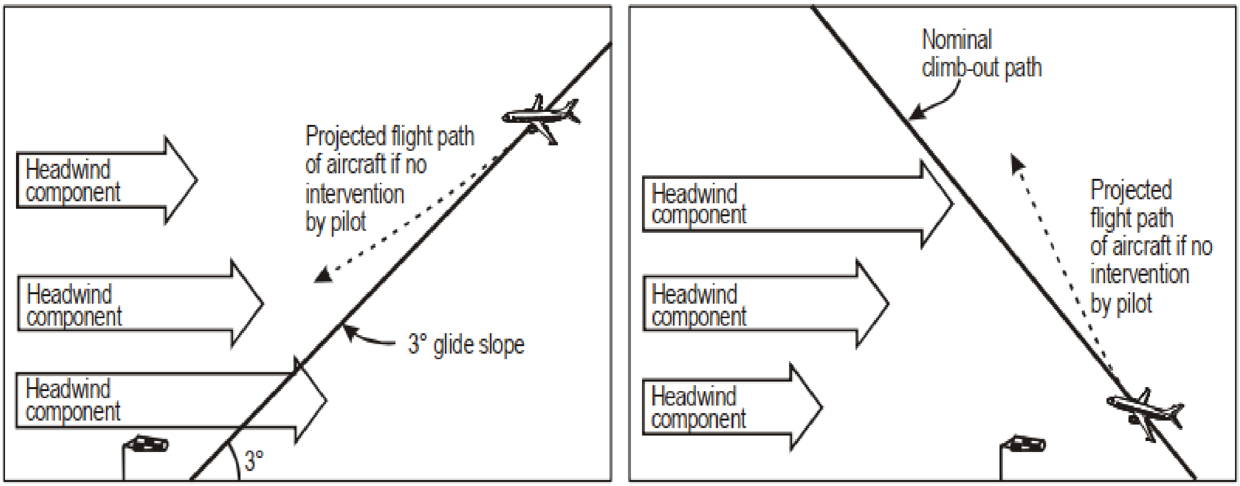
Headwind or tailwind shear

The headwind decreases on the descent slope of an airplane on landing but increases on the initial climb trajectory of an airplane on takeoff. In the case of an aircraft landing against a rapidly diminishing headwind or with an increasing tailwind, the airspeed regression is performed at about the same rate as the deceleration of the headwind or the acceleration of the tailwind. This regression explains that the aircraft is flying under the slope of the descent alignment radio beacon. Landing against an increasing headwind or with a decreasing tailwind causes an acceleration of airspeed corresponding to the speed of the shear, the airplane then flying over the radio beacon slope of descent alignment.



a) Landing in decreasing headwind

b) Take-off in decreasing headwind



c) Landing in increasing headwind

d) Take-off in increasing headwind

Figure 13:Effect of headwind / tailwind shear on an airplane assuming that the pilot does not intervene (ICAO DOC 9817 AN / 449)

In summary, wind variations are potentially dangerous in all phases of aircraft use.

- In the parking, as soon as the wind strengthens, it can move or rotate an aircraft;

- When taxiing, in rear or transverse component, the wind limits the maneuverability of the aircraft; beyond certain thresholds, the trajectory is not always manageable, especially if the runway is wet.

- On takeoff and landing, an aircraft can be affected in different ways by wind shear:

  - A tailwind shear corresponding to an increase in the tailwind or a decrease in the headwind changes the trajectory of the aircraft downward
  - A headwind or upward wind shear changes the trajectory upwards.

- A cross shear constitutes a takeoff and landing limitation for values from 5 to 30 KT depending on the runway condition and the type of aircraft. It affects the angles of drift and skid.
- A downward wind shear corresponds to an increase in the downdraft and modifies the trajectory downwards. In the landing phase, the aircraft can therefore touch the ground before the runway.

- Strong or severe turbulence can lead to imprecision of the indications provided by the on-board instruments, loss of aircraft controls, difficulty in maneuvering at take-off and landing, a reduction in the resistance of the structural elements experienced by overload and vibration forces, etc.

Fog and Mist

Fog is a significant meteorological phenomenon for aviation because it has a high impact in aviation operations.

It is an obscuring phenomenon associated with the presence of small droplets of liquid water (as many as in a cloud) suspended in the atmosphere. Fog is nothing but a cloud that "sticks" to the ground. It is signaled when the visibility is less than 1000 m. Foggy conditions occur with relative humidity close to 100% favored by small temperature dew point spread. Therefore, fog is prevalent in coastal areas where moisture is abundant. Also, abundant condensation nuclei enhances the formation of fog. Thus, fog is prevalent in industrial areas where by-products of combustion provide a high concentration of these nuclei. The fog is qualified as freezing if the air temperature is below 0°C (code: FZFG: Freezing Fog); white frost forms. The aeronautical description of fog is completed by the important characteristics. When qualified as thin (MIFG), it is a surprising fog sometimes for a crew. The scenario is once again that of a visual and early acquisition of the runway, which is abruptly interrupted on very short final when the airplane approaches or encounters the localized slick.

The horizontal distribution of fog around and on the aerodrome is also specified by the qualifiers PRFG (partial occupation of the runway by fog) and BCFG (patches of fog).

Fogs can be classified according to certain formation processes. It is:

Radiation fog: it forms at the end of the night when the sky is clear or slightly cloudy, the wind weak, the relative humidity high. In summary, the formation of radiation fog requires:

- High relative humidity in the lower layers of the atmosphere
- A light wind (1 to 4kt)
- A clear or slightly cloudy sky, until the formation of fog.

Figure 14: Schematic illustration of radiation fog (Aviation Handbook, FAA)

Advection fog: This type of fog occurs when warm, moist air is carried (or advected, hence the term advection) by the wind over a cold surface. At sea, it is called “sea fog”. Advection fog deepen as wind speed increases up to about 15 knots. Wind much stronger than 15 knots lifts the fog into a layer of low stratus or stratocumulus. The air ends up being saturated by isobaric cooling and condenses the excess water vapor (fog takes shape). The advection fog invades in widespread and thick sheets the cold surface regions located downwind of a source of humidity. Favorable weather conditions:

- Temperature difference > 10°C,
- High air humidity over a thickness of a few decameters,
- Wind speed from 5kt to 10kt

Upslope fog: Fog can also occur on mountain tops. This type of fog occurs when warm, moist air becomes saturated after adiabatic expansion along a slope. Once the upslope wind ceases, the fog dissipates. Unlike radiation fog, it can form under cloudy skies.

Steam fog: Steam fog often forms in the fall or winter when cold air blows over a much warmer water surface (temperature difference of at least 10°C). The water evaporates and saturates the cold air. If evaporation continues, the additional water vapor condenses to form fog. This fog is also called cold advection fog.

Fog dissipation: there are four main fog dissipation processes which are:
- The increase in the surface wind which dissipates the stratus fog.
- The increase in cloud cover which dissipates the fog by radiation of long wavelength on the top of the fog (the most effective method).
- Advection of drier air.
- Solar radiation

Mist (BR): It is a hydrometeor made up of small droplets of liquid or supercooled water suspended in the atmosphere (the same as in clouds but in fewer numbers). It causes reduced visibility and is reported when visibility is at least 1000 m but does not exceed 5000 m. Conditions of mist formation are encountered with relative humidity above 80%. Below this value the droplets evaporate quickly. It is common in continental humid regions, coastal and maritime regions. It is located vertically near the ground or is sometimes concentrated below a level corresponding to a temperature inversion.

CLOUDS

A cloud is formed by a collection of water droplets and/or ice crystals suspended in the air which form when the atmosphere becomes saturated with respect to water or ice. The appearance of the cloud depends on the light it receives and the particles that make it up. A cloud forms by condensation of water vapor when the humid air cools. Near the ground, the air is relatively warm and humid, then it cools and dries up at higher altitudes. Clouds form when this warm, moist air

cools, causing the water vapor in it to condense into tiny, but visible, water droplets. If the temperatures at altitude are cold enough, water vapor can sublimate directly into ice crystals. The cooling process necessary to produce cloud droplets or ice crystals often results from air being lifted by one of the following mechanisms:
-Winds that push air up a slope or up a mountain;
♦ A cold air mass displacing a warmer air mass;
♦ Eddies created by winds blowing over rough terrain;
♦ Upward warm air convection currents resulting from uneven heating of the earth’s surface;

Clouds can also form by cooling moist air through direct contact with a colder surface or by increasing the amount of water vapour. Cooling of an air mass can also occur when relatively warm air moves over a cooler surface, and contact cooling causes low clouds to form. This phenomenon is called advection. Cloud type is determined by its height, shape, and behavior. They are classified according to the height of their bases as low, middle, or high clouds, as well as clouds with vertical development (Figure 15).

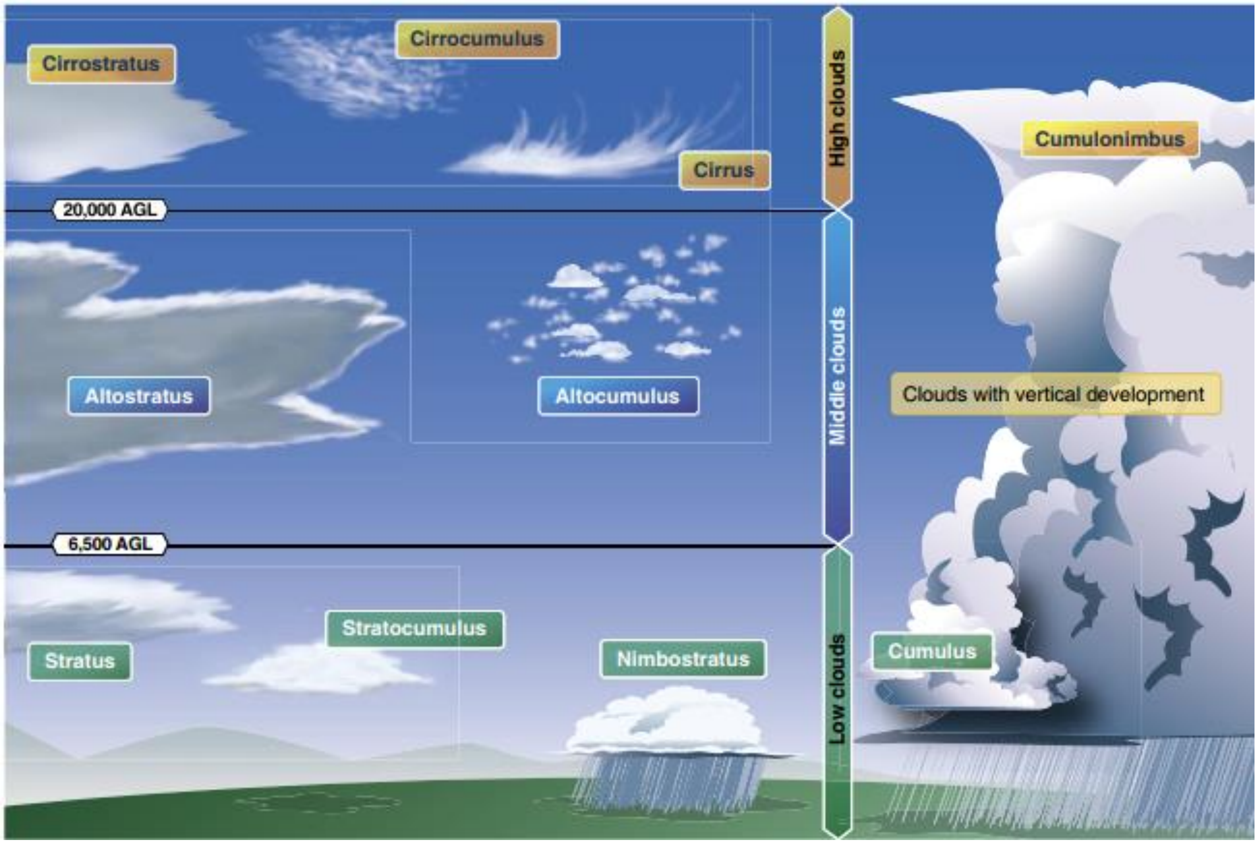


Figure 15: Schematic illustration of the basic cloud types (Aviation Handbook, FAA)

Cumulonimbus, cumulus and nimbostratus, are clouds with significant vertical development and occupy several "stages".

Aviation risks associated with clouds other than cumulonimbus clouds is that aviation regulations set horizontal visibility and ceiling values (height of the first cloud base from the ground of nebulosity corresponding to more than half of the celestial vault) which serve as a lower limit for operation in degraded meteorological conditions. The horizontal visibility and ceiling conditions combined with other criteria relating to the qualification of the crew, the on-board equipment and that of the runway used, but also the performance of the aircraft, make it possible to determine a minimum descent height (MDH) or a decision height (DH) from which the visual cues not being acquired (or being such that the landing is compromised), the pilot makes the decision to abort the approach. However, clouds can considerably affect not only the ceiling, but also the horizontal visibility in the event of precipitation. In addition, other risk factors such as icing, turbulence, etc. can also be associated with clouds.

The most dangerous cloud type for aircraft is cumulonimbus cloud. During the formation of a cumulonimbus, a strong updraft develops within the cloud, making the ground winds converge towards the cloud. When the cloud matures, downward movements are created which generate showers as well as significant gusts giving the impression of "gale" which in principle accompanies the arrival of thunderstorms. In addition, during the dissipation of cumulonimbus, the downdrafts become generalized with a decrease in their intensity over time. Strong localized subsidences can cause devastating winds on the ground or near the ground. These subsidences are given the name of "downburst".

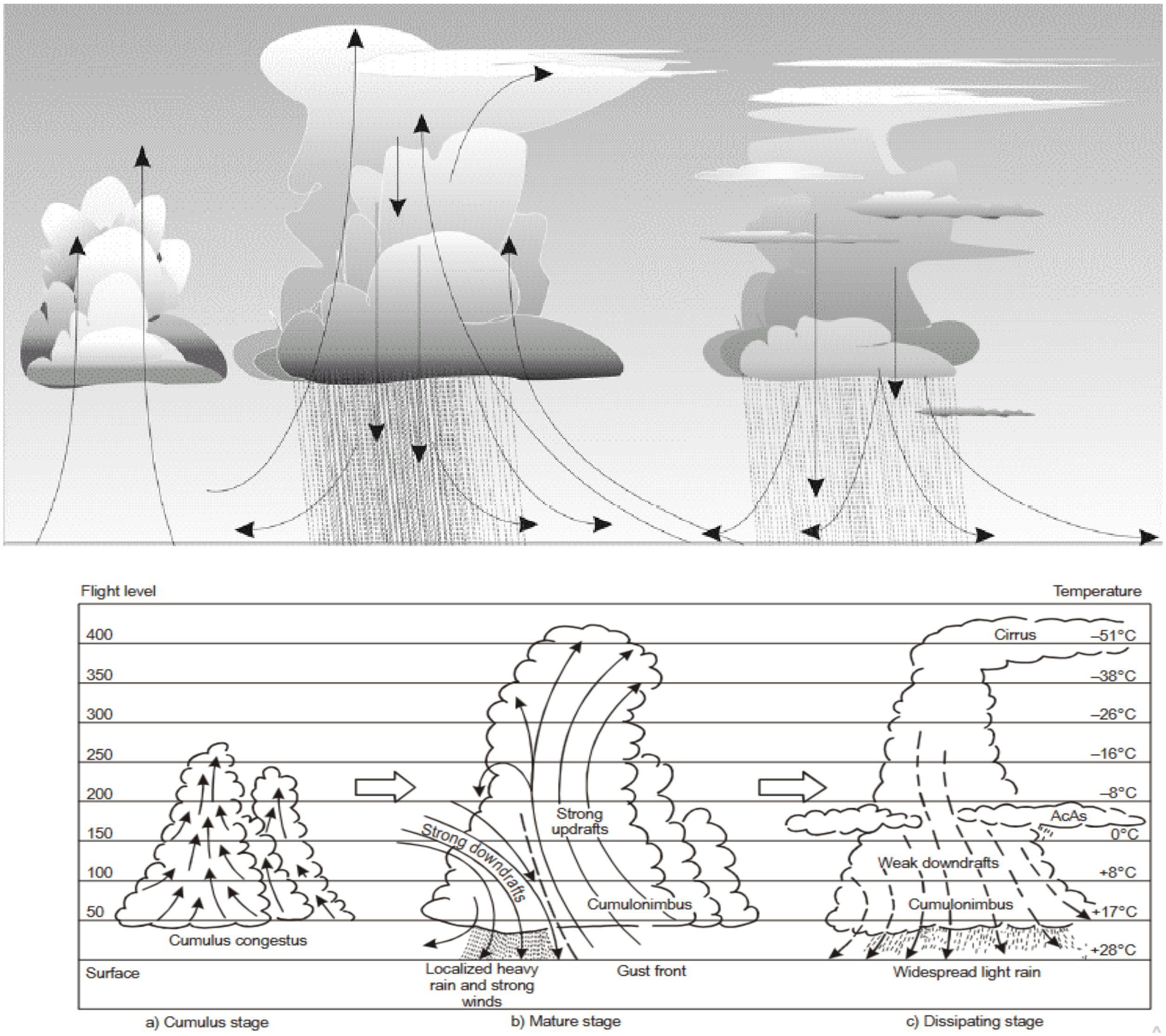


Figure 16: (a) and (b): Life cycle of a thunderstorm (Météo France and ICAO circular 186-AN / 122.1967)

Thunderstorms are associated with cumulonimbus. Several hazardous phenomena for aeronautics are associated with thunderstorm. These are turbulence, wind shear, icing, reduced visibility, hail, water ingestion, heavy precipitation, lightning, effect on altimeters, tornadoes and waterspouts. Thus, a thunderstorm area is a hostile air environment, not really frequentable, for aircraft.

The operating instructions of most airlines impose the circumvention of Cb. The consequences of lightning on an aircraft are: disruption of communications, structural damage (very limited), ignition of fuel in particular during ground operations. On people the consequences can be electrocution, shock, disorientation and temporary blindness.

Nowadays, with satellite products, synoptic observations and model outputs, it is possible to assess the potential risks of heavy rainfall and stormy activities. A range of products is intended to warn the user of the occurrence or forecast of a thunderstorm:

- Terminal Aerodrome Forecasts (TAF), METAR-type observation messages and warning messages (AD WRNG): intended for users of airport platforms;
- SIGMET type messages, but also TEMSI significant weather forecast charts: for en route users.

Ceiling and Visibility

The generic term thunderstorm includes a number of phenomena of sometimes extreme intensity produced by fully developed cumulonimbus clouds: thunder and lightning, torrential rain, hail, strong wind, tornado, etc.

Ceiling and Visibility

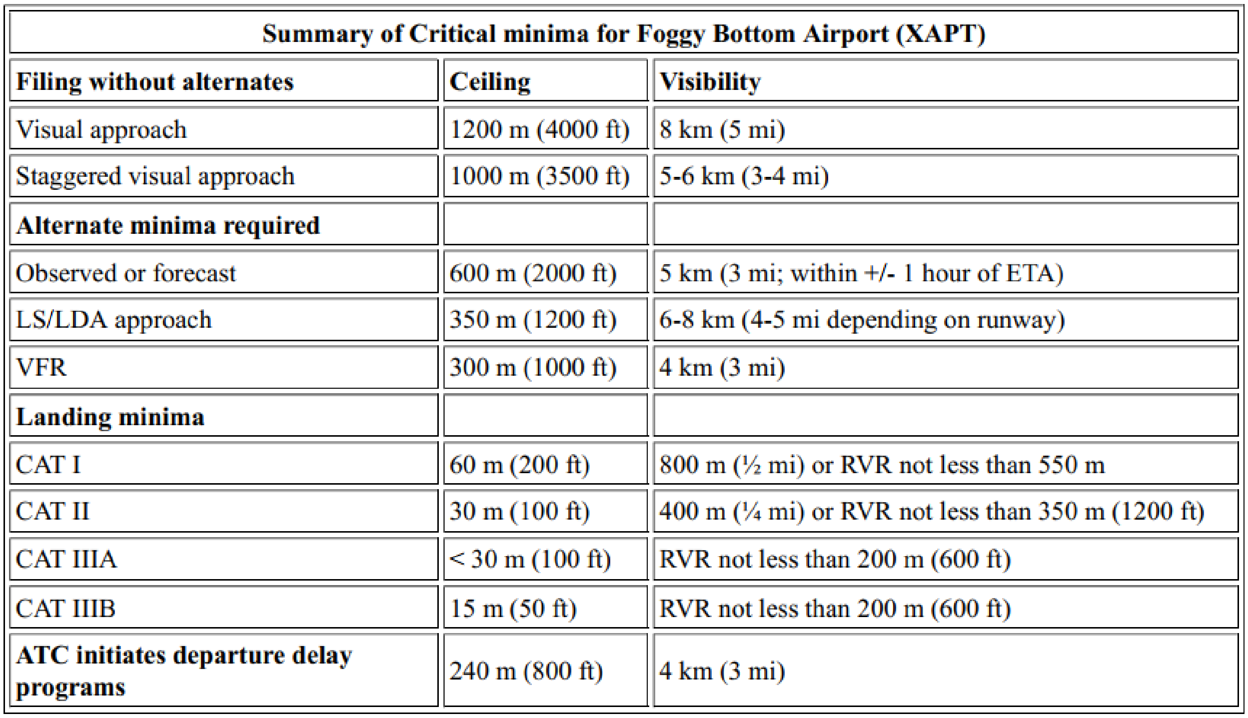
Rick Curtis: ‘’Really, that’s not very restrictive to us with the exception of one thing…and that is that when the plane is descending, it has to be able to see the runway lights at the decision height. If they’re not able to see the runway lights at the decision height, then they have to go around and do a missed approach.’’ (Source: COMET® Program)

For aviation purposes, a ceiling is the lowest layer of clouds reported as being broken or overcast, or the vertical visibility into an obscuration like fog or haze. Clouds are reported as broken when five-eighths to seven-eighths of the sky is covered with clouds. Overcast means the entire sky is covered with clouds. Current ceiling information is reported by the aviation routine weather report (METAR) and automated weather stations of various types.

Closely related to cloud cover and reported ceilings is visibility information. Visibility refers to the greatest horizontal distance at which prominent objects can be viewed with the naked eye. Current visibility is also reported in METAR and other aviation weather reports, as well as by automated weather systems. Visibility information, as predicted by meteorologists, is available for a pilot during a preflight weather briefing.

A ten year study of aviation accidents by the US National Transportation Safety Board (NTSB) indicated that low ceiling and visibility contributed to over 20% of the accidents. Of those accidents, 68% were specifically due to fog and low ceilings (NTSB Weather Related Accidents). The table below is a summary of critical minima for Foggy Bottom Airport (XAPT)

Table 7: Summary of critical minima for Foggy Bottom Airport (XAPT) (Source: COMET® Program)



Summary of Critical minima for Foggy Bottom Airport (XAPT)		
Filing without alternates	**Ceiling**	**Visibility**
Visual approach	1200 m (4000 ft)	8 km (5 mi)
Staggered visual approach	1000 m (3500 ft)	5-6 km (3-4 mi)
Alternate minima required		
Observed or forecast	600 m (2000 ft)	5 km (3 mi; within +/- 1 hour of ETA)
LS/LDA approach	350 m (1200 ft)	6-8 km (4-5 mi depending on runway)
VFR	300 m (1000 ft)	4 km (3 mi)
Landing minima		
CAT I	60 m (200 ft)	800 m (½ mi) or RVR not less than 550 m
CAT II	30 m (100 ft)	400 m (¼ mi) or RVR not less than 350 m (1200 ft)
CAT IIIA	< 30 m (100 ft)	RVR not less than 200 m (600 ft)
CAT IIIB	15 m (50 ft)	RVR not less than 200 m (600 ft)
ATC initiates departure delay programs	240 m (800 ft)	4 km (3 mi)

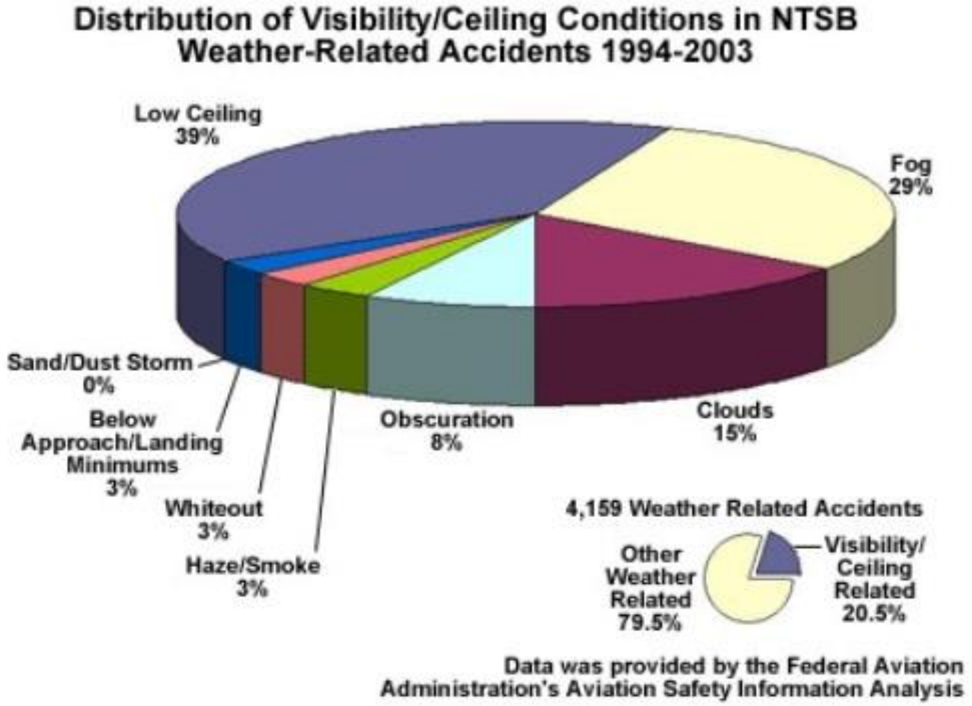


Figure 17: Distribution of visibility/ceiling conditions in NTSB weather-related accidents 1994-

On March 27, 1977, in conditions of reduced visibility, two B747s collided on the only runway in Tenerife, resulting in the death of 578 people. As one of the two planes climbs the runway, the other takes off. The visibility of about 500 m did not prevent this collision. Thus, the prevention of collisions of all kinds, between aircraft on the ground or aircraft in flight and terrain ensured by multiple systems and procedures also requires a good knowledge of visibility conditions. Let's add, in addition, an awareness of all weather phenomena that degrade visibility.

Precipitation:

Precipitation refers to any type of water particles that form in the atmosphere and fall to the ground. Precipitation occurs because water or ice particles in clouds grow in size until the atmosphere can no longer support them. It can occur in several forms as it falls toward the Earth, including drizzle, rain, ice pellets, hail, snow, and ice. Drizzle is classified as very small water droplets, smaller than 0.02 inches in diameter. Drizzle usually accompanies fog or low stratus clouds. Water droplets of larger size are referred to as rain. Rain that falls through the atmosphere but evaporates prior to striking the ground is known as virga.

Freezing rain and freezing drizzle occur when the temperature of the surface is below freezing; the rain freezes on contact with the cooler surface.

If rain falls through a temperature inversion, it may freeze as it passes through the underlying cold air and fall to the ground in the form of ice pellets. Ice pellets are an indication of a temperature inversion and that freezing rain exists at a higher altitude. In the case of hail, freezing water droplets are carried up and down by drafts inside clouds, growing larger in size as they come in contact with more moisture. Once the updrafts can no longer hold the freezing water, it falls to the Earth in the form of hail. Hail can be pea sized, or it can grow as large as five inches in diameter, larger than a softball.

Snow is precipitation in the form of ice crystals that falls at a steady rate or in snow showers that begin, change in intensity, and end rapidly. Falling snow also varies in size, being very small grains or large flakes. Snow grains are the equivalent of drizzle in size.

It should be noted that precipitation whatever the form is a threat to flight safety. Often, precipitation comes together with low ceilings and reduced visibility. Aircraft that have ice, snow or frost on their surfaces should be thoroughly cleaned before commencing a flight due to possible disruption of airflow and loss of lift. Rain can contribute to water in fuel tanks. Precipitation can create hazards on the runway surface itself, making take-offs and landings difficult or even impossible due to snow, ice or water accumulation and very slippery surfaces.

1.2 Statement of the Problem

The statistics show that the adverse phenomena are of particular importance for aircraft in critical phase of speed and height during landing and takeoff. During the ascent and approach phases of the flight, the aircraft speed and altitude are very close to the critical values and make the aircraft particularly vulnerable to the effects of the phenomena.

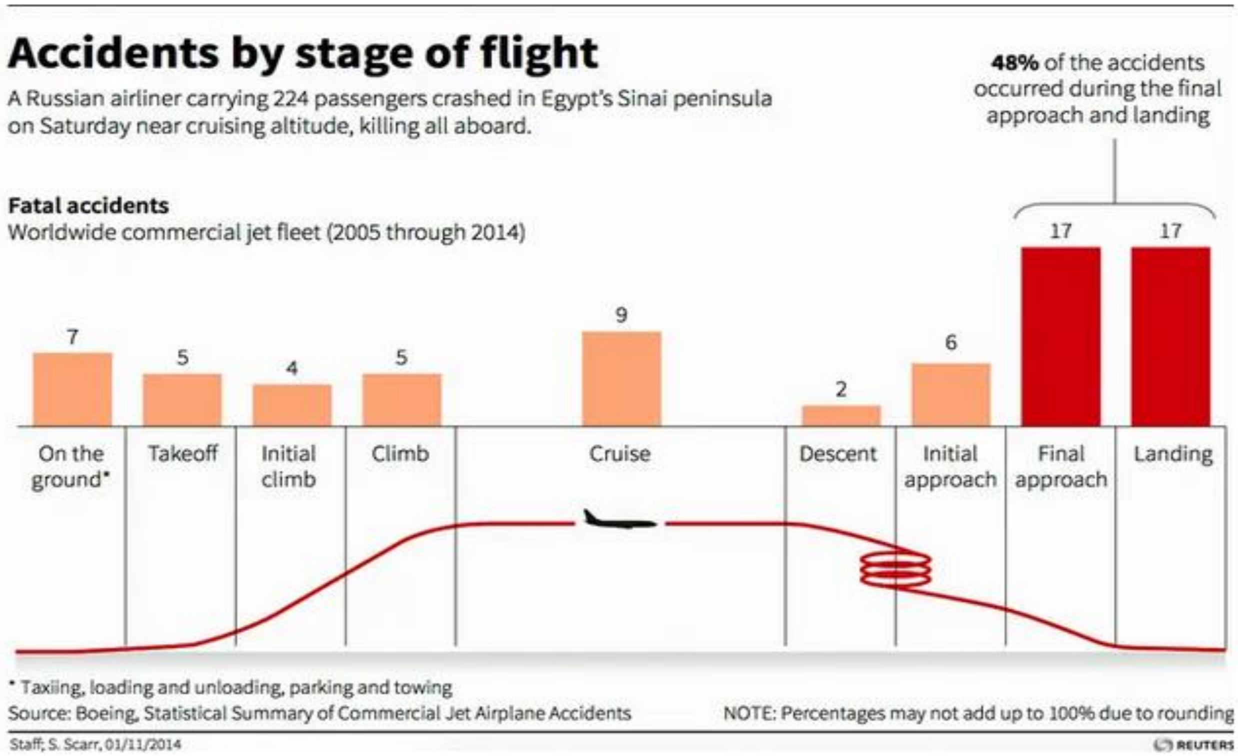


Figure 18: Accidents by stage of flight (REUTERS)

Weather is the cause of almost a third of aircraft accidents. While it is blamed for causing most of air traffic delays, costing world airlines four billion dollars, and thunderstorms present some of the biggest hazards to aircraft in general. In fact, a single thunderstorm contains multiple threats to aircraft including heavy precipitation, hail, lightning, very severe turbulence, low level wind shear, microburst and icing conditions. Wind, mist and fog, particularly with regard to light aircraft, that impair visibility and air pressure have been noted to lead to air crashes.

According to Baum (2010), failing to heed up-to-date weather forecasts is unwise especially where the elements are particularly changeable and intense due to the mountainous terrain and the prevalence of strong winds and turbulence. Severe weather can test the structural strength of aircraft designed for less rigorous conditions, and the skill of the pilots (Swabrick, 2009). Although poor weather conditions are beyond the control of pilots, airlines and flight crew, these people have a responsibility for the safety of their passengers. When the decision is made to go ahead with a flight despite weather advisories, the lives of others are put at risk.

These accident inducing-phenomena are rightly feared and avoided by the crews of an aircraft and their avoidances give rise to cancellations, diversions and delays. Thus, adverse weather significantly influences the aviation industry; the safety and operating efficiency of air traffic, particularly in the terminal area.

A flight delay is defined when the actual time of flights departure or arrival within airports is later than the scheduled operation time. A flight delay is a phenomenon raised with the world airline. The world airline industry is witnessing an unprecedented developing period. Klein *et al*. (2009) integrated the convective weather forecasts, terminal airports weather forecasts and scheduled flights information to predict the daily airport delay time based on a metric called Weather Impacted Traffic Index (WITI). The capacity limit of an airport can be reached following an increase in demand. It can be greatly reduced by a small change in weather conditions. The operations of an aerodrome in all its aspects can be affected by the change in weather. Adverse weather conditions are likely to significantly reduce the airspace capacity of an entire region. Thus, flight delays, diversions and cancellations could be corollaries of such a situation. These weather-related disruptions could lead to alterations in flight operations. Therefore, weather conditions negatively and considerably influence the safety, efficiency and capacity of aircraft, as well as airport operations.

Muiruri (2011) showed that there is a link between delay and diversion incidents of aircraft and inclement weather from JKIA and Wilson airports. His study demonstrated that aircraft delays and diversions were in majority caused by poor visibility, thunderstorms and wind shear. 30,000,000 kenya shillings and 1.9 billion Kenya shillings were the costs induced respectively by delays and diversions at JKIA and Wilson airports over the ten years.

1.3 Research Questions

Based on the identified problem, the main research question that will guide thus study is:

Is it possible to implement a weather impact index on aviation delays at JKIA as a decision making support tool for better operational and financial decisions?

The formulated specific questions will be:

1) What weather phenomena are the highest contributors in causing aviation delay and diversion incidents and what weather phenomena are the highest contributors in causing aviation delay and diversion times?
2) What are the annual, monthly and hourly distribution of aviation delay and diversion per weather phenomena?
3) How accurate is the Terminal Aerodrome Forecast issued at JKIA and what is the implication of TAF accuracy on aviation delays and diversions occurring at JKIA?
4) Is it possible to develop a weather impact index of delays at JKIA using the data for the study period?

1.4 Objectives of the Study

The main objective of this study was to assess the potential implementation of a weather impact index on aviation delays at JKIA. There are 4 specific objectives that were pursued in order to achieve the main objective.

1. To identify the meteorological phenomena which cause delays and diversions in departing and arriving flights at JKIA
2. The determine the temporal evolution of meteorological phenomenon and flight delays and diversions at JKIA
3. To evaluate the accuracy of the Terminal Aerodrome Forecasts
4. To develop a weather impact index on aviation delays and diversions at JKIA

1.5 Justification

The airline industry is subject to a host of unforeseen events that result in delays in scheduled aircraft arrivals and departures. In 2010, Airlines for America (A4A) was running 99 million minutes late and established their direct operating costs, including fuel, crew, maintenance, aircraft and other costs, at 6.5 billion of dollars. This represented a direct operating cost of $ 65.19 per minute, an increase of 7% more than in 2009. For the same year, the A4A association estimated the additional costs, that is to say those associated with travelers' compensation to $ 3.3 billion. Every year in this industry, delays represent additional lost revenue.

At JKIA, several cases of air traffic service (ATS) irregularities are attributable to bad weather conditions causing delays and diversions at departure and arrival of airplanes. So, these bad weather conditions often resulted in disruptions with the consequence of additional fuel consumption and loss of time for operators and passengers, which shows that it constitutes a real problem for aeronautical activity. In fact, the complexity of these disruptions lies in the interdependence of operational activities and the stakeholders involved in each flight. Thus, a delay on one flight can cause cascading delays to other flights which in turn disrupt the departure of other aircraft, affect operator efficiency and generate additional costs. As a result, flight plans need to be changed and promises made to customers are changed as well.

Hence the importance of studying their occurrence criteria and to develop a weather impact index as comprehensive tool to help airline operational staff and air traffic management strategies staff for the purpose that controllers can follow in case of adverse weather avoidance, to manage and reduce the impacts of these delays, also to control the resulting costs.

1.6 Area of Study

This study was carried out over the Jomo Kenyatta International Airport (JKIA) in Nairobi, Kenya, as shown in Figure 10. Kenya has more than 60 airports and more than 450 airstrips in Kenya. JKIA (denoted as HKJK) was chosen because of its international stature. HKJK is regarded as the fourth busiest airport in Africa, according to data from the latest Airports Council International, (2019) report.

Figure 19: Aerial view of Jomo Kenyatta International Airport (JKIA), Nairobi, Kenya

2 LITERATURE REVIEW

In the airline industry, disruptions caused either by mechanical aircraft problems, the lack of crew or weather impact can occur and change the schedule of operations as originally planned. Clausen *et al*. (2001) define a disruption as a sufficiently large difference between the current state of operations and that predicted by the planning schedule for there to be a change in the planned operations. In the airline industry, these are commonly referred to as irregular operations.

According to Gang (1998), these deviations lead to a re-routing of activities throughout the flight schedule planning system on three levels: passengers, crews and airplanes. According to Clausen *et al*. (2001), when a disruption occurs in the course of operations, several airlines solve the problem sequentially in the following order: planes, crews, ground operations, and passengers. Similarly, Ball *et al*. (2007) claim that the flight schedule is the basis of three other types of schedules: the schedule of planes, crews and passenger routes. In general, in the literature, the restoration of the schedule, called schedule recovery, can be carried out by analyzing one aspect at a time: either the restoration of the schedule of planes (flight recovery), crews (crew recovery) and passenger itineraries.

Regarding the re-establishment of the aircraft schedule, authors Teodorovic *et al*., (1984) investigated the situation where an aircraft is taken out of service and made an effort to minimize passenger delays by interchanging and delaying aircraft. Because airline schedules are very tight and due to the ripple effect, downstream flights are heavily impacted by delays and diversions. Unexpected and unplanned bad weather is one of the factors that often compromises the efficiency of airport operations; which leads to a compromise of operations in terms of regularity and punctuality, thus inducing unexpected traffic jams and prolonged delays. Disruptions can cause the temporary closure of an entire airport. In this case, incoming flights have only two options: either wait and land after the reopening time, or divert to another airport. Two main criteria are considered for the choice of the diversion aerodrome: First, the aircraft must have a sufficient amount of fuel remaining to be able to arrive at the alternate airport. Second, runway length, spare capacity, apron facilities are the characteristics of the diversion airport to consider.

The negative effects of the flight delay which happens to be unavoidable are of an economic nature on the airlines, the airport and the passengers. On the other hand, the increased fuel consumption due to the delay is a damaging factor of the environment due to the emission of polluting gases. In addition, the increase or decrease in ticket sales and by extension the transportation of goods is very dependent on the customers trust. This is how customer trust can be gained by on-time flight and lost by flight delay.

US domestic airlines suffer a loss of approximately US$3 billion per year due to delays caused by bad weather, which accounts for 65% of the delays recorded (Evans,1995). At US airports, improved weather forecasting accuracy in winter and icing diagnostics could save up to US$600 million per year (Klein *et al*., 2009). Good control of an airline's delays through on-time performance would not only make it possible to retain customers and attract others, but also constitutes a key factor in achieving significant financial savings.

If a planned flight schedule is subject to disruptions, pilots may be unavailable as will future aircraft flights (Abdelghany *et al*., 2004). Thus, a disconnection of crew members on their next scheduled flight is very likely. Therefore, passengers, airport operators and air carriers will benefit greatly when there is a decrease in delays (Markovic *et al*., 2008). Often the similarity of the causes of delays even under traffic and weather conditions does not produce the same response in operation because of the various factors that produce non-linear effects in the response (Klein *et al*., 2009).
Airspace procedures and regulations as well as poor weather conditions are closely linked to unavoidable delays (Klein *et al*., 2009).

There is a strong positive correlation between the accuracy of weather forecasts and avoidable delays (Klein *et al*., 2009). When a weather forecast is overestimated, it will promote delays that should not have happened. In the event of underestimations, one might think that operations and air traffic will go well, but one finds oneself powerless in the face of an unforeseen and degraded meteorological condition which imposes actions to manage a large flow of air traffic without a warning sign. , forcing either to keep the aircrafts in holding position which leads to delays, or to divert them towards an alternate aerodrome; with the potential for a ripple effect across the entire national airspace (Klein *et al*., 2009).

Current cancellations and delays with their associated cost which are generated by bad weather conditions and especially convective clouds could be avoided by up to sixty percent (Klein *et al.*, 2009). The ICAO requirements concerning each provider of aeronautical meteorological services are such that the latter holds the certification of the International Organization for Standardization while placing particular emphasis on the verification of meteorological forecasts with a view to obtaining this (ICAO Annex 3, 2010).

Recommendations for enhancing the accuracy assessment of aeronautical weather forecasts have been made by Mahringer (2008) and Muiruri (2006, 2011). At least twelve and a half million US dollars: this is the amount that a study conducted by NavCanada found could be saved if one hundred percent accurate terminal aerodrome forecasts are used (Klein *et al.*, 2009). By conducting a study on a single airline, Quantas Airways, a study estimated 6.8 million Australian dollars as the economic value in 1993 of the aviation weather forecast for Sydney Airport (Fabbian *et al*, 2006). Decision making to perform a landing as well as flight planning are the capabilities that forecast accuracy offers to the pilot (Muiruri, 2010).

A very considerable impact on airport activities is generated by unplanned visibility reduced below the minimum threshold (Mahringer, 2008). Adverse weather conditions disrupt airport operations, and for this reason ensuring the safety, efficiency and regularity of air transport is very reliant on timely information about weather changes that manifest themselves without warning. The failure to take into account the various physical processes such as humidification that are associated with the forecast of fog by NWP models is a limiting factor in methods for estimating visibility (Jacobs *et al*, 2004).

To evaluate whether mitigation measures are suitable, it is necessary to weigh the costs against the benefits. And Rose *et al.*, (2007) conducted an analysis in this way. The planning of flight schedules at airports are greatly disrupted by adverse weather conditions causing aviation delays. This situation has become very serious as mainly American researchers have not stood idly by and are looking for a solution by conducting weather impact studies on aviation. In Europe, the proportion is lower. Africa, only Lara Peck (2015) has conducted a study of this kind on departure delays and becomes the pioneer in this field.

3 DATA TYPES AND METHODOLOGY

3. 1 Introduction

The chapter explains the many forms of data that were collected and the approach used to accomplish the particular goals stated in section 1.4 (objective of study: WITI). The strategies utilized to accomplish the specified objectives are outlined after the datasets used are discussed.
Analyzing the airline and airport operations directly from data is displaying an exciting research future. Data-driven research starts from data and can discover many phenomena which are difficult for people to understand and compute directly. This study was carried out using specific methods of collection of two types of data for the years 2000 to 2009 at JKIA in order to achieve the specific objectives.

3.2 Data Types and Sources

The following two types of data were used in this study: meteorological data and aviation data.

3.2.1 Meteorological Data

Meteorological Aviation Reports (METARs) and Terminal Aerodrome Forecast (TAFs) were used in this study, and the data was gathered from KMD and JKIA. The decoding of the METAR and SPECI messages made it possible to identify the weather phenomena (causing aviation delays). The times, dates, months and year of each occurrence of aircraft delay or diversion made it easy to find the METAR or SPECI and TAF messages that were associated with the incident.

3.2.2 Aviation Data

We qualify as ‘’aviation delay’’ in this study when the aircraft has not landed or taken off at the airport at the time scheduled in the flight plan and ‘’delay duration’’ as the additional difference in time of the real time from the time scheduled in the flight plan at departure from JKIA or arrival to JKIA.

We also assume that the diversion at an alternate aerodrome constitutes a delay relative to its schedule flight time of arrival at the JKIA. The duration of the diversion, in this case, would be the additional difference in time of the real arrival flight time at the alternate airport from scheduled arrival flight time at JKIA. So the study will not consider the delay and its duration of the flight in the " recovery leg " which is by definition comparable to the return of the aircraft to JKIA airport for the following reasons among others: firstly the meteorological phenomenon which induced the diversion has ended at the JKIA, secondly it will allow us to avoid a double accounting in the costs related to the delay and finally because a new flight plan has been issued from the alternate airport and the fact that a new flight plan constitutes a new contract between the airline and the airports of departure and destination.

It is important to remember that a flight plan ‘’ is a document containing all the information relating to a flight or to a part of the planned flight which is transmitted to the air traffic units. It reflects the pilot's flight intentions, and is drawn up in from the regulated model developed by ICAO. In Africa-Indian Ocean Region (AFI), the submission of a flight plan is mandatory except for local flights. RAC part (Rules of air circulation) contains the information required by air traffic units for air traffic control purposes.

Another hypothesis is that we consider a weather-related delays only for the aircraft flights fulfilling ICAO regulations, that is the general air traffic (GAT). This is the set of movements generated by the evolution of civil aircraft and sometimes State aircraft when they perform missions comparable to those of civil aircraft. The regulations that are the subject of this study will apply to the GAT. Operational Air Traffic (OAT) flights are not in the scope of the study. It concerns the movement of military aircraft in commanded missions or air training in a specified area. These operations therefore concern tactical aviation (hunting, interception, bombardment, etc.) and as such escape civilian control. The rules of the OAT therefore do not apply to the GAT. Also, we are not going to consider air traffic of tests and acceptance: It concerns the movements of civil or military aircraft under test with a view to their certification. These are therefore prototype or pre-production aircraft that escape civilian control for reasons of discretion and technological protection. Here too, the GAT rules do not apply.

Our data included weather phenomena that caused aviation delays and diversions during our period of study, weather-related delays and diversions, alternate airports during aircraft diversions, date and time of occurrence of aircraft delays and/or diversions and duration of these incidents. These data were sourced from Kenya Aviation Authority (KAA) database. The analysis also extended to the filtering out of the aviation delays and diversions, because the raw data contains diversions of aircrafts to JKIA due to bad weather at initial arrival airport in the flight plan. Raw number of weather related delay/diversion incidents and duration (in minutes) associated with them together with the refined number of incidents during departure and arrival of aircrafts from/to JKIA and the duration associated with them are as shown in Table 2.

Table 8: raw number of weather-related delays/diversions and the duration (in minutes) associated with them together with the refined number of incidents during departure and arrival of aircrafts from/to JKIA and the duration associated with them

YEAR	**RAW DATA**		**REFINED DATA**							
	combined Delay/Diversion Incidents	combined Delay/Diversion Minutes	Departure delay, arrival delay and diversion Incidents				Departure delay, arrival delay and diversion Minutes			
			DEP	ARR	DIV	TOTAL	DEP	ARR	DIV	TOTAL
2000	10	300	0	7	3	10	0	120	180	300
2001	57	2900	0	13	44	57	0	232	2668	2900
2002	46	2627	3	8	35	46	128	164	2335	2627
2003	28	1455	3	7	18	28	119	106	1230	1455
2004	37	1810	0	12	25	37	0	188	1622	1810
2005	36	1894	1	7	28	36	48	129	1717	1894
2006	22	951	2	9	9	20	68	225	596	889
2007	91	3822	5	33	41	79	318	732	2400	3450
2008	81	3267	14	34	17	65	857	591	1030	2478
2009	14	515	0	7	4	11	0	134	288	422

3.3 Weather Categories Design

In order to identify the meteorological phenomena which cause delays and diversions in departing and arriving flights at JKIA, weather categories were designed. Hydrometeors reducing visibility have been grouped into a single category. These are fog, mist, thin fog and patch fog. Haze is also designated as a separate category as a visibility-reducing lithometeor. The other categories are Cumulonimbus clouds, Towering cumulus clouds (TCU), Low Level Clouds, Rain, Wind Change and Temperature. Thus, 8 categories of weather were listed and were representative of the phenomena that threaten airport operations at JKIA airport as shown in table 3 with their sub-types (sub-categories.

In accordance with the regulations in annex 3, often, there are cases where more than 3 types of weather can be included in a single METAR or SPECI message when encryption conditions permit. The need for a simplifying hypothesis for the analysis of incidents of delays and diversions led the study to operate a method of ranking the weather categories adopted, as can be seen in table 3. This hierarchy is important insofar as it makes it possible to assign a specific category in the specific case where several categories are coded in the same message associated with an aircraft delay or diversion.

Table 9: Shows the weather categories and sub-types

Category (Type)	**Sub-type**		**Remarks**
CB Clouds	Cumulonimbus with Thunderstorms	Cumulonimbus without Thunderstorms	
	Cumulonimbus with thunderstorm, but no rain	Cumulonimbus without Thunderstorm, but no rain	
	Cumulonimbus with Thunderstorm, rain, but no reduction in visibility	Cumulonimbus without Thunderstorm, precipitation, but no reduction in visibility	
	Cumulonimbus with Thunderstorm, rain, and a reduction in visibility	Cumulonimbus with Thunderstorm, rain, and a reduction in visibility	
	Less than 1000m	Less than <1000	
	1000m to less than 3000m	1000m to less than 3000m	
	3000m to 5000m	3000m to 5000m	
TCU Clouds	Towering cloud, no rain	Towering cloud, rain, and a reduction in visibility	
	Towering , rain, but no reduction in visibility:	Less than 1000 m	
		1000 to less than 3000 m	
		3000 to 5000 m	

Fog/Mist			FOG, BR, MIFG and BCFG (without considering the presence or no of low cloud)
Rain			not originating from cumuliform clouds
			This category includes Drizzle
Haze			
Wind Change			crosswind, tailwind … causing change in use of runway
Temperatures			
Low Level Clouds			low clouds reported only i.e., no fog, no mist, no rainfall

3.4 Methods

This section outlines the many techniques that were used to analyze the datasets described in Section 3.1 in order to accomplish the precise goals mentioned in Section 1.4.

3.4.1 Temporal Analysis

The temporal analysis in this study is composed of the monthly analysis and the analysis of the 4 daily time slots which reflect the intensity of the airport operations at JKIA which is a function of the airport capacity. The monthly analysis gives us an overview of the distribution of delays and diversions over the 10 years, but also monthly totals or monthly averages. This analysis will also allow for the variation of delays and diversions over the months for each category. As for the time-of-day analysis, the daily variation of aircraft delays and diversions according to the 4 time slots will be examined, as will the variation of delays and diversions during the 4 time slots of the day for each category.

Table 10: The 4 time slots of a day at JKIA

S/N0	Time Slot	Name of the Time Slot
1	04H30-08H30	Morning Peak
2	08H30-13H00	Morning Off-Peak
3	13H00-23H00	Evening Peak
4	23H00-04H30	Night Off-Peak

3.4.2 Technique of TAF Assessment

In order to assess the Terminal Aerodrome Forecast (TAF), a TAF assessment technique was adopted. The evaluation of the TAF consists, for each unit of delay or diversion, in using the METAR which is the actual meteorological situation observed to test the accuracy of the TAF. The considered TAF is the one at least 6 hours before since this time is more than enough to allow good flight planning. The result of the evaluation is binary: HIT or MISS. The conduct of the evaluation is done methodically in a three-step sequence: -The first step is to analyze whether the weather forecast by the TAF at which bad weather is supposed to occur is correct. -If this is satisfactory, then the second step is to analyze whether the type of weather according to the various categories of table 3 has been exactly predicted -If successful, the third step is to check whether the horizontal visibility is exactly provided in accordance with the ICAO regulations contained in Annex 3 as shown in Figure 21. If the analysis passes these 3 steps, then the TAF forecast is considered a success (HIT). Otherwise, it is a MISS.

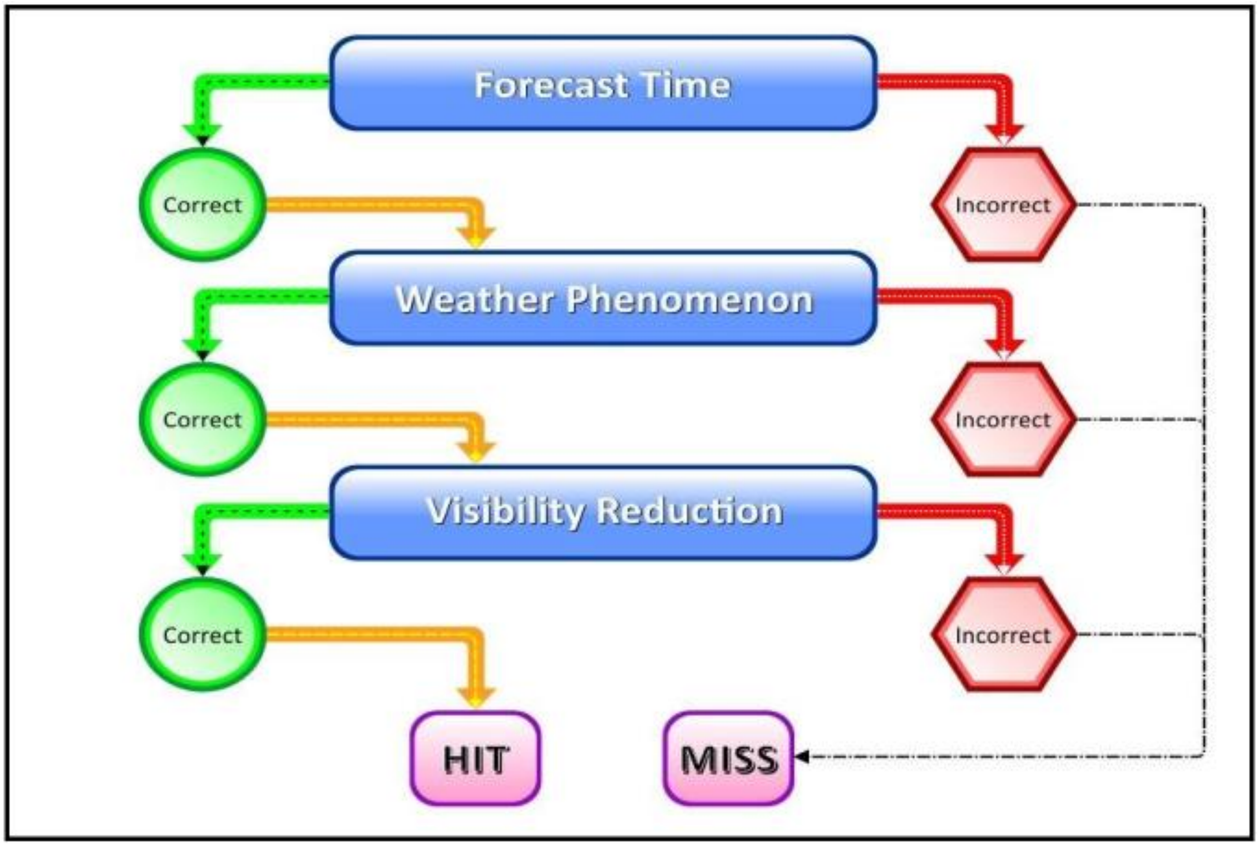
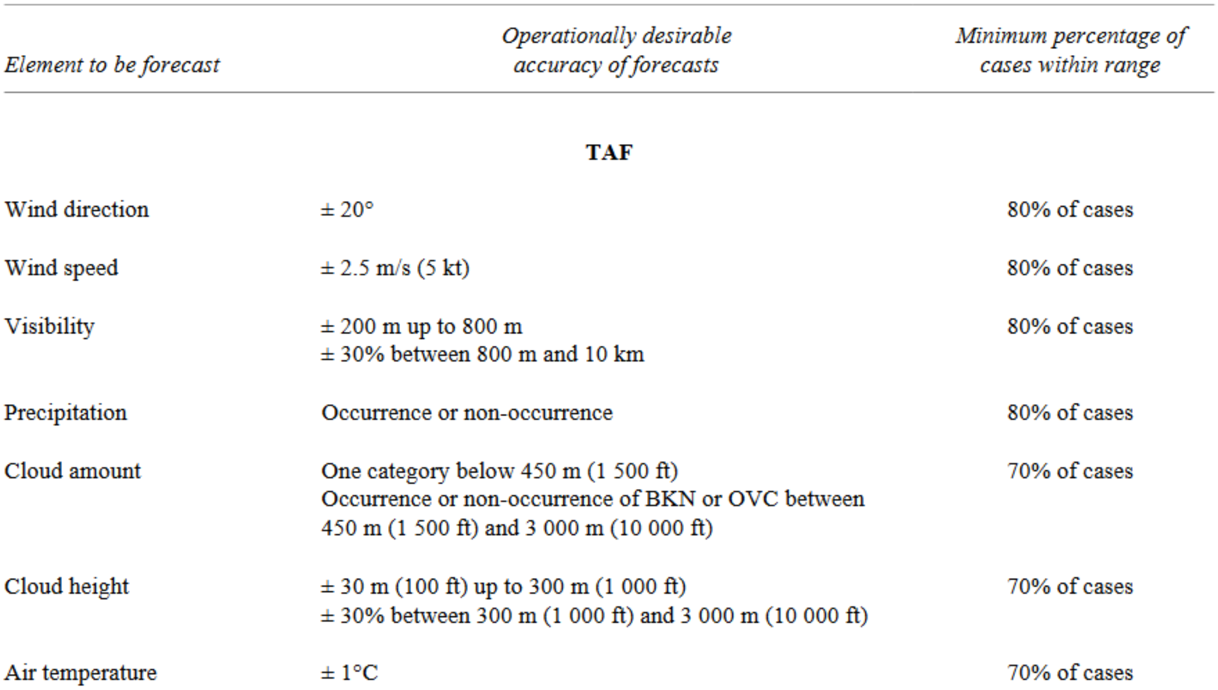


Figure 20: shows the flowchart of the TAF assessment procedure (Lara, 2015)

The main document describing requirements for quality of meteorological information is Annex 3 issued in the form of recommendation by International Civil Aviation Organization (ICAO) and in cooperation with World Meteorological Organization (WMO). Annex 3 is an international ordinance containing international standards and recommended practices for providing meteorological service for navigation in aviation.
It is nationally adjusted, but in conformity with ICAO standards. This standard is crucial directive for all meteorological staff as well as for superiors at the forecast centers, as it provides rules and guidelines that shall be followed during providing meteorological service. It constitutes a base for compulsory national documents.

ICAO regulation from Annex 3 for operationally desirable accuracy of forecasts is used for visibility, cloud amount and cloud height verification in this study.



Element to be forecast	*Operationally desirable accuracy of forecasts*	*Minimum percentage of cases within range*
TAF		
Wind direction	± 20°	80% of cases
Wind speed	± 2.5 m/s (5 kt)	80% of cases
Visibility	± 200 m up to 800 m ± 30% between 800 m and 10 km	80% of cases
Precipitation	Occurrence or non-occurrence	80% of cases
Cloud amount	One category below 450 m (1 500 ft) Occurrence or non-occurrence of BKN or OVC between 450 m (1 500 ft) and 3 000 m (10 000 ft)	70% of cases
Cloud height	± 30 m (100 ft) up to 300 m (1 000 ft) ± 30% between 300 m (1 000 ft) and 3 000 m (10 000 ft)	70% of cases
Air temperature	± 1°C	70% of cases

Figure 21: Shows the ICAO regulation from Annex 3 that was used for visibility, cloud amount and cloud height verification

The production of TAFS is standardized by ICAO regulations. These regulations are set out in documentation, namely Annex 3: Meteorological Service for International Air Navigation, which is followed by all meteorological organizations. As per this documentation, the forecast of horizontal visibility should be forecasted within specific ranges, as set out in Table 5.

Table 5 shows the ranges within which the horizontal visibility should be forecasted.

Table 11: Shows the six specific ranges with which the horizontal visibility should be forecasted (Adapted from ICAO, 2013)

S/NO	**Horizontal Visibility Groups**
1	150m-350m
2	350m-600m
3	600m-800m
4	800m-1500m
5	1500m-3000m
6	3000m-5000m

Note that the category Wind Change does not undergo TAF Assessment Technique. This results in 372 TAFs assessed (Table 6).

Table 12: annual distribution of unassessed and assessed TAFs

YEAR	**annual distribution of unassessed TAFs**	**annual distribution of assessed TAFs**
2000	0	10

2001	0	57
2002	2	44
2003	1	27
2004	0	37
2005	0	36
2006	0	20
2007	3	76
2008	10	55
June 2009	1	10
TOTAL	17	372

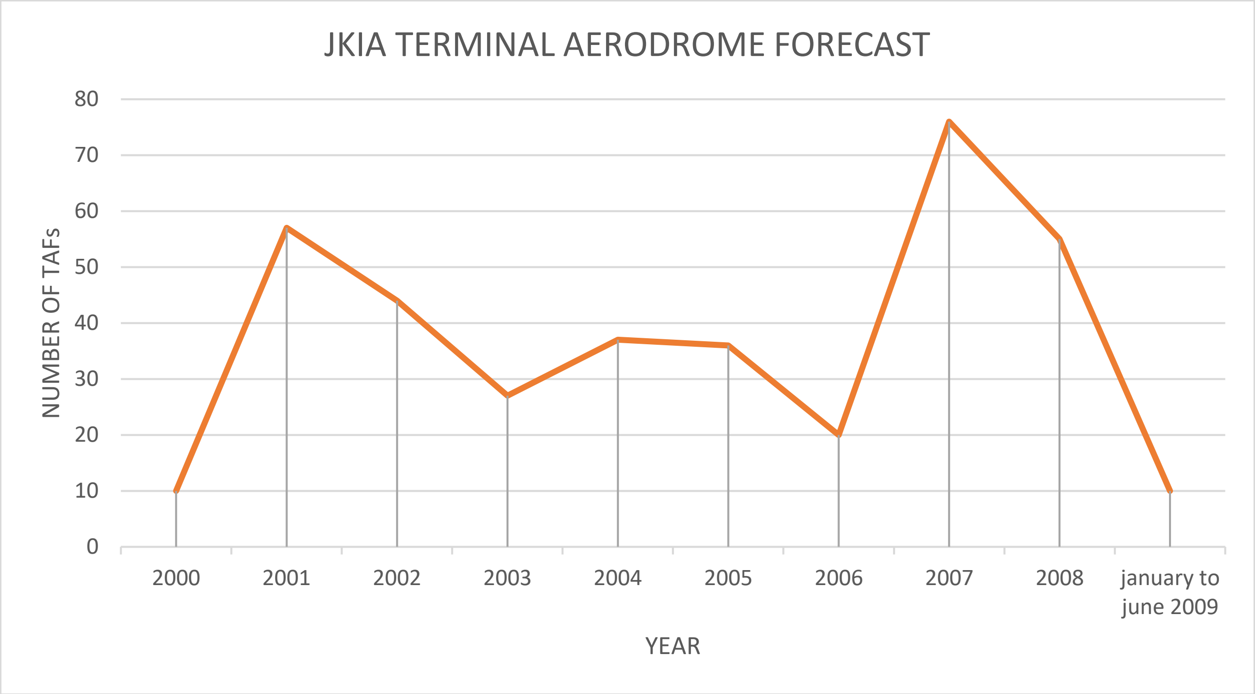


Figure 22: annual distribution of assessed TAFs

3.4.3 Weather Impact Index

The study strives to develop a weather impact index that could be used by air traffic management and other users operating at JKIA airport. The model is designed only for JKIA airport and cannot be used in any other airport because the weather conditions vary from one airport to another and the data on which the model will be developed is not representative of the data from another airport.

3.5 Data Analysis

Prior to carrying out data analysis data quality control was carried out by checking if the coding follows the standard rules and if there are no errors in the elaborated messages. The data was then classified by category of meteorological weather, by time slots, by month as well. Averaging is used to smooth extreme values.

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i$$

A = arithmetic mean
n = number of values
a_i = data set values

……………………Equation 1

In order to develop the weather impact index model for JKIA, two necessary concepts were created:

Combined delay/diversion: refers to a set of impact where the elements are departure delay, arrival delay and diversion.

In-flight delay/diversion: refers to a set of impact where the elements are arrival delay and diversion.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Delay and Diversion Analysis Results

4.1.1 Analysis of Delays and Diversion Incidences

An analysis of the weather-related delays and/or diversions was performed. This section examines the distribution of departure delay, arrival delay, diversion, in-flight delay/diversion incidents and combined-delay/diversion incidents.

The annual distribution of departure delays as function of weather category is displayed in figure 23. It exhibits the frequency of departure delay occurrence of each year per weather category to the total number of departure delays for each year of the study period.

28 departure delays due to inclement weather occurred at JKIA over the ten years. Year 2008 recorded the highest frequency of departure delays, namely 14.

The rank shows that Low Level Clouds category is the highest contributor of departure delay incidents, followed by the categories CB clouds, FOG/MIST, Wind Change and finally Rain category as the lowest contributor.

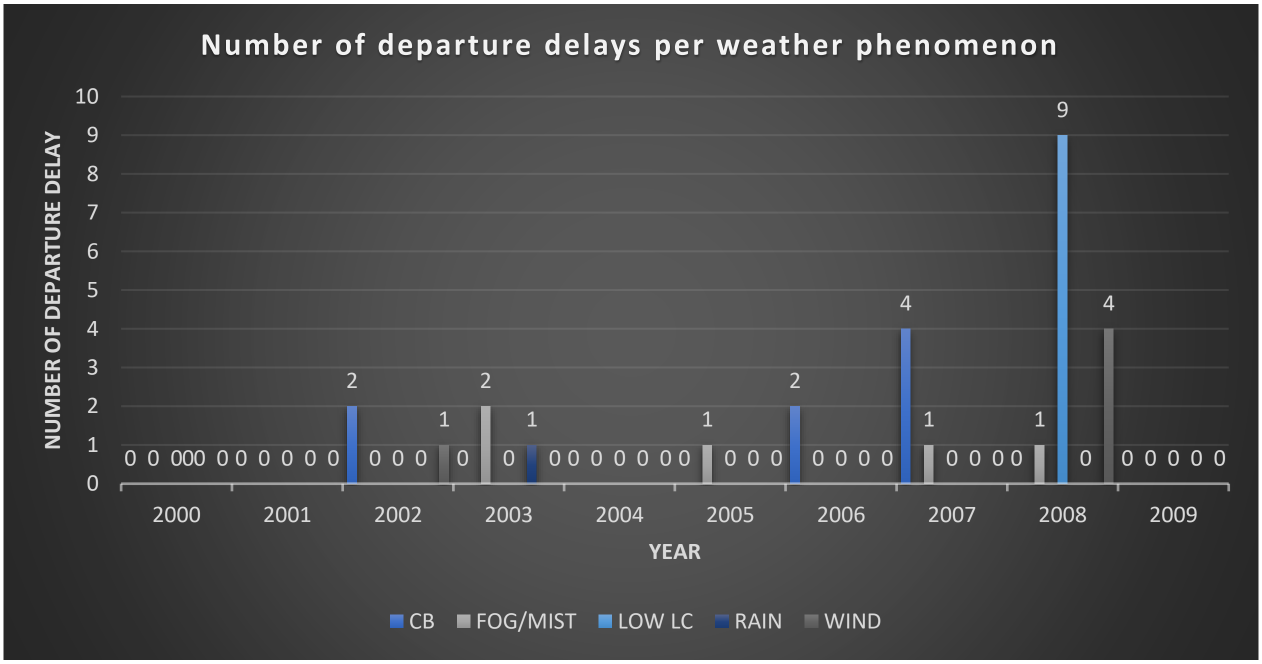


Figure 23: The annual distribution of departure delay incidents per weather phenomenon for years 2000 to 2009

The annual distribution of arrival delays as function of weather category is displayed in figure 24. It shows the frequency of arrival delay occurrence of each year per weather category to the total number of arrival delays for each year of the study period. 137 arrival delays due to inclement weather occurred at JKIA over the ten years. Year 2008 recorded the highest frequency of arrival delays, namely 34 against 33 for the year 2007. The rank shows that Fog/Mist category is the highest contributor of arrival delay incidents, followed by the categories CB clouds, Low level Clouds, Rain and Wind Change as the lowest contributor.

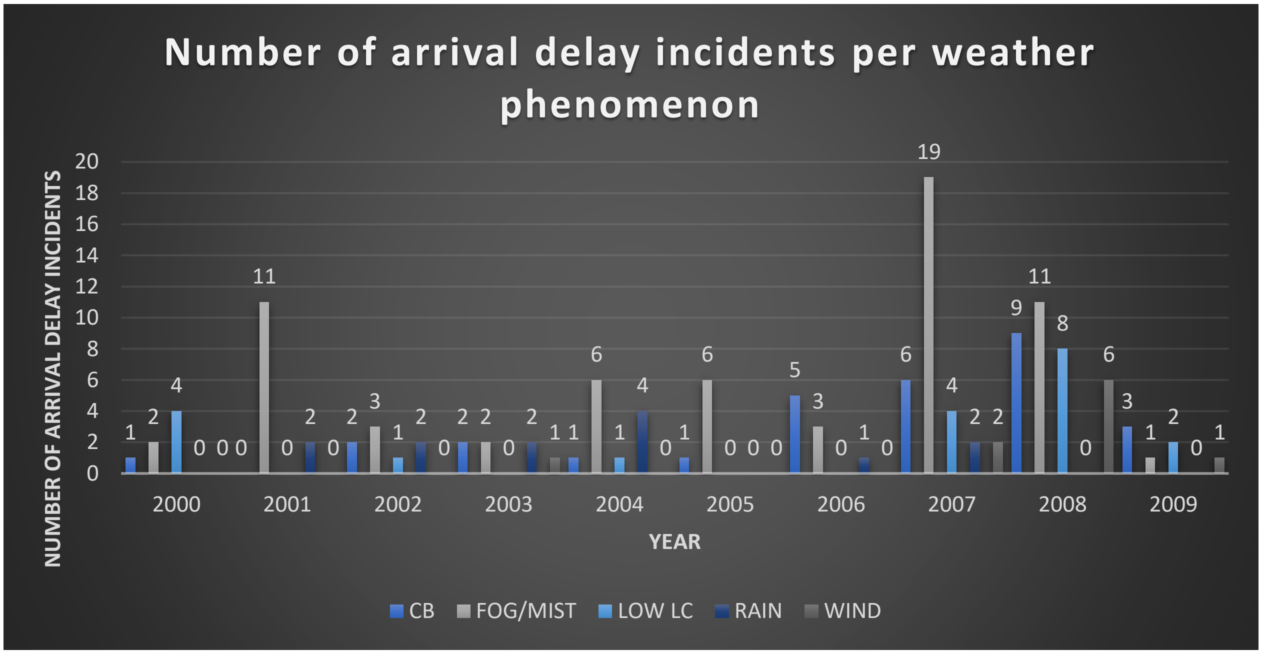


Figure 24: The annual distribution of arrival delay incidents per weather phenomenon for years 2000 to 2009

The annual distribution of diversion as function of weather category is displayed in Figure 25. It shows the frequency of diversion occurrence of each year per weather category to the total number of diversions for each year of the study period. 224 diversions due to inclement weather occurred at JKIA over the ten years. Year 2001 recorded the highest frequency of diversions, namely 44, followed by the year 2007 with 41 diversion incidents. The rank shows that Fog/Mist category is the highest contributor of diversion incidents (174), followed by the categories CB clouds (23), Low Level Clouds (18), Rain (7) and Wind Change (2) as the lowest contributor.

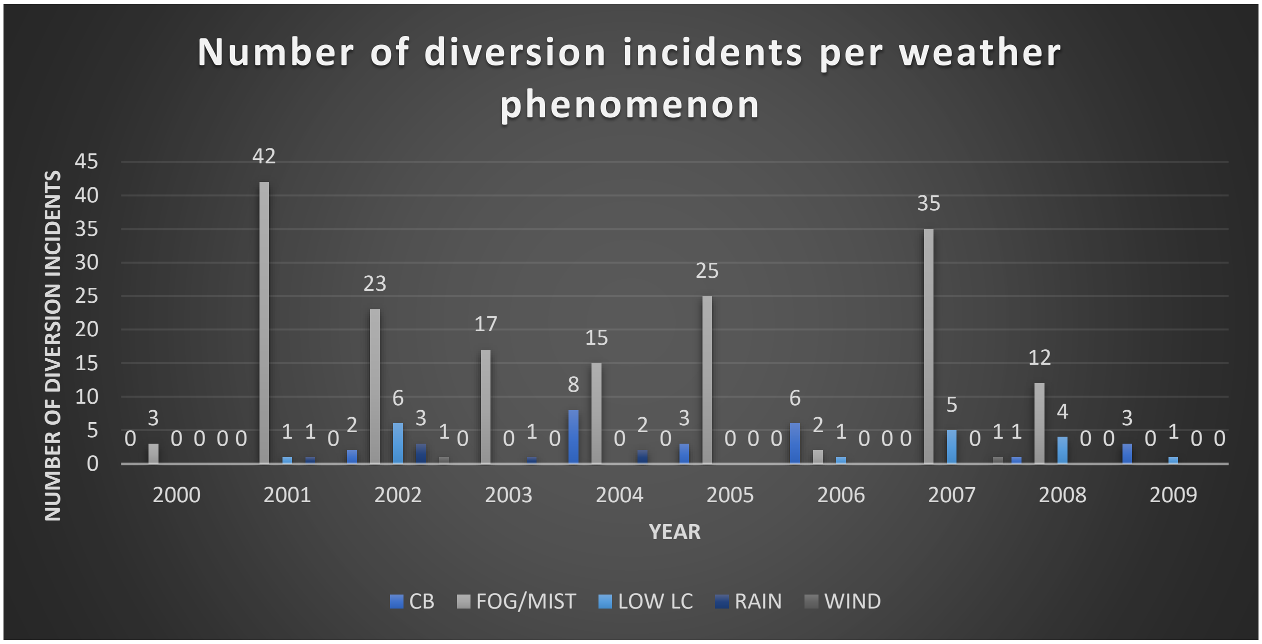


Figure 25: The annual distribution of diversion incidents per weather phenomenon for years 2000 to 2009

The annual distribution of in-flight delay/diversion incidents as function of weather category, and totals over the ten years for each weather category are displayed in Table 7. Figure 26 displays the frequency of in-flight delay/diversion incidents occurrence of each year per weather category to the total number of in-flight delay/diversion incidents for each year of the study period. 361 in-flight delay/diversion incidents due to inclement weather occurred at JKIA over the ten years. Year 2007 recorded the highest frequency of in-flight delay/diversion incidents, namely 74, followed by the year 2008 with 51. The rank shows that Fog/Mist category is the highest contributor of in-flight delay/diversion incidents with 66%, followed by the category CB clouds with 15%.

Table 7: The annual distribution of in-flight delay/diversion incidents as function of weather category, and totals over the ten years for each weather category with rank from highest to lowest frequency for years 2000 to 2009

Weather Phenomenon	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**TOTAL**
FOG/MIST	5	53	26	19	21	31	5	54	23	1	238
	50%	93%	61%	76%	57%	89%	28%	73%	45%	9%	66%
CB	1	0	4	2	9	4	11	6	10	6	53
	10%	0%	9%	8%	24%	11%	61%	8%	20%	55%	15%
LOW LC	4	1	7	0	1	0	1	9	12	3	38
	40%	2%	16%	0%	3%	0%	6%	12%	24%	27%	11%
RAIN	0	3	5	3	6	0	1	2	0	0	20
	0%	5%	12%	12%	16%	0%	5%	3%	0%	0%	5%
WIND	0	0	1	1	0	0	0	3	6	1	12
	0%	0%	2%	4%	0%	0%	0%	4%	12%	9%	3%
TOTAL	10	57	43	25	37	35	18	74	51	11	361

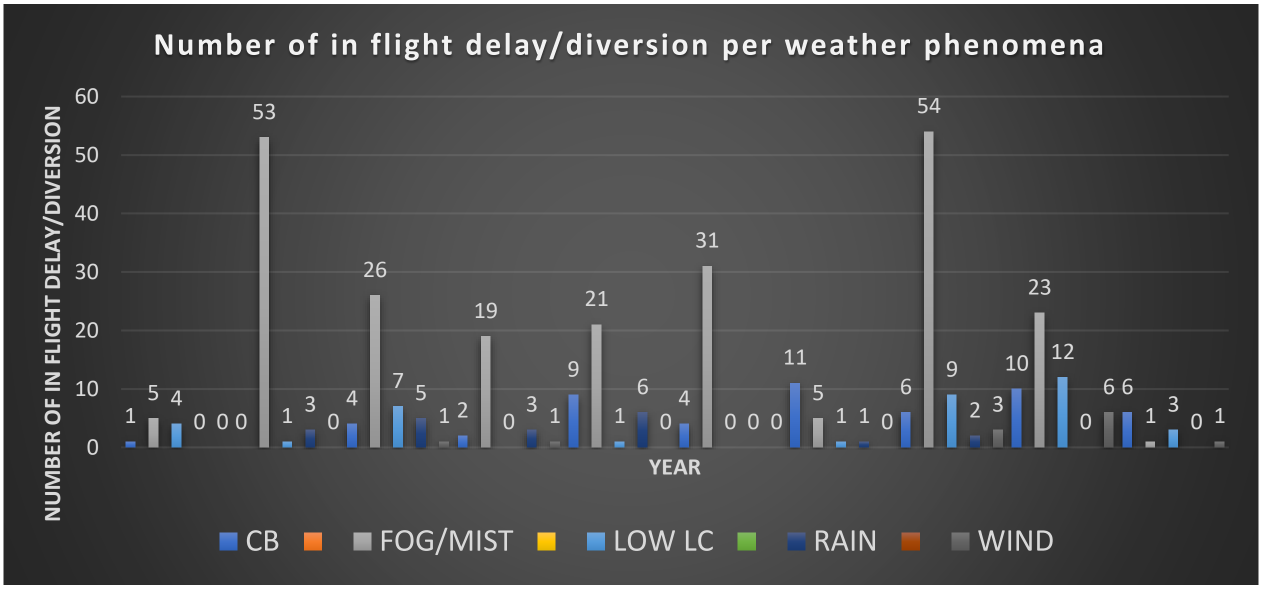
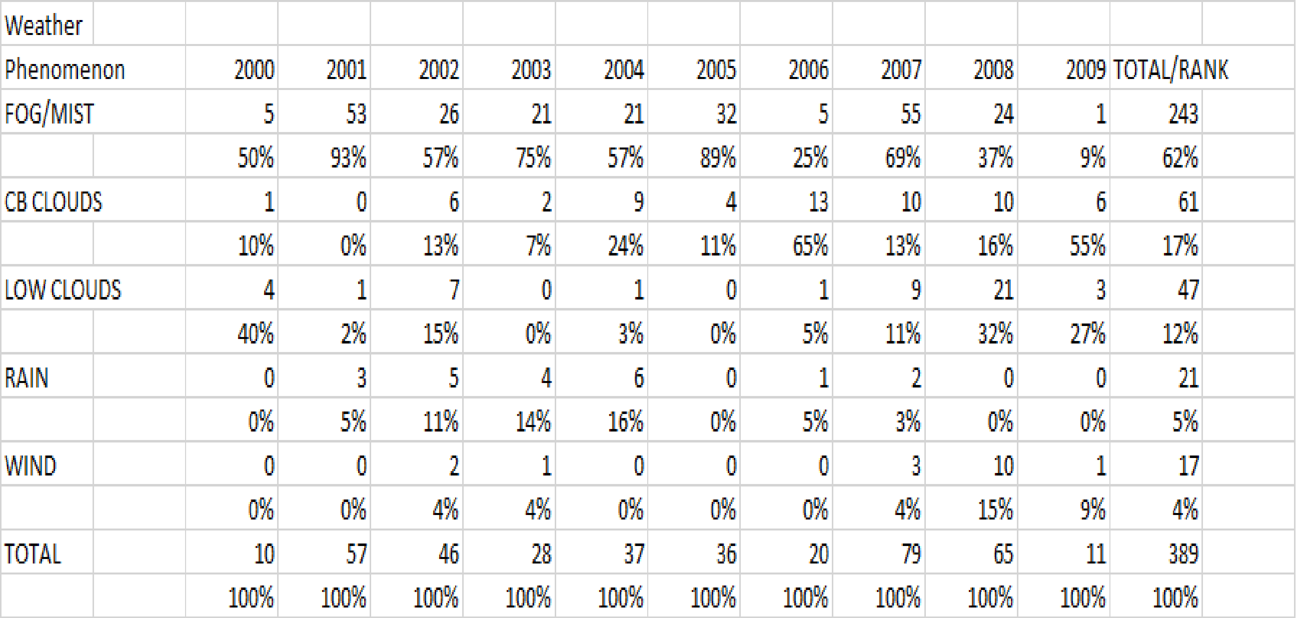


Figure 26: The annual distribution of in-flight delay/diversion incidents per weather phenomenon for years 2000 to 2009

The annual distribution of combined delay/diversion incidents as function of weather category, and totals over the ten years for each weather category are displayed in Table 8. 389 combined delay/diversion incidents due to inclement weather occurred at JKIA over the ten years. Year 2007 recorded the highest frequency of combined delay/diversion incidents, namely 79, followed by the year 2008. The rank shows that Fog/Mist category is the highest contributor of combined delay/diversion incidents with 62%, followed by the category CB clouds with 17%.

Table 8: The annual distribution of combined delay/diversion incidents as function of weather category, and totals over the ten years for each weather category with rank from highest to lowest frequency



Weather Phenomenon	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL/RANK
FOG/MIST	5	53	26	21	21	32	5	55	24	1	243
	50%	93%	57%	75%	57%	89%	25%	69%	37%	9%	62%
CB CLOUDS	1	0	6	2	9	4	13	10	10	6	61
	10%	0%	13%	7%	24%	11%	65%	13%	16%	55%	17%
LOW CLOUDS	4	1	7	0	1	0	1	9	21	3	47
	40%	2%	15%	0%	3%	0%	5%	11%	32%	27%	12%
RAIN	0	3	5	4	6	0	1	2	0	0	21
	0%	5%	11%	14%	16%	0%	5%	3%	0%	0%	5%
WIND	0	0	2	1	0	0	0	3	10	1	17
	0%	0%	4%	4%	0%	0%	0%	4%	15%	9%	4%
TOTAL	10	57	46	28	37	36	20	79	65	11	389
	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 27 displays the relative frequency of combined delay/diversion incidents occurrence of each year to the total number of combined delay/diversion incidents over the study period. 389 weather-related combined-delay/diversion incidents occurred at JKIA, with the year 2007 recording the highest percentage, namely 20.31%, followed by the year 2008 with 16.71% of occurrences.

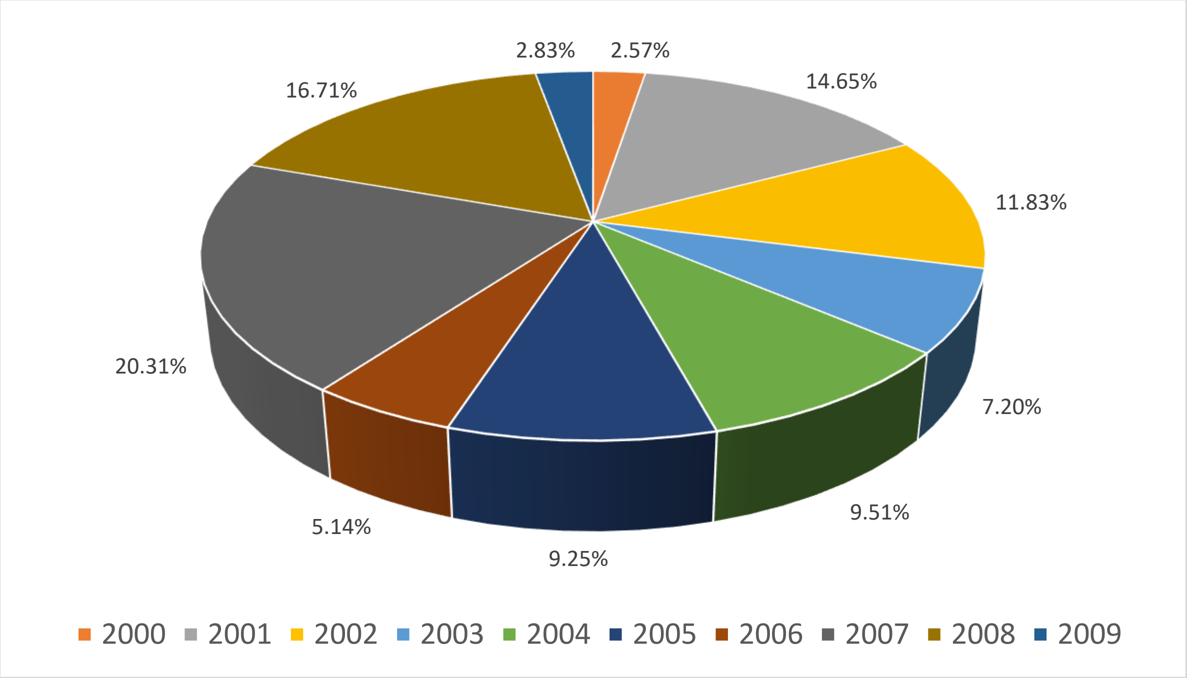


Figure 27: the relative frequency of combined delay/diversion incidents occurrence of each year to the total number of combined delay/diversion incidents

The category Fog/Mist is the first contributor to combined-delay/diversion incidents due to weather at JKIA with 62%, followed by CB Clouds 17%. The third highest weather phenomenon contributing to weather-related combined-delay/diversion incidents is Low Level Cloud, followed by rain from non-convective clouds, and finally Wind Change which caused the least during the study period.

4.1.2 Delay and Diversion Duration Analysis

Figure 28 shows the annual distribution of departure delay minutes per weather phenomenon. A total of 1538 minutes of departure delay time was the record over the airfield. The rank of the phenomena of figure 23, namely Low-Level Clouds, CB Clouds, Fog/Mist, Wind Change and finally Rain is reversed in figure 28 with CB category being the highest contributor of delay minutes, followed by the category Fog/Mist, Low Level Clouds, Rain and finally Wind Change. The frequency of departure delay incidents and consequently the frequency of departure delay minutes due to category Fog/Mist are lessened by cancellation incidents in number and time which we have not considered in our study. The reasons of numerous cancellations of departure flights due to fog is that fog event has the characteristics of large intensity and long duration due to persistence lasting for hours.

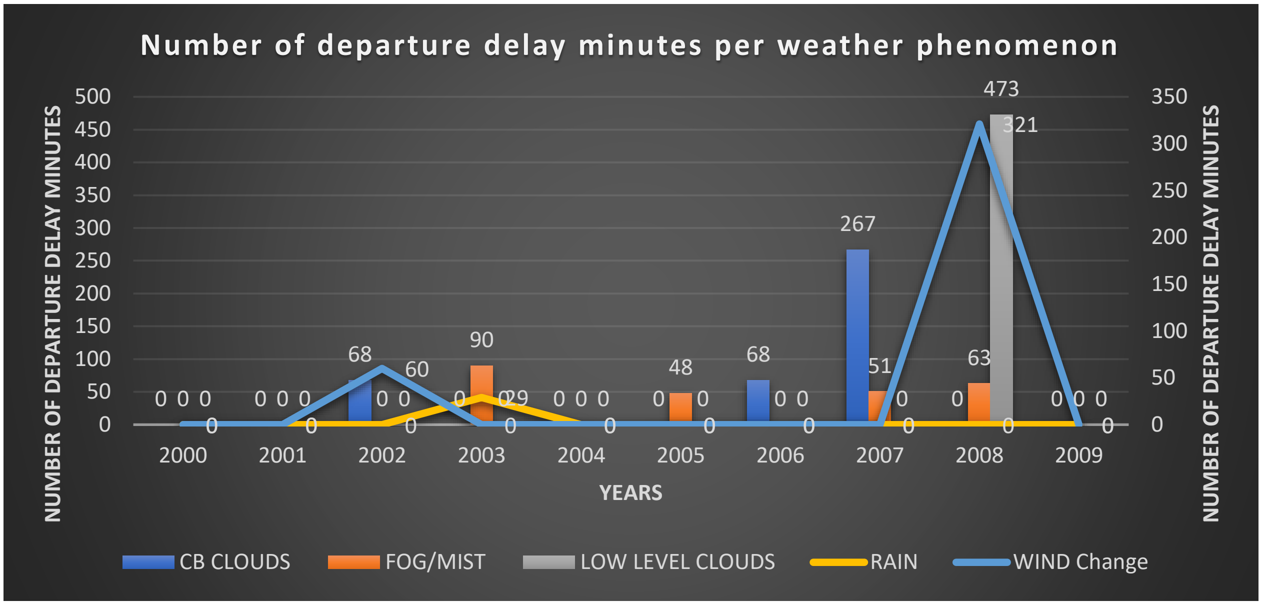


Figure 28: The annual distribution of departure delay minutes per weather phenomenon for years 2000 to 2009

Figure 29 shows the annual distribution of arrival delay minutes per weather phenomenon. A total of 2621 minutes of arrival delay time was the record over the airfield. Compared to the figure 24 on the distribution of arrival delay incidents over the ten years, the contribution-related rank of the phenomena for arrival delay minutes from the largest to the smallest is reversed for the first two phenomena, namely the CB as first and FOG becoming second. The rank in contribution to arrival delay minutes from highest to lowest of the last three phenomena i.e Low Level Clouds, Rain and Wind Change is similar to that of the figure 24 (arrival delay incidents per each phenomena).

The year 2007 recorded the largest arrival delay minutes, followed by the year 2008.

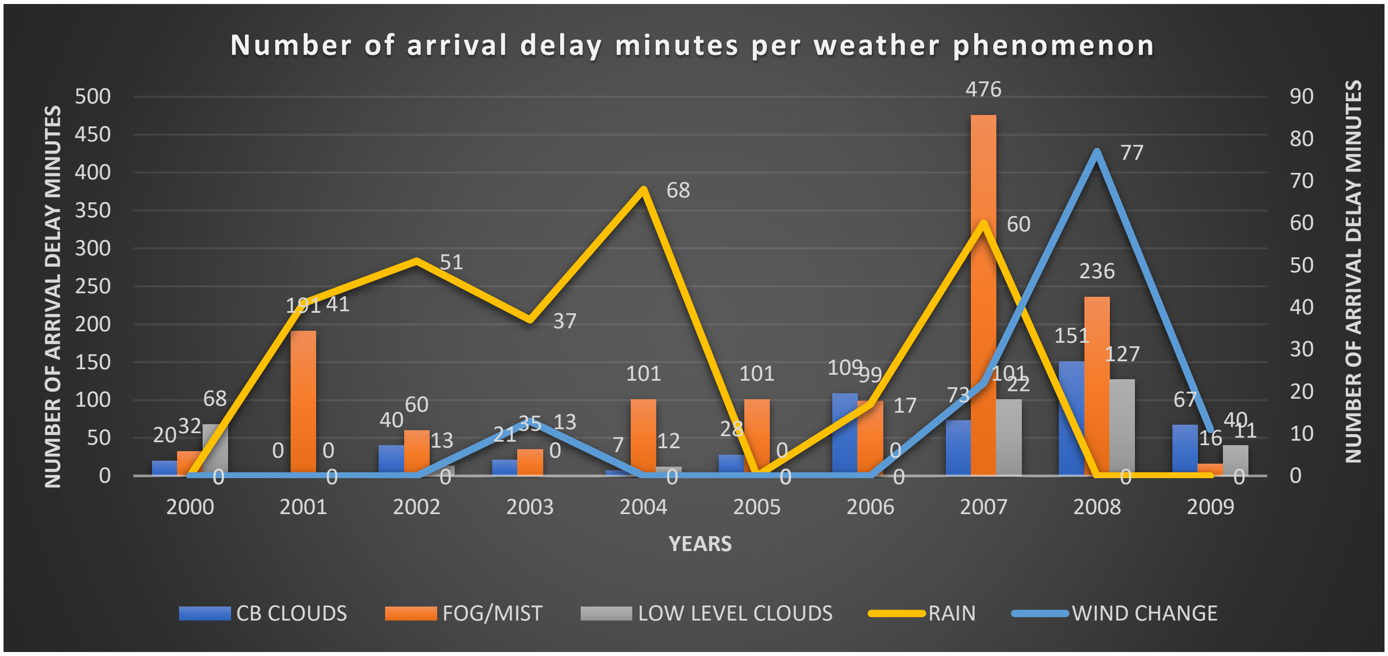


Figure 29: The annual distribution of arrival delay minutes per weather phenomenon for years 2000 to 2009

Figure 30 shows the annual distribution of diversion minutes per weather phenomenon. A total of 14066 minutes of diversion time was the record over the airfield. Compared to figure 25 on the distribution of diversion incidents over the ten years, the contribution-related rank of the phenomena for diversion minutes from largest to smallest is reversed for the first two phenomena, namely the CB as first and FOG becoming second. The rank in contribution to diversion minutes from highest to lowest of the last three phenomena i.e Low Level Clouds, Rain and Wind Change is similar to that of the figure 25. The year 2001 recorded the largest diversion minutes, followed by the year 2007.

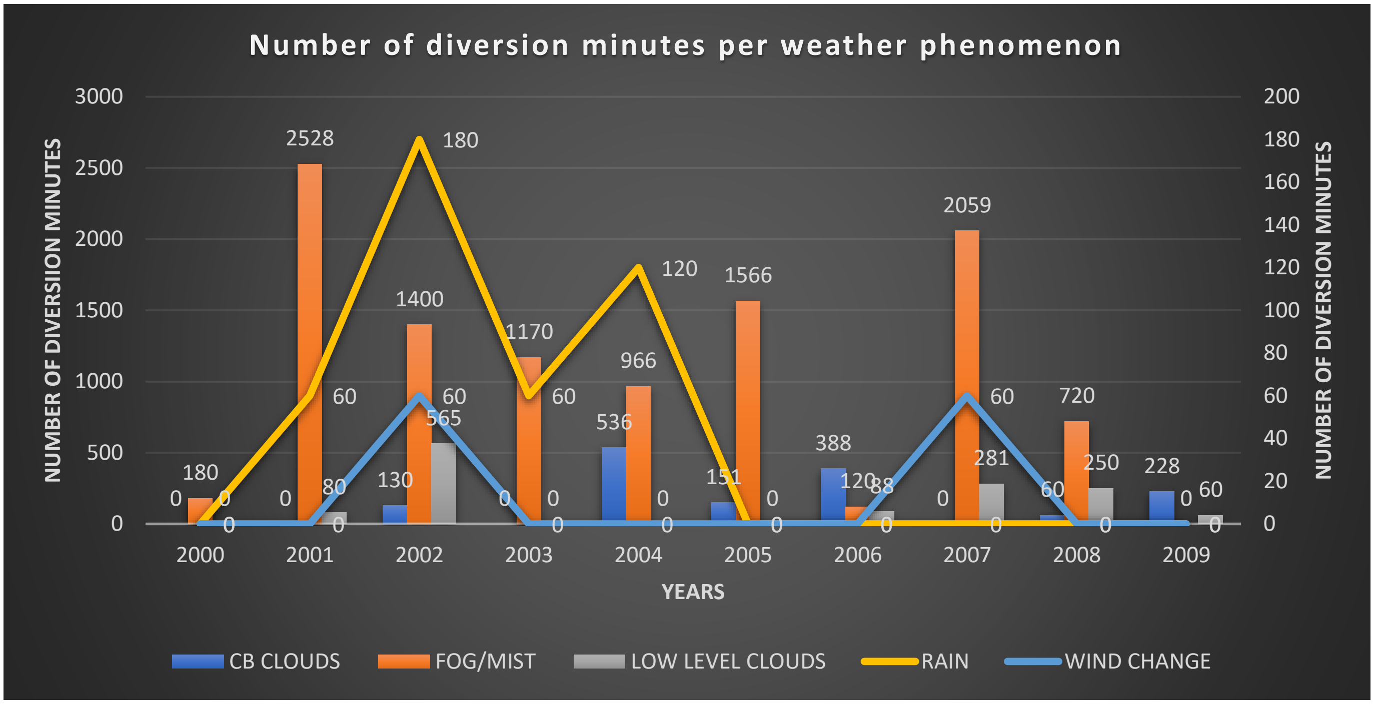


Figure 30: The annual distribution of diversion minutes per weather phenomenon for years 2000 to 2009

Table 9 shows the annual distribution of in-flight (arrival and diversion) delay/diversion minutes per weather phenomenon. A total of 16687 minutes of in-flight delay/diversion time was the record over the airfield. It also displays the relative frequency to the annual number of in-flight delay/diversion minutes with ranking in descending order of contribution. Considering the overall number of in-flight delay/diversion minutes, each year contribution is shown in figure 31. There is similarity in rank of table 7 to the table 9, with the categories Fog/Mist, CB Clouds and Low-Level Clouds contributing the most to in-flight delay/diversion minutes. For the case of weather-related in-flight delay/diversion minutes, conclusion can be made that both move in the same direction: the increase in the number of incidents is accompanied by the increase in the number of minutes.

The year 2007 recorded the largest in-flight delay/diversion minutes, followed by the year 2001 and 2002.

Table 9 The annual distribution of in-flight (arrival and diversion) delay/diversion minutes as function of weather phenomenon

Weather	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**TOTAL**
FOG/MIST	212	2719	1460	1205	1067	1667	219	2535	956	16	12056
	70.67%	93.76%	58.42%	90.19%	58.95%	90.30%	26.67%	80.94%	58.98%	3.79%	72.25%
CB CLOUD	20	0	170	21	543	179	497	73	211	295	2009
	6.67%	0%	6.80%	1.57%	30%	9.70%	60.54%	2.33%	13.02%	69.91%	12.04%
LOW LEVE	68	80	578	0	12	0	88	382	377	100	1685
	22.67%	2.76%	23.13%	0%	0.66%	0%	10.72%	12.20%	23.26%	23.70%	10.10%
RAIN	0	101	231	97	188	0	17	60	0	0	694
	0%	3.48%	9.24%	7.26%	10.39%	0%	2.07%	1.92%	0%	0%	4.16%
WIND CH	0	0	60	13	0	0	0	82	77	11	243
	0%	0%	2.40%	0.97%	0%	0%	0%	2.62%	4.75%	2.61%	1.46%
TOTAL	300	2900	2499	1336	1810	1846	821	3132	1621	422	16687

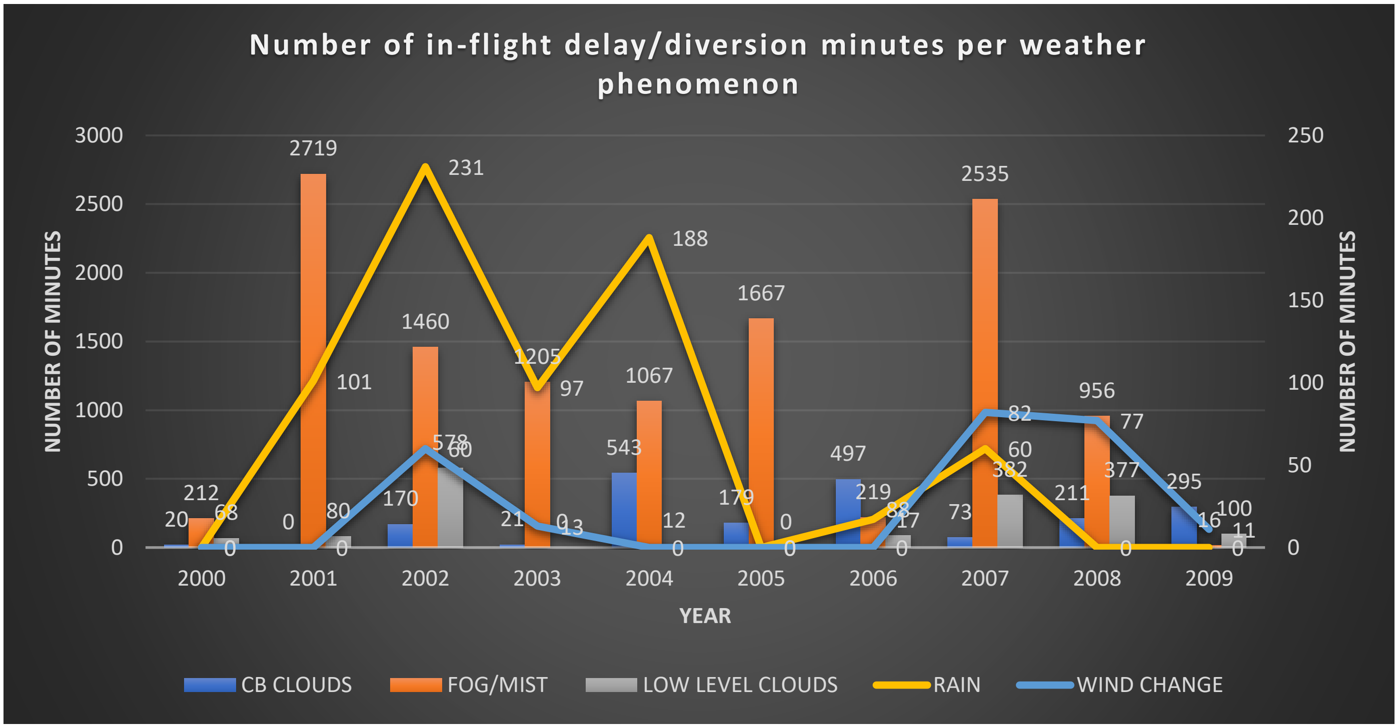


Figure 31: The annual distribution of in-flight (arrival and diversion) delay/diversion minutes per weather phenomenon

Table 10 displays the total number of combined (departure, arrival and diversion) delay/diversion minutes produced by each weather category for each year. Over the airfield, the study found that 18225 minutes of combined delay/diversion time was the overall record during the 10 years. It also displays the relative frequency to the annual number of combined delay/diversion minutes with ranking in descending order of contribution.

Considering the overall number of combined delay/diversion minutes, each year contribution is shown in Figure 32. There is similarity in rank of Table 10 to the Table 8 with category Fog/Mist, CB Clouds ang Low level Clouds contributing the most to combine delay/diversion minutes. For the case of weather-related combined delay/diversion minutes, conclusion can be made that both move in the same direction maintaining rank order of weather categories: the increase in the number of incidents is accompanied by the increase in the number of minutes. Similar to in-flight delay/diversion minutes, the year 2007 recorded the largest combined delay/diversion minutes, followed by the year 2001 and 2002.

Table 10: The number of combined delay/diversion minutes as function of weather phenomenon

Weather	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	TOTAL/RA
FOG/MIST	212	2719	1460	1295	1067	1715	219	2586	1019	16	12308
	70.67%	93.76%	55.58%	89.00%	58.95%	90.55%	24.63%	74.96%	41.12%	3.79%	67.53%
CB	20	0	238	21	543	179	565	340	211	295	2412
	6.67%	0%	9.06%	1.44%	30.00%	9.45%	63.55%	9.86%	8.51%	69.91%	13.23%
LOW LC	68	80	578	0	12	0	88	382	850	100	2158
	22.67%	2.76%	22.00%	0%	0.66%	0%	9.90%	11.07%	34.30%	23.70%	11.84%
RAIN	0	101	231	126	188	0	17	60	0	0	723
	0%	3.48%	8.79%	8.66	10.39%	0%	1.91%	1.74%	0%	0%	3.97%
WIND	0	0	120	13	0	0	0	82	398	11	624
	0%	0%	4.57%	0.89%	0%	0%	0%	2.38%	16.06%	2.61%	3.42%
TOTAL	300	2900	2627	1455	1810	1894	889	3450	2478	422	18225

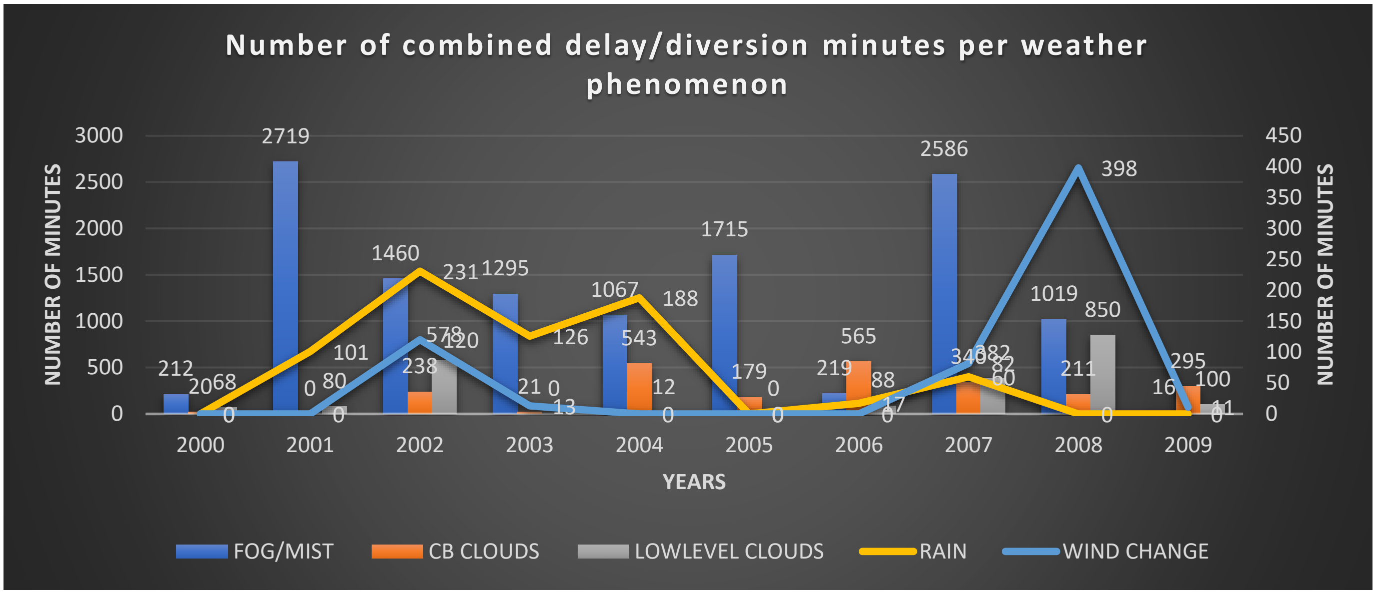


Figure 32: The number of combined delay/diversion minutes as function of weather phenomenon

In conclusion, the statement ‘’ both move in the same direction maintaining rank order of weather categories: the increase in the number of incidents is accompanied by the increase in the number of minutes’’ is verified for the cases of in-flight delay/diversion and combined delay/diversion, but it is steered by in-flight delay/diversion.

4.1.3 Analysis of average delay and/or diversion time per single delay event

What weather phenomenon causes the longest delay and/or diversion time during an incident? This analysis answers this question.

Table 11: Classification in descending order of the meteorological phenomena which cause the longest average time of departure delay per single event

Weather Phenomenon	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Grand Average Minutes**
WIND Change	none	none	60	none	none	none	none	none	80.25	none	70.13
Low Clouds	none	none	none	none	none	none	none	none	52.56	none	52.56
FOG/MIST	none	none	none	45	none	48	none	51	63	none	51.75
CB Clouds	none	none	34	none	none	none	34	66.75	none	none	44.92
RAIN	none	none	none	29	none	none	none	none	none	none	29

All calculations done and staggering the categories of meteorological phenomena in descending order, it turns out that the Wind Change category causes the longest time in departure delay of aircraft while the rain causes the least.

Table 12: Classification in descending order of the meteorological phenomena which cause the longest average time of arriival delay per single event

Weather Phenomenon	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Grand Average Minutes**
RAIN	none	20.5	25.5	18.5	17	none	17	30	none	none	21.42
FOG/MIST	16	17.36	20	17.5	16.83	16.83	33	25.05	21.45	16	20.002
CB CLOUD	20	none	20	10.5	7	28	21.8	12.17	16.78	22.33	17.62
LOW Cloud	17	none	13	none	12	none	none	25.25	15.88	20	17.19
WIND Change	none	none	none	13	none	none	none	11	12.83	11	11.96

All calculations done and staggering the categories of meteorological phenomena in descending order, it turns out that the Rain category causes the longest time in arrival delay of aircraft while the category Wind Change causes the least.

Table 13: Classification in descending order of the meteorological phenomena which cause the longest average time of diversion per single event

Weather Phenomenon	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Grand Average Minutes**
LOW Clouds	none	80	94.17	none	none	none	88	56.2	62.5	60	73.48
CB Clouds	none	none	65	none	67	50.33	64.67	none	60	76	63.83
FOG/MIST	60	60.19	60.87	68.82	64.4	62.64	60	58.83	60	none	61.75
RAIN	none	60	60	60	60	none	none	none	none	none	60
WIND Change	none	none	60	none	none	none	none	60	none	none	60

All calculations done and staggering the categories of meteorological phenomena in descending order, it turns out that the Low Cloud category causes the longest time in diversion of aircraft while the categories Rain and Wind Change cause the least.

Table 14: Classification in descending order of the meteorological phenomena which cause the longest average time of in-flight delay/diversion per single event

Weather Phenomenon	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Grand Average Minutes**
LOW Clouds	17	80	82.57	none	12	none	88	42.44	31.42	33.33	48.35
FOG/MIST	42.4	51.3	56.15	63.42	50.81	53.77	43.8	46.94	41.56	16	46.62
CB Clouds	20	none	42.5	10.5	60.33	44.75	45.18	12.17	21.1	49.17	33.97
RAIN	none	33.67	46.2	32.33	31.33	none	17	30	none	none	31.76
WIND Change	none	none	60	13	none	none	none	27.33	12.83	11	24.83

All calculations done and staggering the categories of meteorological phenomena in descending order, it turns out that the Low Cloud category causes the longest time in in-flight delay/diversion incident of aircrafts while the category Wind Change causes the least.

Table 15: Classification in descending order of the meteorological phenomena which cause the longest average time of combined-delay/diversion per single event

Weather Phenomenon	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Grand Average Minutes**
Low Clouds	17	80	82.57	none	12	none	88	42.44	40.48	33.33	49.48
FOG/MIST	42.4	51.3	56.15	61.67	50.81	53.59	43.8	47.02	42.46	16	46.52
CB Clouds	20	none	39.67	10.5	60.33	44.75	43.46	34	21.1	49.17	35.89
RAIN	none	33.67	46.2	31.5	31.33	none	17	30	none	none	31.62
WIND Change	none	none	60	13	none	none	none	27.33	39.8	11	30.23

All calculations done and staggering the categories of meteorological phenomena in descending order, it turns out that the Low Cloud category causes the longest time in combined delay/diversion incident of aircrafts while the category Wind Change causes the least. In summary, Low-level clouds generate on average much more fuel consumption than the other phenomena in the event of diversion while rain generates on average much more fuel consumption for arrival delays. From a more general synoptic view, it is the low-level clouds that generate the most fuel consumption on average.

4.1.4 Diagnosis of the phenomena contributing to the combined delay/diversion incident and those contributing to the combined-delay/diversion minutes

In the light of this analysis, it appears that the Fog/mist category causes more incidents than the other categories, while the Low cloud category is the causal agent of the longest disturbance time.

Table 16: phenomena contributing to the combined delay/diversion incident and those contributing to the combined-delay/diversion minutes

Weather category contributing to incidents	Weather category contributing to delay/diversion minutes
Fog/Mist	Low Level Clouds
Cumulonimbus Clouds	Fog/Mist
Low Level Clouds	Cumulonimbus Clouds
Rain	Rain
Wind Change	Wind Change

Table 15 shows that a single low clouds event causes, on average, 50 minutes delay/diversion, 47 minutes for a single Fog/Mist event and 36 minutes for a single cumulonimbus cloud.

Table 17: The daily highest number of delay/diversion incidents, and highest delay/diversion minutes

Weather Phenomenon	**Highest number of incidents**	**Date of occurrence**	**Highest number of minutes**	**Date of occurrence**
Fog	9	13-Mar-02	540	13-Mar-02
CB Clouds	8	14-Mar-08	476	24-Jan-04
Low Clouds	9	14-Jul-08	388	29-Apr-02
Rain	2	20-Nov-04	120	20-Nov-04
Wind Change	2	12-May-02	131	13-Jul-08

4.2 Results on Temporal Analysis

4.2.1 Monthly Analysis

Table 18 displays the monthly number of departure delay incidents for each year of the study period. The monthly number of departure delay incidents are greatly reduced by the large number of flight cancellations caused by Fog/Mist category and low clouds category that persist for hours at high intensity. Flight cancellations are not included in our study. Over the ten-year period, when examining the total number of departure delays per month, the month of July records the highest number. The months without event of aviation departure delay incidents are March, August and

October. The month of July 2008 has the highest number of departure delays, followed by the month of April 2007.

Table 18: The monthly distribution of departure delay incidents

Months	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Sum
January	0	0	0	0	0	0	0	1	0	0	1
February	0	0	0	0	0	0	2	0	0	0	2
March	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	4	0	0	4
May	0	0	2	0	0	0	0	0	0	0	2
June	0	0	0	0	0	0	0	0	3	0	3
July	0	0	0	0	0	1	0	0	10	0	11
August	0	0	0	0	0	0	0	0	0	0	0
September	0	0	1	0	0	0	0	0	0	0	1
October	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	1	0	0	0	0	0	0	1
December	0	0	0	2	0	0	0	0	1	0	3
Sum	0	0	3	3	0	1	2	5	14	0	28

The table also shows the distribution of monthly total of departure delays. Cumulative number of incidents for the successive months of April, May, June and July with monthly delays in departure without interruption is higher than that of November, December, January and February.

Table 19 displays the amount of arrival delays that were registered per month over the study period. Over ten-year period, when examining the total number of arrival delays per month, the month of April records the highest total number whereas the months of August and September have the least total number. The month of March 2008 has the highest number of arrival delays, followed by the month of November 2007.

Table 19: The monthly distribution of arrival delay incidents over years 2000-2009

Months	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Sum**
January	0	0	0	0	2	0	0	6	1	0	9
February	1	3	0	0	0	0	1	0	7	1	13
March	1	0	0	0	3	0	2	5	11	2	24
April	5	3	2	2	2	2	3	2	5	0	26

May	0	0	2	1	0	0	2	1	0	1	7
June	0	0	0	0	0	0	0	1	2	3	6
July	0	3	1	3	3	0	0	2	2	0	14
August	0	1	0	0	0	0	0	1	0	0	2
September	0	0	1	0	0	0	0	0	1	0	2
October	0	0	0	1	0	1	0	3	0	0	5
November	0	2	1	0	1	4	0	9	3	0	20
December	0	1	1	0	1	0	1	3	2	0	9
Sum	7	13	8	7	12	7	9	33	34	7	137

The table also shows the total monthly amount of arrival delay incidents over the ten years. Cumulative number of total arrival delay incidents for MAM season is higher than that of OND season. Therefore, it is evident that the MAM season is most at risk for arrival delay incidents. It can also be seen that the dry season summertime (January-February) recorded twenty-two total amount of arrival delay incidents whereas the dry winter season (June, July, August and September) recorded twenty-four.

Table 20 displays the number of diversions that were registered per month over the period of study. Over ten-year period, when examining the total number of diversions per month, the month of April records the highest total number, namely 49, whereas June and September have the least total amount. The month of April 2005 has the highest number of diversions, followed by the month of May 2002.

Table 20: The number of diversion incidents per month over years 2000-2009

Months	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Total**
January	0	0	1	0	12	3	2	3	0	0	21
February	0	6	5	0	3	0	5	4	3	0	26
March	1	12	0	0	0	3	0	3	1	0	20
April	0	0	4	1	4	19	2	11	8	0	49
May	2	0	14	1	0	0	0	9	1	1	28
June	0	0	0	0	0	2	0	1	0	3	6
July	0	3	3	4	0	1	0	5	0	0	16
August	0	5	0	2	0	0	0	0	0	0	7
September	0	0	0	0	0	0	0	1	0	0	1
October	0	3	3	0	4	0	0	2	0	0	12
November	0	5	1	3	2	0	0	2	0	0	13
December	0	10	4	7	0	0	0	0	4	0	25
Sum	3	44	35	18	25	28	9	41	17	4	224

The same table shows the total monthly number of diversions over 2000 to 2009. Cumulative total number of diversion incidents during MAM season is almost two times higher than that of OND season. Therefore, it is evident that the MAM season is most at risk for diversion incidents. It can also be seen that the dry season summertime (January-February) recorded forty-seven total amount of diversion incidents whereas the dry winter season (June, July, August and September) recorded thirty which is the lowest number compared to the other three seasons.

Table 21 shows the amount of in-flight delay/diversion incidents that were registered per month over years 2000-2009. Over ten-year period, when examining the total number of in-flight delay/diversion incidents per month, the month of April records the highest total number, namely 75 whereas the months of August and September have the least total number with respectively 9 and 3 total numbers. The month of April 2005 (with 21) has the highest number of in-flight delay/diversion incidents, followed by the month of May 2002 (16).

Table 21: The number of in-flight delay/diversion incidents per month over years 2000-2009

Months	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Total
January	0	0	1	0	14	3	2	9	1	0	30
February	1	9	5	0	3	0	6	4	10	1	39
March	2	12	0	0	3	3	2	8	12	2	44
April	5	3	6	3	6	21	5	13	13	0	75

May	2	0	16	2	0	0	2	10	1	2	35
June	0	0	0	0	0	2	0	2	2	6	12
July	0	6	4	7	3	1	0	7	2	0	30
August	0	6	0	2	0	0	0	1	0	0	9
September	0	0	1	0	0	0	0	1	1	0	3
October	0	3	3	1	4	1	0	5	0	0	17
November	0	7	2	3	3	4	0	11	3	0	33
December	0	11	5	7	1	0	1	3	6	0	34
Total	10	57	43	25	37	35	18	74	51	11	361

The table also shows the total monthly frequency of in-flight delay/diversion incidents over the ten-year period. The cumulative total number of in-flight delay/diversion incidents during MAM season (154) is higher than that of OND season (84). Therefore, it is evident that the MAM season is most at risk for in-flight delay/diversion incidents. It can also be seen that the dry season summertime (months of January and February) recorded 69 in-flight delay/diversion incidents whereas the dry winter season (June, July, August and September) recorded 54 which is the lowest number compared to the other three seasons.

Table 22 displays the amount of combined delay/diversion days and the combined delay/diversion incidents that were monthly registered over years 2000-2009. 18 days with combined delay/diversion incidents was the annual average. The months with the highest amount of combined delay/diversion days were March 2007, November 2007 and February 2008; each one with 6 delay days. April had the most average number of combined-delay/diversion days with about 3 days. Therefore, the month of April is the most at risk for late days.

Examining the total amount of combined delay/diversion incidents per month, the month of April records the highest total number, namely 79 whereas the months of August and September have the least total number with respectively 9 and 4 incidents. The month of April 2005 (with 21) has the highest number of combined delay/diversion incidents, followed by the month of May 2002 (18) and the month of April 2008 (13).

Table 22: Monthly amount of combined delay/diversion days and monthly amount of combined delay/diversion incidents over years 2000-2009

Months	**2000**		**2001**		**2002**		**2003**		**2004**		**2005**		**2006**		**2007**		**2008**		**2009**	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
JANUARY	0	0	0	0	1	1	0	0	4	14	1	3	1	2	5	10	3	1	0	0
FEBRUARY	1	1	2	9	1	5	0	0	2	3	0	0	1	8	1	4	6	10	1	1
MARCH	1	2	3	12	0	0	0	0	2	3	2	3	1	2	6	8	5	12	2	2
APRIL	3	5	1	3	2	6	2	3	5	6	5	21	2	5	4	17	3	13	0	0
MAY	1	2	0	0	5	18	2	2	1	0	0	0	2	2	4	10	1	1	3	2
JUNE	0	0	0	0	0	0	0	0	0	0	1	2	0	0	2	2	3	5	3	6
JULY	0	0	2	6	1	4	3	7	2	3	1	2	0	0	3	7	5	12	0	0
AUGUST	0	0	1	6	0	0	1	2	0	0	0	0	0	0	2	1	0	0	0	0
SEPTEMBER	0	0	0	0	1	2	0	0	0	0	0	0	0	0	1	1	2	1	0	0
OCTOBER	0	0	1	3	1	3	1	1	1	4	1	1	0	0	5	5	0	0	0	0
NOVEMBER	0	0	4	7	1	2	2	4	2	3	1	4	0	0	6	11	3	3	0	0
DECEMBER	0	0	5	11	2	5	2	9	1	1	0	0	1	1	2	3	1	7	0	0
Total	6	10	19	57	15	46	13	28	20	37	12	36	8	20	41	79	32	65	9	11

Legend: A: Number of combined delay/diversion days; B: Number of combined delay/diversion incidents

Figure 33 shows the total monthly frequency of combined delay/diversion incidents over the ten-year period. The cumulative total number of combined delay/diversion incidents during MAM season (160) is higher than that of OND season (88). Therefore, it is evident that the MAM season is most at risk for combined delay/diversion incidents. It can also be seen that the dry season summertime (months of January and February) recorded 72 combined-delay/diversion incidents whereas the dry winter season (June, July, August and September) recorded 69 which is the lowest number compared to the other three seasons.

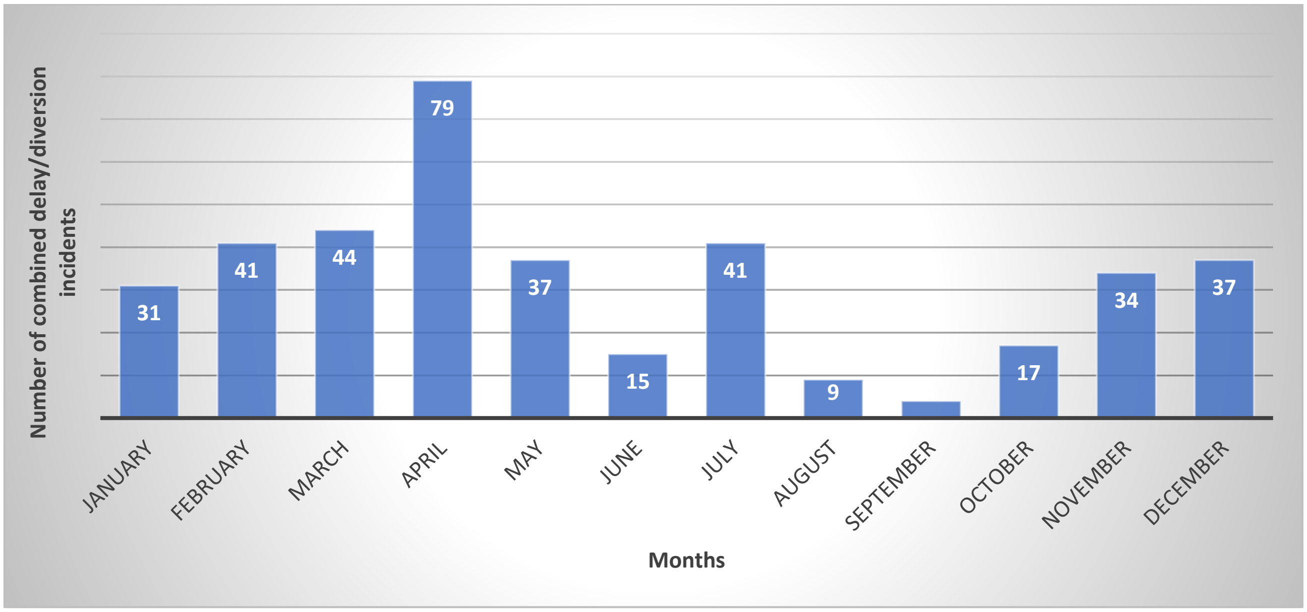


Figure 33: Monthly total number of combined delay/diversion incidents over years 2000-2009

Figure 34 shows the mean monthly frequency of combined-delay/diversion days and incidents over the ten-year period. The cumulative average number of delay/diversion days during MAM season (7) is higher than that of OND season (5). Therefore, it is evident that the MAM season is most at risk for combined-delay/diversion days. Looking at the averages, months with smallest in significance of aviation delay/diversion days and incidents are August and September, that is they are safest at JKIA in the context of inclement weather.

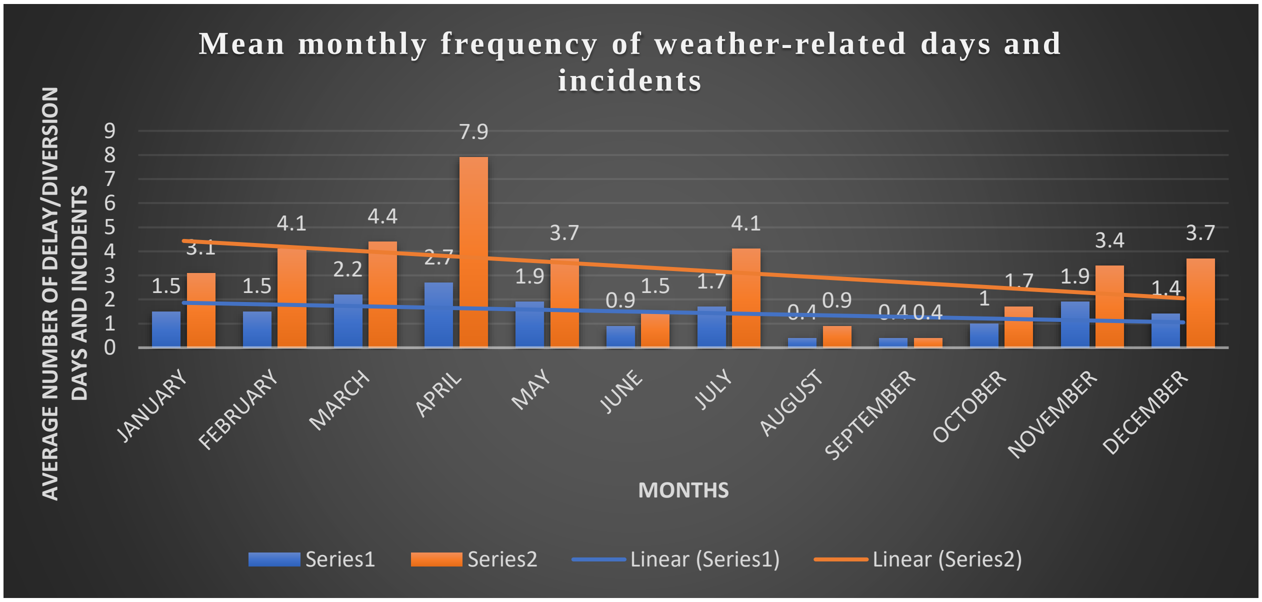


Figure 34: The mean monthly frequency of weather-related delay/diversion days and delay/diversion incidents

4.2.2 Distribution per weather category of the average monthly amount of combined-delay/diversion incidents

The classification by each weather category of average monthly amount of combined-delay/diversion shows the following results.

Figure 35 displays the average monthly amount of combined-delay/diversion incidents due to the category CB cloud. The data visualization displays that Cumulonimbus clouds can cause delays and diversions throughout the year except the month of August. Most prevalent months for CB clouds to bring about diversions or delays are months from January to June. MAM season records the high number of delays and diversions due to cumulonimbus clouds, followed by the summertime dry season.

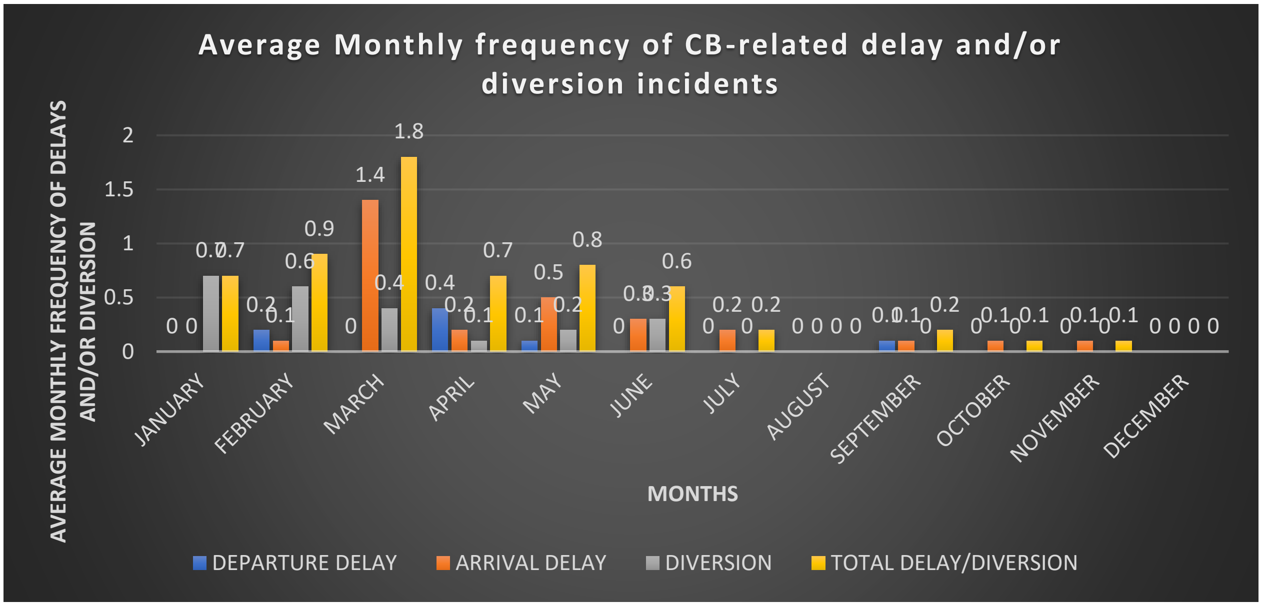


Figure 35: The average monthly frequency of cumulonimbus clouds-related delay and diversion incidents

Figure 36 shows the average monthly frequency of category (Obscuring Phenomena – Hydrometeors) Fog/Mist-related delays and diversions. According to the data, FG, BCFG, MIFG, VCFG and BR can cause delays throughout the year except the month of September.

Most prevalent months for Fog/Mist category to bring about delays and/or diversions were April and December. MAM season records the high number of delays and diversions due to Fog/Mist, followed by the OND season.

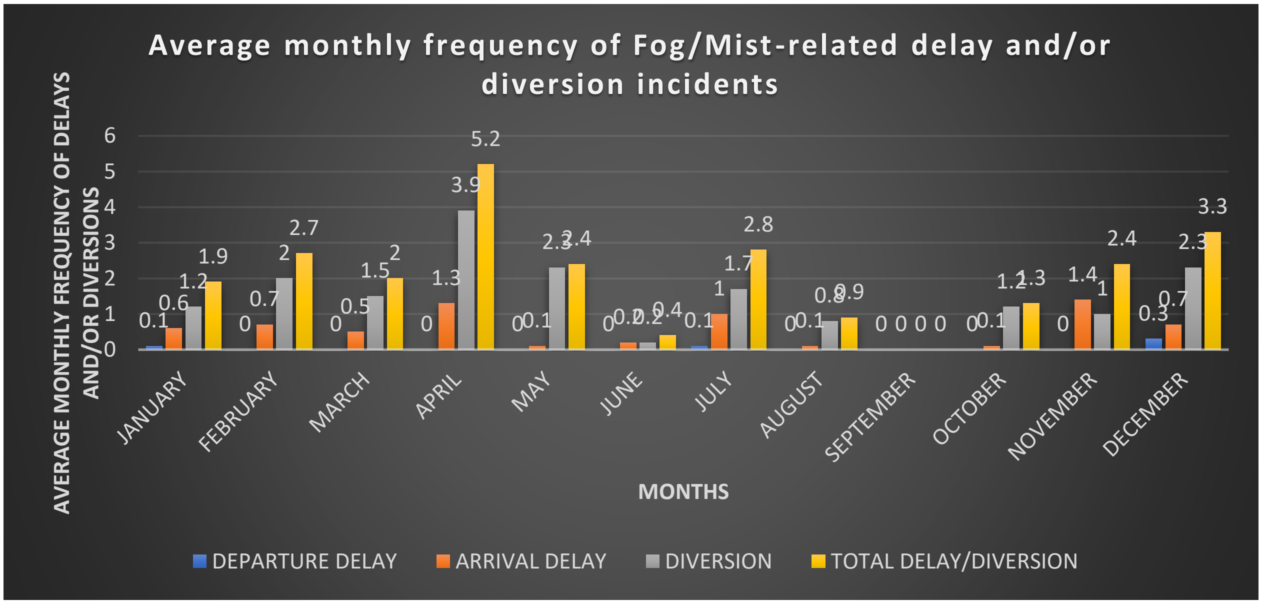


Figure 36: The average monthly frequency of Fog/Mist-related delay and/or diversion incidents

Figure 37 displays the mean monthly amount of delays and diversions due to Low level Clouds. Data display indicates that Low Level Clouds can cause delays and diversions throughout the year except the month of August and September.

The most frequent months for Low Level Clouds category to cause delays and diversions are months of April and July. MAM season records the high number of delays and diversions due to Low Level, followed by the dry winter season.

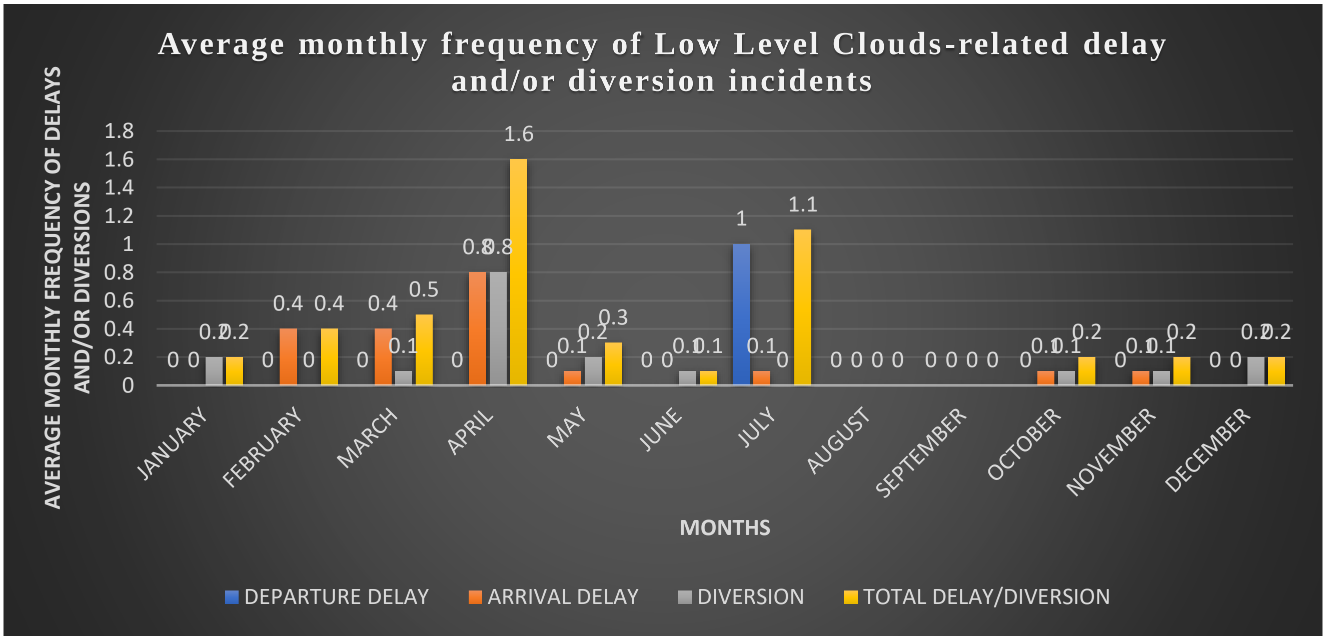


Figure 37: The average monthly frequency of Low Level Clouds-related delay and/or diversion incidents

Figure 38 points out the average monthly amount of delays and diversions due to Rain. Rain can cause delays and diversions throughout the year, except the month of August and September.

Months of November and December, on average, registered the highest amount of delay and diversion incidents.

OND rainy season records the high number of delays and diversions due to Rain, followed by the MAM season, especially the month of April.

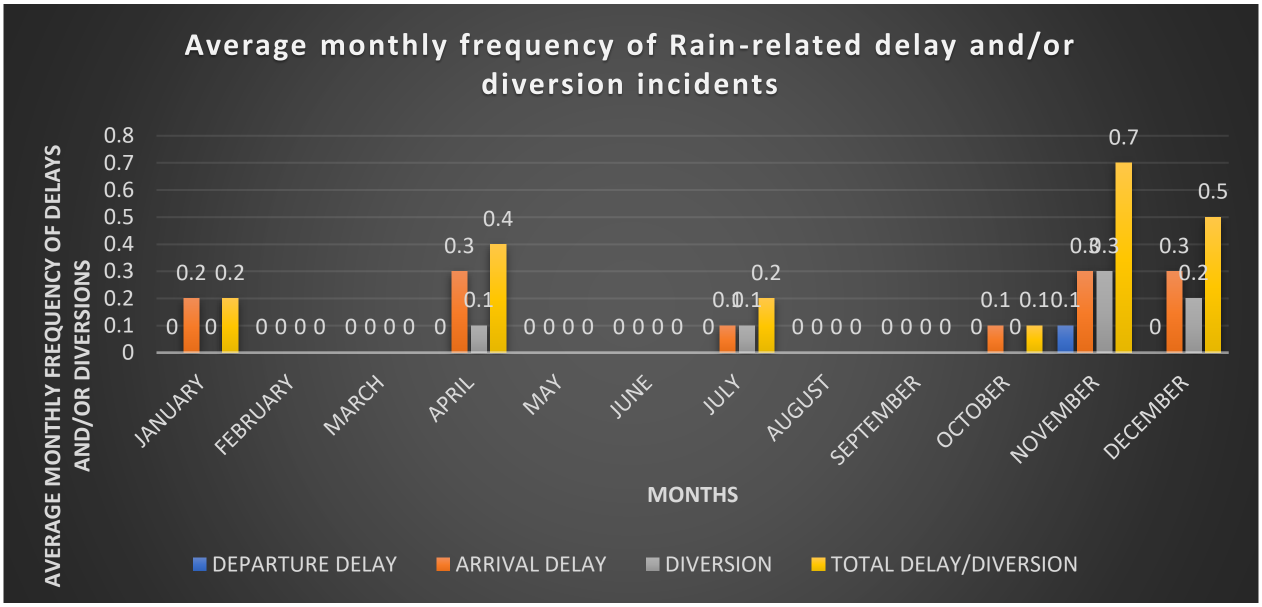


Figure 38: The average monthly frequency of Rain-related delay and/or diversion incidents.

Figure 39 indicates the mean monthly amount of delays and diversions due to Wind Change. Wind Change can cause delays and diversions throughout the year with exception of the month of April and December.

The month of June had the highest number of delay and diversion events on average.

Dry winter season records the high number of delays and diversions due to Wind change, followed by the OND season.

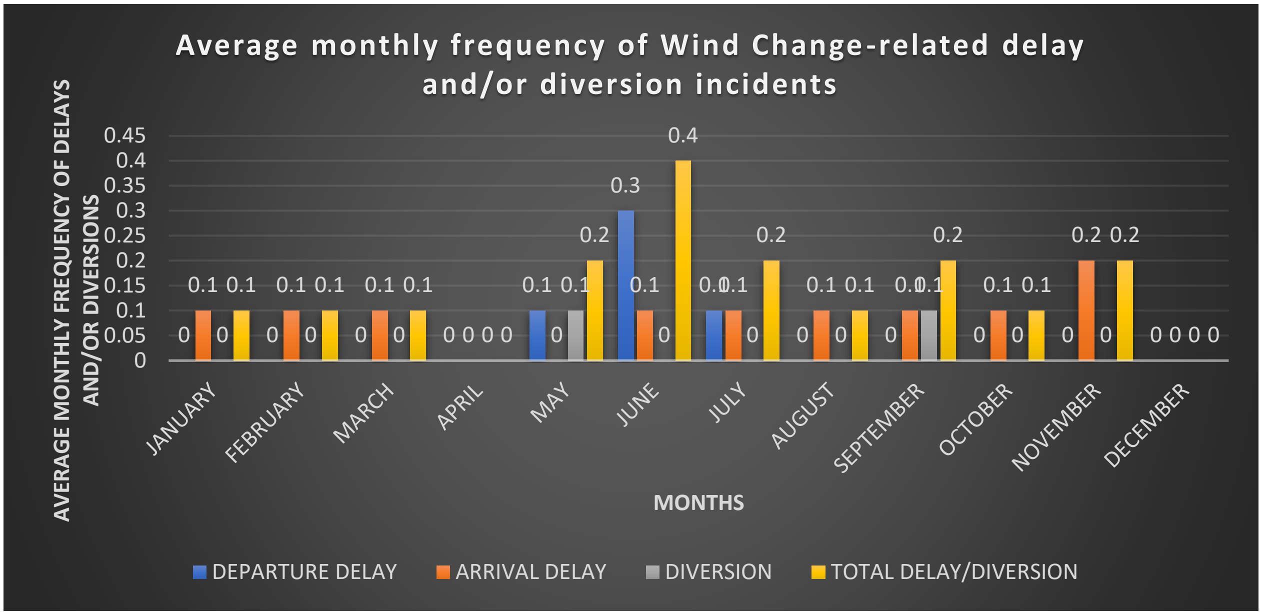


Figure 39: The average monthly frequency of Wind Change-related delay and/or diversion incidents

4.2.3 Analysis of Daytime

The data display in table 23 indicates the distribution of departure delays into the daily four time slots over years 2000-2009, and the grand totals obtained by summation over the ten years for each time slot.

Morning Peak (04H30-08H30) and Evening Peak 13H00-23H00 record the highest quantity of departure delays as shown in the column of grand totals. The two account for 64% of aircraft departure delays.

The off-peak hours which are less busy time slots at JKIA, namely Morning Off-Peak (08H30-13H00) and Night Off-Peak (23H00-04H30) account for 36% of departure delays.

A ranking in descending order of contribution to aircraft departure delays shows that the Morning Peak (04H30-08H30) and Evening Peak 13H00-23H00 are equal, followed by Night Off-Peak (23H00-04H30) which was the third and Morning Off-Peak (08H30-13H00) is at the end of the ladder.

Table 23: Daily distribution of departure delays as function of the diurnal 4 time slots over years 2000-2009

Time Slot	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Grand Totals**
Morning Peak (04H30-08H30)	0	0	0	0	0	0	0	0	9	0	9
Morning Off-Peak (08H30-13H00)	0	0	1	1	0	0	1	0	1	0	4
Evening Peak 13H00-23H00	0	0	2	0	0	0	1	4	2	0	9
Night Off-Peak	0	0	0	2	0	1	0	1	2	0	6

23H00-04H30											

The table also shows that the year 2008 records the unique and high number of departure delays during morning peak hours. The year 2008 alone counts 50% of all departure delays over the study period.

The data display indicates the distribution of arrival delays into the daily four time slots over years 2000-2009, and the grand totals obtained by summation over the ten years for each time slot. As shown in the column of grand totals, Night Off-Peak (23H00-04H30) records the highest quantity of arrival delays, followed by Evening Peak 13H00-23H00. The Night Off-Peak (23H00-04H30) accounts for about 56% of aircraft arrival delays while the Evening Peak 13H00-23H00 accounts for 24%. Morning Peak (04H30-08H30) and Morning Off-Peak (08H30-13H00) register respectively 12% and 8%.

A ranking in descending order of contribution to aircraft arrival delays shows that the Night Off-Peak (23H00-04H30) is the first contributor, afterwards Evening Peak 13H00-23H00 represents the second contributor, followed by Morning Peak (08H30-13H00) becoming the third and finally Morning Off-Peak (08H30-13H00) at the end of the ladder.

Table 24: Daily distribution of arrival delays as function of the diurnal 4 time slots over years 2000-2009

Time Slot	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Grand Totals**
Morning Peak (04H30-08H30)	1	1	2	1	3	0	0	1	7	1	17
Morning Off-Peak (08H30-13H00)	0	0	1	1	0	0	2	2	4	1	11
Evening Peak 13H00-23H00	0	2	2	1	3	1	4	8	9	3	33
Night Off-Peak 23H00-04H30	6	10	3	4	6	6	3	22	14	2	76

It also shows that the years 2007 records the high number of arrival delays during night off-peak hours. The years 2007 and 2008 counts 49% of all arrival delays over the study period.

The data display in table 25 indicates the distribution of diversions into the daily four time slots over years 2000-2009, and the grand totals obtained by summation over the ten years for each time slot. As shown in the column of grand totals, Night Off-Peak (23H00-04H30) records the highest quantity of diversions, followed by Evening Peak 13H00-23H00. The Night Off-Peak (23H00-04H30) accounts for about 82% of aircraft diversions while the Evening Peak 13H00-23H00 accounts for 9%.

Morning Peak (04H30-08H30) and Morning Off-Peak (08H30-13H00) register respectively 7% and 2%. A ranking in descending order of contribution to aircraft diversions shows that the Night Off-Peak (23H00-04H30) is the first contributor, afterwards Evening Peak 13H00-23H00 represents the second contributor, followed by Morning Peak (08H30-13H00) becoming the third and finally Morning Off-Peak (08H30-13H00) at the end of the ladder. Evening Peak 13H00-23H00 is nine times lesser than Night Off-Peak (23H00-04H30) in contributing to diversions.

The years 2001 and 2007 record the high number of diversions during night off-peak hours. The years 2001 and 2007 counts 38% of all diversions over the study period.

Table 25: Daily distribution of diversions as function of the diurnal 4 time slots over years 2000-2009

Time Slot	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Grand Totals

Morning Peak (04H30-08H30)	3	3	1	2	0	3	0	3	1	0	16
Morning Off-Peak (08H30-13H00)	0	0	0	0	0	0	3	0	1	0	4
Evening Peak 13H00-23H00	0	1	3	0	8	3	2	0	0	3	20
Night Off-Peak 23H00-04H30	0	40	31	16	17	22	4	38	15	1	184
Totals	3	44	35	18	25	28	9	41	17	4	224

The data display in table 26 indicates the distribution of in-flight delay/diversion incidents into the daily four time slots over years 2000-2009, and the grand totals obtained by summation over the ten years for each time slot. As visualized in the column of grand totals, Night Off-Peak (23H00-04H30) records the highest amount of in-flight delay/diversion incidents, followed by Evening Peak 13H00-23H00. The Night Off-Peak (23H00-04H30) accounts for about 72% of aircraft in-flight delay/diversion incidents while the Evening Peak 13H00-23H00 accounts for 15%. Morning Peak (04H30-08H30) and Morning Off-Peak (08H30-13H00) register respectively 9% and 4%.

A ranking in descending order of contribution to aircraft in-flight delay/diversion incidents shows that the Night Off-Peak (23H00-04H30) is the first contributor, afterwards Evening Peak 13H00-23H00 represents the second contributor, followed by Morning Peak (08H30-13H00) becoming the third and finally Morning Off-Peak (08H30-13H00) at the end of the ladder. Morning Off-Peak (08H30-13H00) is more than seventeen times lesser than Night Off-Peak (23H00-04H30) in contributing to in-flight delay/diversion incidents.

During night off-peak hours the year 2007 records the high number of in-flight delay/diversion incidents, followed by the year 2001. The years 2001 and 2007 counts 36% of all in-flight delay/diversion incidents over the study period.

Table 26: Daily distribution of in-flight delay/diversion incidents as function of the diurnal 4 time slots over years 2000-2009

Time Period	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Totals**
Morning Peak (04H30-08H30)	4	4	3	3	3	3	0	4	8	1	33
Morning Off-Peak (08H30-13H00)	0	0	1	1	0	0	5	2	5	1	15
Evening Peak 13H00-23H00	0	3	5	1	11	4	6	8	9	6	53
Night Off-Peak 23H00-04H30	6	50	34	20	23	28	7	60	29	3	260

The data display in table 27 indicates the distribution of combined-delay/diversion incidents into the daily four time slots over years 2000-2009, and the grand totals obtained by summation over the ten years for each time slot. As visualized in the column of grand totals, Night Off-Peak (23H00-04H30) records the highest amount of combined-delay/diversion incidents, followed by Evening Peak 13H00-23H00. The Night Off-Peak (23H00-04H30) accounts for about 68% of aircraft combined-delay/diversion incidents while the Evening Peak 13H00-23H00 accounts for 16%.

Morning Peak (04H30-08H30) and Morning Off-Peak (08H30-13H00) register respectively 11% and 5%. A ranking in descending order of contribution to aircraft combined-delay/diversion incidents shows that the Night Off-Peak (23H00-04H30) is the first contributor, afterwards Evening Peak 13H00-23H00 represents the second contributor, followed by Morning Peak (08H30-13H00) becoming the third and finally Morning Off-Peak (08H30-13H00) at the end of the ladder. Morning Off-Peak (08H30-13H00) is about fourteen times lesser than Night Off-Peak (23H00-04H30) in contributing to combined-delay/diversion incidents.

During night off-peak hours the year 2007 registers the highest amount of combined-delay/diversion incidents, followed by 2001. The years 2001 and 2007 counts 35% of combined-delay/diversion incidents over the study period.

Table 27: Daily distribution of combined-delay/diversion incidents as function of the diurnal 4 time slots over years 2000-2009

Time Slot	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Grand Totals
Morning Peak (04H30-08H30)	4	4	3	3	3	3	0	4	17	1	42
Morning Off-Peak (08H30-13H00)	0	0	2	2	0	0	6	2	6	1	19

Evening Peak 13H00-23H00	0	3	7	1	11	4	7	12	11	6	62
Night Off-Peak 23H00-04H30	6	50	34	22	23	29	7	61	31	3	266

Figure 40 investigates what sort of weather category accountable for departure and arrival delays, diversions and combined-delay/diversion incidents during morning peak time slot (04H30-08H30). Data visualization exhibits the total departure delays, the total arrival delay incidents, the total diversion incidents and the total combined-delay/diversion incidents for each weather category during morning peak time slot over 2000-2009. A ranking in descending order of contribution to aircraft combined-delay/diversion incidents during the morning peak time slot (04H30-08H30) shows that Fog/Mist category is the first contributor. Low Level Cloud category occupies the second position, followed by Wind Change category becoming the third contributor. The simultaneous manifestation of fog and low level clouds during this morning peak time slot leads to heavy congestion at the airport. If their intensities are considerable, this will impose more separations of the aircrafts horizontally and vertically over a longer distance. A complete closure of the airport is even possible.

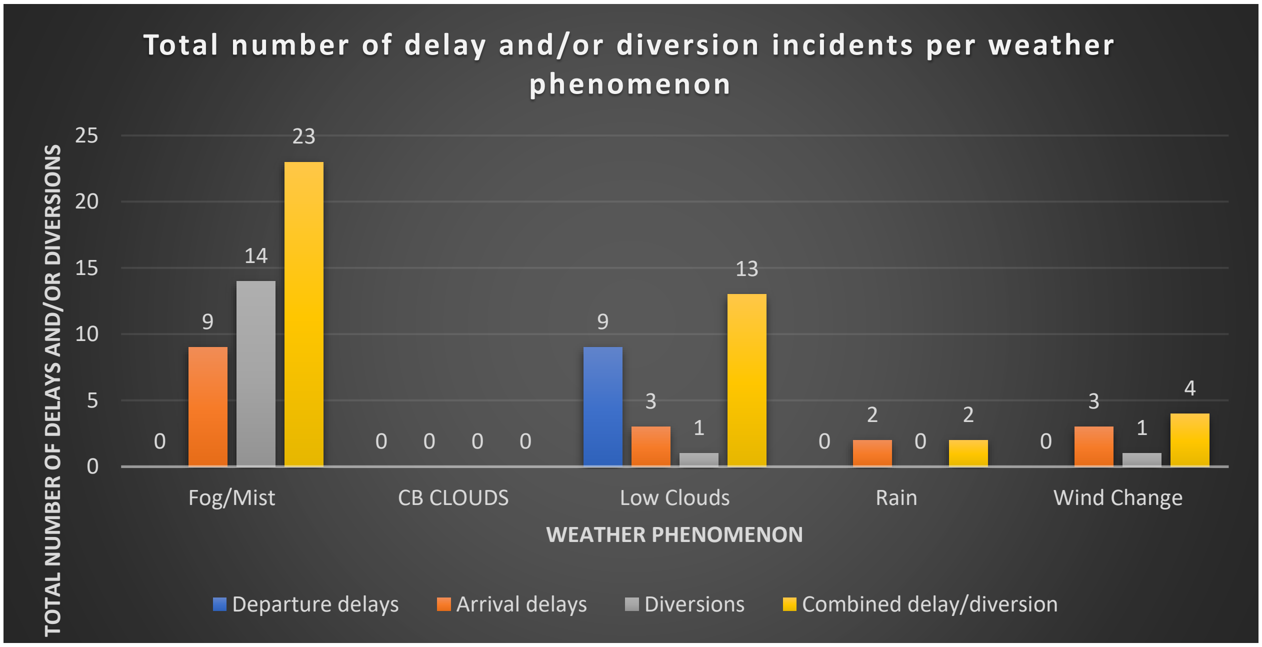


Figure 40: Distribution of total delay and/or diversion incidents per weather phenomenon during morning peak time slot (04H30-08H30)

Figure 41 investigates what sort of weather category accountable for departure and arrival delays, diversions and combined-delay/diversion incidents during morning off-peak time (08H30-13H00).

Data visualization exhibits the total departure delays, the total arrival delay incidents, the total diversion incidents and the total combined-delay/diversion incidents for each weather category during morning off-peak time slot (08H30-13H00) over 2000-2009. A ranking in descending order of contribution to aircraft combined-delay/diversion incidents during the morning off-peak time (08H30-13H00) shows that CB Cloud category is the first contributor. Wind Change category occupies the second position, followed by Rain category (not associated with convective cloud) becoming the third contributor.

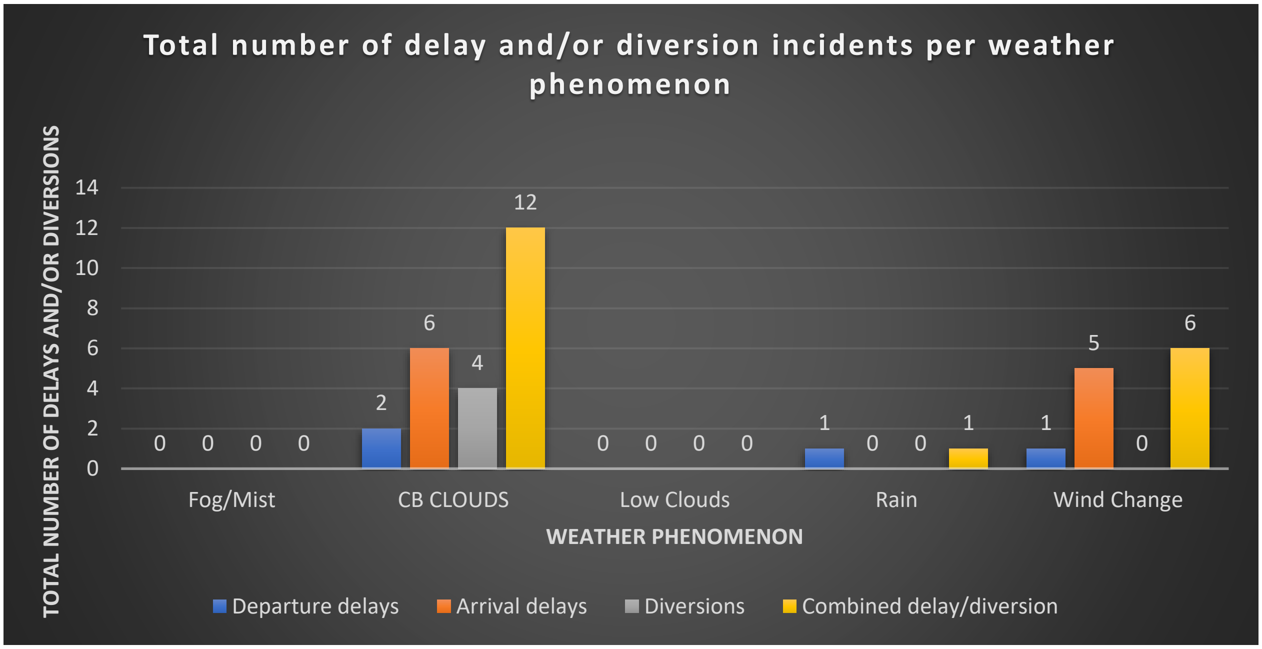


Figure 41: Distribution of total delay and/or diversion incidents per weather phenomenon during morning off-peak time slot (08H30-13H00).

Figure 42 investigates what sort of weather category accountable for departure and arrival delays, diversions and combined-delay/diversion incidents during evening peak time slot (13H00-23H00). Data visualization exhibits the total departure delays, the total arrival delay incidents, the total diversion incidents and the total combined-delay/diversion incidents for each weather category during evening peak time slot (13H00-23H00) over 2000-2009.

A ranking in descending order of contribution to aircraft combined-delay/diversion incidents during the evening peak time slot (13H00-23H00) shows that CB Cloud category is the first contributor. Rain category (not associated with convective cloud) occupies the second position, followed by Wind Change category becoming the third contributor.

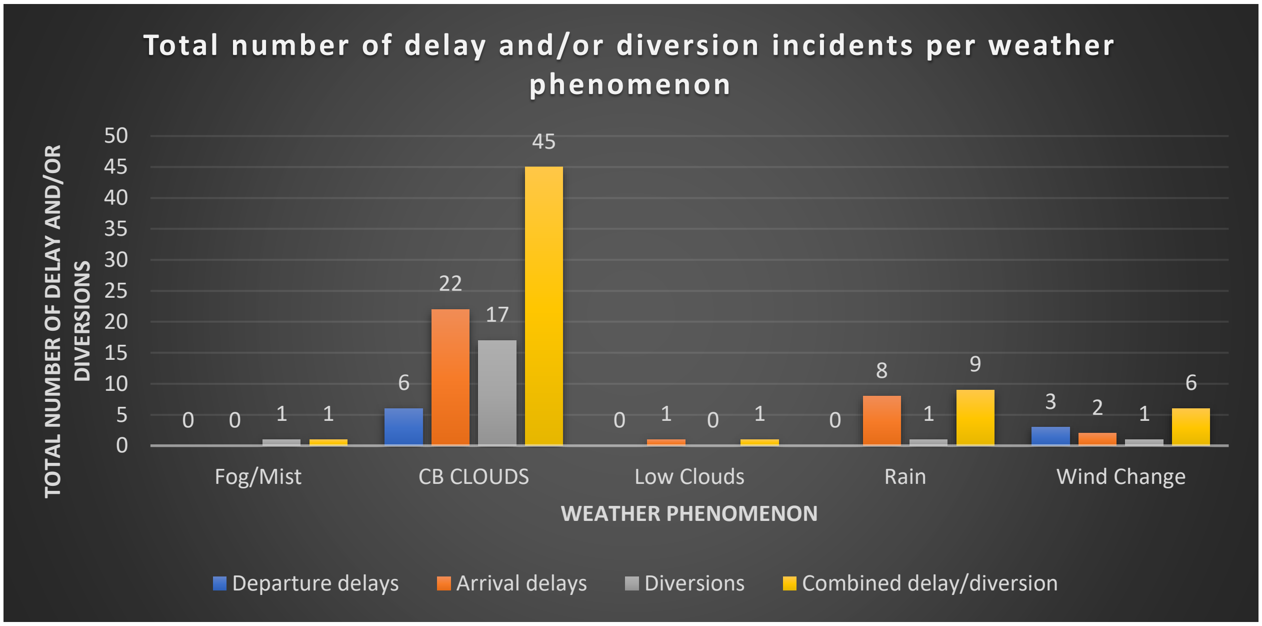


Figure 42: Distribution of total delay and/or diversion incidents per weather phenomenon during evening Peak time slot (13H00-23H00)

Figure 43 investigates what sort of weather category accountable for departure and arrival delays, diversions and combined-delay/diversion incidents during night off-peak time slot (23H00-04H30). Data visualization exhibits the total departure delays, the total arrival delay incidents, the total diversion incidents and the total combined-delay/diversion incidents for each weather category during night off-peak time slot (23H00-04H30) over 2000-2009.

A ranking in descending order of contribution to aircraft combined-delay/diversion incidents during the night off-peak time slot (23H00-04H30) shows that Fog/Mist category is the first contributor. Low level cloud Category occupies the second position, followed by Rain category Rain (not associated with convective cloud) becoming the third contributor.

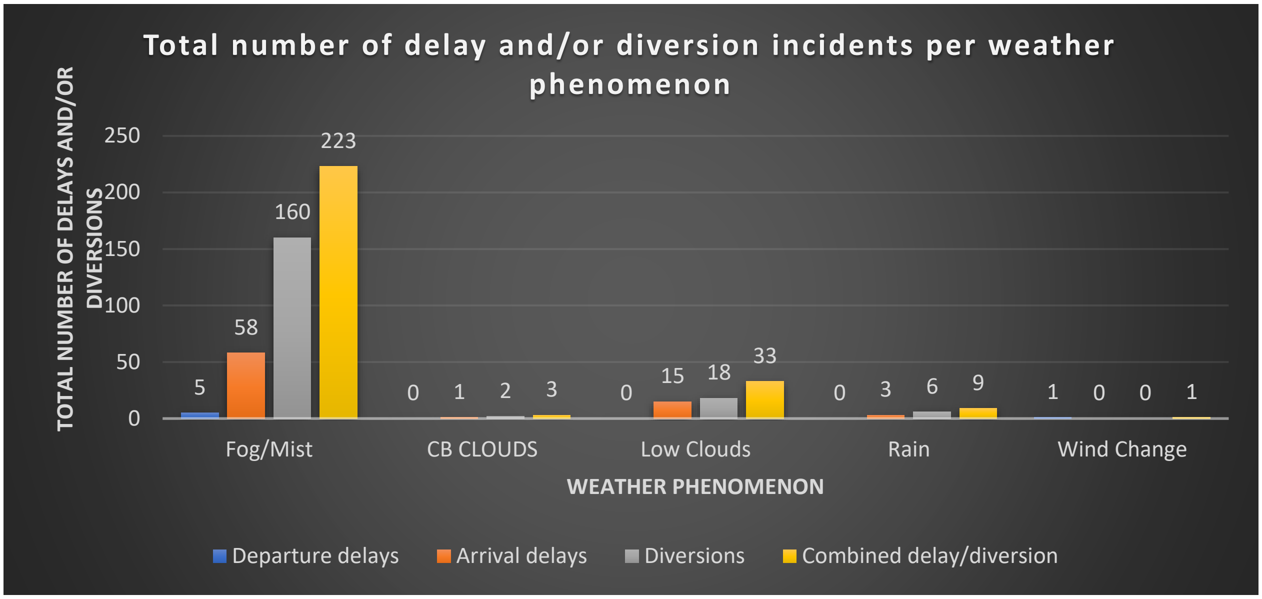


Figure 43: Distribution of total delay and/or diversion incidents per weather phenomenon during Night Off-Peak time slot (23H00-04H30)

Analysis of Obscuring Phenomena: Category Fog/Mist

Table 28: Distribution of delay and diversion incidents per visibility range according to ICAO classification

Visibility Range	150m-350m	350m-600m	600m-800m	800m-1500m		1500m-3000m	3000m-5000m
				800m-1000m	1000m-1500m		
Number of delay/diversion incidents	95	48	11	41	4	31	13

It can be seen that visibility in the range of 150m-350m accounts for 39% of delay/diversion incidents induced by the category Fog/Mist and the range 350m-600m is the second contributor with 20%.

Table 29: Distribution of delay and diversion incidents per hydrometeor events

FG	MIFG, BCFG, VCFG	BR
195	16	32

Fog accounts for 80% of delay/diversion incidents due to category Fog/Mist, followed by Mist with 13%.

Cumulonimbus Analysis

The table shows that regardless of the sub-categories (with thunderstorm or without, accompanied by precipitation involving a significant reduction in visibility or not), the mere presence of the cumulonimbus causes delays and diversions because of its great potential to cause harm; due to the fact that the greatest numbers of aviation weather hazards are bundled up in one single source, the Cumulonimbus cloud.

An event of single cumulonimbus cloud category accompanied by thunderstorm, indifferently of its intensity, yields in average a combined-delay/diversion time of thereabouts 48 minutes. While an event of single cumulonimbus cloud category unaccompanied by thunderstorm, indifferently of its intensity, yields in average a combined-delay/diversion time of thereabouts 19 minutes. Wherefore, An event of single cumulonimbus cloud category accompanied by thunderstorm gives rise to much longer length of delay time than an event of single cumulonimbus cloud category unaccompanied by thunderstorm.

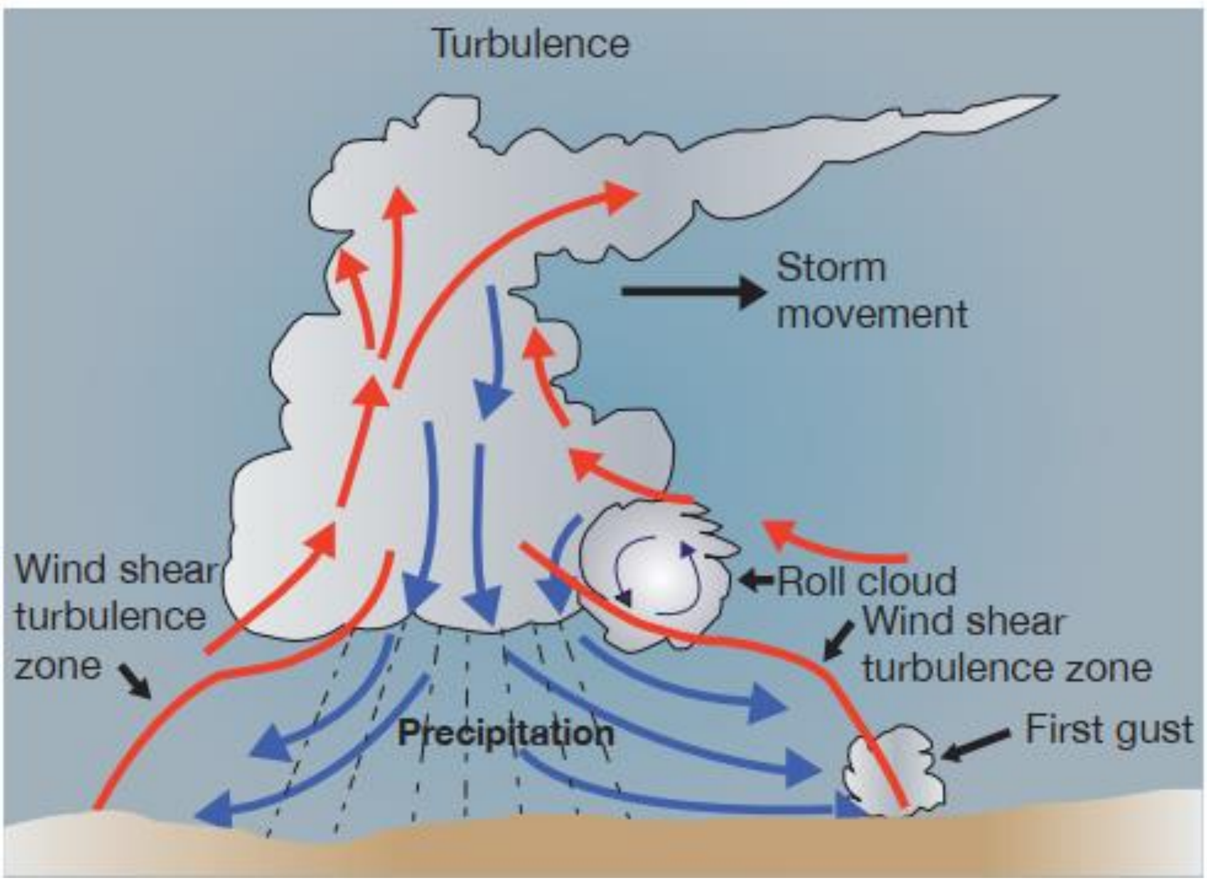


Figure 44: Cross-section of a thunderstorm (UNISDR Africa)

Table 30: Annual distribution of average amount of combined-delay/diversion minutes per combined-delay/diversion occurrence owing to CB Cloud category, accompanied and unaccompanied by Thunderstorm signalized, over years 2000-2009, and the grand average

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**Grand Average**
CB with TS											
No precipitation occurred	0	0	0	0	0	0	0	0	0	0	N/A
Precipitation occurred, but no reduction in visibility	0	0	0	0	0	50	60	0	0	57	56
Precipitation and a reduction of less than or equal to 5000m in visibility	0	0	36	0	60	0	0	0	21	0	39
CB without TS											
No precipitation occurred	20	0	0	0	0	0	12	12	0	0	15
Precipitation occurred, but no reduction in visibility	0	0	47	9	0	28	27	49	0	10	28
Precipitation and a reduction of less than or equal to 5000m in visibility	**0**	**0**	**0**	**12**	**0**	**0**	**0**	**0**	**0**	**0**	**12**

4.3 Results on Terminal Aerodrome Forecast Analysis

The very negative incidence of bad weather conditions on the safety, regularity and efficiency of air navigation is quintessentially the primary reason for the need to observe, to monitor and to predict these inclement weather conditions, in order to supply pilots, ai traffic management center and airline dispatchers with vital information as a decision-making tool before taking off and landing.

The study was devoted to analyzing the accuracy of weather forecasts by TAFs which are selected on the basis of aircraft delays and diversions recorded at JKIA airport and which were then supposed to be used for flight planning by pilots; this is why the TAFs selected are those that were issued at least 6 hours before each delay or diversion event. The TAF evaluation analysis focused on four categories of meteorological conditions, namely the Fog/Mist category, the CB Cloud category, the Low-Level Cloud category and finally the Rain category, the Wind Change category being excluded from the analysis due the fact that this type of forecast is supported by Take-off forecast which is not the scope of the study.

After analyzing the period from 2006 to 2009, the study arrived at the results below in Table 31: The year 2009 recorded 89% of forecasts which were correct and corresponds to the year which has achieved the most success in the accuracy of forecasts. At the bottom of the ranking, the year 2007 achieved 33%. A brief visualization of the table shows a decrease in the accuracy of predictions in the TAF from 2006 to 2007, followed by an increase from 2007 to 2009. The annual average of TAF successes is 63%.

Table 31: Annual distribution of TAF accuracy at JKIA from years 2006 to 2009.

Years	**Accuracy of TAF**
2006	73%
2007	33%
2008	56%
2009	89%
Overall	63%

The study went on to analyze the accuracy of the TAFs for each category of meteorological phenomenon taken individually and annually, before computing their averages over the four years. This led to the results presented in Table 32 and Figure 45. The study shows that the model used at JKIA airport was able to well predict the CB Cloud category. 75% of the annual forecasts were 100% successful. Even the year 2006 which did not reach 100% achievement of success is well beyond the minimum threshold set by ICAO. This makes the CB Cloud category to have the highest success rate percentage compared to other categories.

The model used at JKIA airport for the forecast of the Low-Level Cloud category was found to be very efficient. The average annual forecast success over the four years is 91% and is therefore the second category to be well forecast. Then comes the rain which has varying success percentages over the four years and has the two extremes one can imagine. Finally, the category Fog/Mist which was very badly forecasted by the model used. The only excuse is that dynamic models in general do not predict fog well.

Table 32: Annual success rate of TAFs at JKIA airport by category of meteorological phenomena, with the annual average of each category over the four years.

Weather Phenomenon	2006	2007	2008	2009	Average
CB Clouds	92	100	100	100	98
Low Clouds	100	78	86	100	91
Rain	100	0	N/A	N/A	50
Fog/Mist	0	24	0	0	6

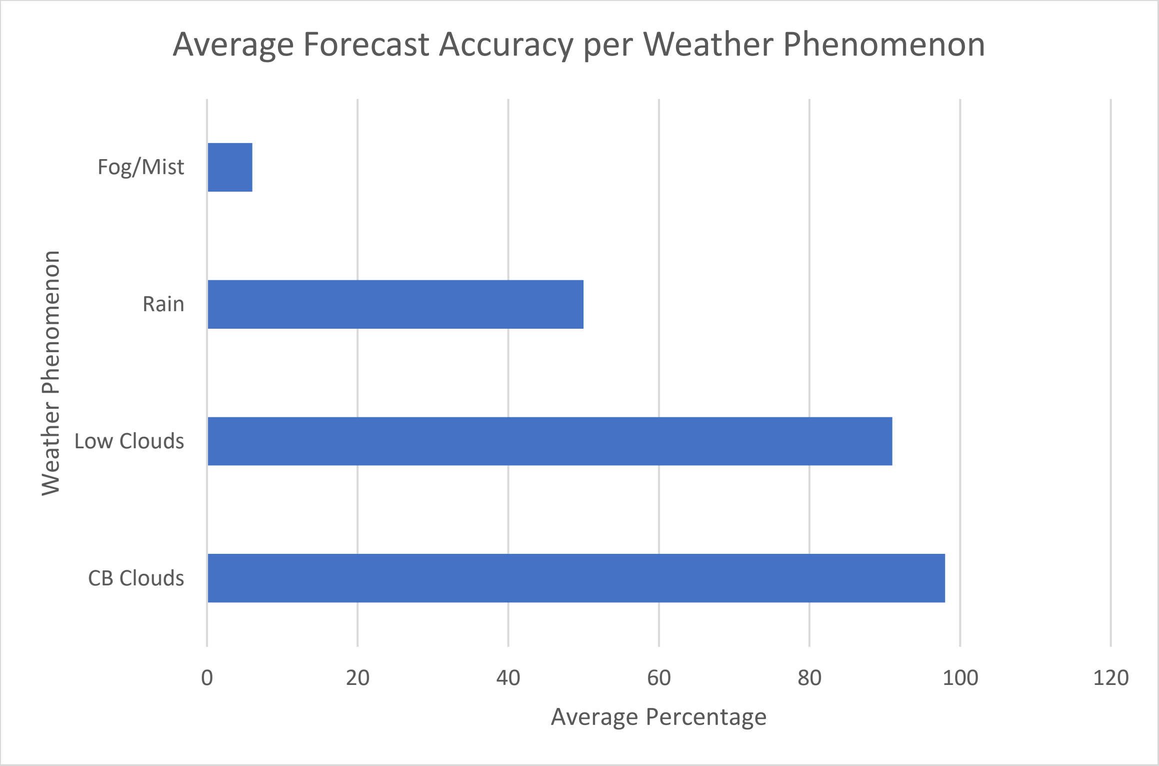


Figure 45: The average forecast accuracy per weather phenomenon (2006-2009).

Display in Table 33 shows the mean amount of departure delay minutes per successful forecast and per incorrect forecast for each selected category. The table shows that all events in the categories CB Clouds and Low-Level Clouds have been correctly forecasted but despite this, departure delays and consequently departure delay times have occurred.

The grand average of the total average minutes of aircraft departure delays when the forecasts are correct is 51 minutes.

The grand average of total average minutes of aircraft departure delays when forecasts are incorrect is 57 minutes.

In light of the results of this calculation, the study makes the following statement regarding the impact of weather forecasts issued at JKIA airport for departure delay minutes:

in average, the amount of departure delay minutes where the selected weather category was successfully forecasted was lesser than the amount where the selected weather category was inaccurately forecasted.

Table 33: The mean amount of departure delay minutes per successful forecast and per missed forecast over years 2006-2009

Category of weather	**2006**		**2007**		**2008**		**2009**	
	Success	**Failure**	**Success**	**Failure**	**Success**	**Failure**	**Success**	**Failure**
CB Clouds	**34**	**0.**	**67**	**0.**	**N.A**	**N.A**	**N.A**	**N.A**
Frog/Mist	**N.A**	**N.A**	**0.**	**51**	**0.**	**63**	**N.A**	**N.A**
Rain	**N.A**	**N.A**	**N.A**	**N.A**	**N.A**	**N.A**	**N.A**	**N.A**
Low Cloud	**N.A**	**N.A**	**N.A**	**N.A**	**53**	**0.**	**N.A**	**N.A**

Display on table 34 indicates the mean amount of arrival delay minutes per successful forecast and per failed forecast for each selected category of weather.

The grand average of the total average minutes of aircraft arrival delays when the forecasts are correct is 20 minutes.

The grand average of total average minutes of aircraft arrival delays when forecasts are incorrect is 24 minutes.

In light of the results of this calculation, the study makes the following statement regarding the impact of weather forecasts issued at JKIA airport for arrival delay minutes:

In average, the amount of arrival delay minutes where the selected weather category was successfully forecasted was lesser than the amount where the selected weather category was inaccurately forecasted.

Table 34: The mean amount of arrival delay minutes per successful forecast and per missed forecast over years 2006-2009

Category of	**2006**	**2007**	**2008**	**2009**

weather	**Success**	**Failure**	**Success**	**Failure**	**Success**	**Failure**	**Success**	**Failure**
CB Clouds	**22**	**0.**	**12**	**0.**	**17**	**0.**	**22**	**0.**
Frog/Mist	**0.**	**33**	**0.**	**24**	**0.**	**21**	**0.**	**16**
Rain	**17**	**0.**	**0.**	**30**	**N.A**	**N.A**	**N.A**	**N.A**
Low Level Cloud	**N.A**	**N.A**	**32**	**6**	**15**	**17**	**N.A**	**N.A**

Visualization on table 35 indicates the mean amount of diversion minutes per successful forecast and per failed forecast for each selected category of weather.

The grand average of the total average minutes of aircraft diversions when the forecasts are correct is 68 minutes.

The grand average of total average minutes of aircraft diversions when forecasts are incorrect is 54 minutes.

In light of the results of this calculation, the study makes the following statement regarding the impact of weather forecasts issued at JKIA airport for diversion minutes:

In average, the amount of diversion minutes where the selected weather category was successfully forecasted was greater than the amount where the selected weather category was inaccurately forecasted. This finding could be due to the greater distances and variations in aircraft speeds to reach the alternate airport. This fact induces much more fuel consumption and the inconveniences of prolonged delay for passengers among others; therefore very costly for the airlines. It looks like a kind of penalization for the pilots for not having made the right decision in the flight planning while the precision of the TAF is perfect on the occurrence of bad weather.

Table 35: The mean amount of diversion minutes per successful forecast and per missed forecast over years 2006-2009

Category of Weather	**2006**		**2007**		**2008**		**2009**	
	Success	**Failure**	**Success**	**Failure**	**Success**	**Failure**	**Success**	**Failure**
CB Clouds	66	60	N.A	N.A	60	0.	76	0.
Fog/Mist	**0.**	60	65	59	**0.**	60	N.A	N.A

Rain	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A
Low Level Cloud	88	0.	63	31	63	0.	60	0.

Visualization on table 36 indicates the mean amount of combined-delay/diversion minutes per successful forecast and per failed forecast for each selected category of weather.

The grand average of the total average minutes of aircraft combined-delay/diversion incidents when the forecasts are correct is 47 minutes.

The grand average of total average minutes of aircraft combined-delay/diversion incidents when forecasts are incorrect is 34 minutes.

In light of the results of this calculation, the study makes the following statement regarding the impact of weather forecasts issued at JKIA airport for combined-delay/diversion minutes:

In average, the amount of combined-delay/diversion minutes where the selected weather category was successfully forecasted was greater than the amount where the selected weather category was inaccurately forecasted. Thus, the average combined-delay/diversion minutes is steered by the average diversion minutes.

Table 36: The mean amount of combined-delay/diversion minutes per successful forecast and per missed forecast over years 2006-2009

Category Of Weather	**2006**		**2007**		**2008**		**2009**	
	Success	**Failure**	**Success**	**Failure**	**Success**	**Failure**	**Success**	**Failure**
CB Clouds	**42**	60	34	0.	21	0.	49	0.
Frog/Mist	**0.**	44	65	44	**0.**	42	**0.**	16
Rain	17	0.	**0.**	30	N.A	N.A	N.A	N.A
Low Cloud	88	0.	49	19	44	17	60	0.

4.4 Discussion

4.4.1 Weather Phenomena

Fog/Mist

The research found that Fog/Mist category (Obscuring Phenomena – Hydrometeors) was the first substantial giver to weather-related diversions and delays at JKIA. Fog/Mist were the cause of 18% of weather-related departure delay incidents, 47% of weather-related arrival delay incidents, 78% of weather-related diversion incidents, 66% of weather-related in-flight delay/diversion incidents and 62% of weather-related combined-delay/diversion incidents at JKIA.

It is of great significance to note that amount of departure delay incidents and consequently number of departure delay minutes due to category Fog/Mist are lessened by cancellation incidents in number and time which we have not considered in our study. The reasons of numerous cancellations of departure flights due to fog is that fog event has the characteristics of large intensity and long duration due to persistence lasting for hours. Fog is more likely to impact takeoff rather than landing since many planes are equipped with automatic landing equipment.

According to the data, FG, BCFG, MIFG, VCFG and BR can cause delays throughout the year except the month of September.

December and April are the months in which the Fog/Mist category is encountered very frequently. MAM season records the high number of delays and diversions due to Fog/Mist, followed by the OND season.

During the morning peak time period (04H30-08H30), the category Fog/Mist was in charge of the greater number of aviation diversions and delays. Also in the course of the night Off-peak time slot (23H00-04H30), the category Fog/Mist was in charge of the greater number of aviation diversions and delays.

Fog/Mist category causes a departure delay time of approximately 52 minutes, an arrival delay time of approximately 20 minutes, a diversion time of approximately 62 minutes, an in-flight delay/diversion time of approximately 47 minutes and a combined-delay/diversion time of approximately 47 minutes.

CB Clouds

The research found that CB was the second substantial donor to weather-related diversions and delays at JKIA. Category of CB cloud were the cause of 29% of weather-related departure delay incidents, 22% at of weather-related arrival delay incidents, 10% of weather-related diversion incidents, 15% of weather-related in-flight delay/diversion incidents and 17% of weather-related combined-delay/diversion incidents at JKIA.

According to the data, Cumulonimbus clouds can cause delays and diversions throughout the year except the month of August.

January to June are the months in which the CB Cloud category is encountered very frequently. MAM season records the high number of delays and diversions due to cumulonimbus clouds, followed by the summertime dry season.

During the morning off-peak time period (08H30-13H00), the category CB Clouds was in charge of the greater number of aviation diversions and delays. Also in the course of the evening Peak time slot (13H00-23H00), the category CB Clouds was in charge of the greater number of aviation diversions and delays.

The study shows that regardless of the sub-categories (with thunderstorm or without, accompanied by precipitation involving a significant reduction in visibility or not), the mere presence of the cumulonimbus causes delays and diversions because of its great potential to cause harm; due to the fact that the greatest numbers of aviation weather hazards are bundled up in one single source, the Cumulonimbus cloud.

Thus, any cumulonimbus cloud event brings about delays, whatever the intensity of the manifestation. A single cumulonimbus cloud event with thunderstorm, whatever the intensity, generally brings about a combined-delay/diversion time of roughly 48 minutes. A single cumulonimbus cloud event without thunderstorm, whatever the intensity, generally brings about a combined-delay/diversion time of approximately 19 minutes. Thus, on average, a cumulonimbus cloud event with thunderstorm will give rise to much longer length of combined-delay/diversion time than an event without TS.

Low Level Clouds

The research found that Low level cloud category was at third position as significant giver to aircraft delays and diversions due to weather at JKIA. Low level cloud category were the cause of approximately 32% of weather-related departure delay incidents (highest contributor in departure delay incidents), approximately 15% of weather-related arrival delay incidents, approximately 8% of weather-related diversion incidents, approximately 11% of weather-related in-flight delay/diversion incidents and approximately 12% of weather-related combined-delay/diversion incidents at JKIA.

According to the data, Low Level Clouds can cause delays and diversions throughout the year except the month of August and September.

The most frequent months for Low Level Clouds category to cause delays are months of April and July. MAM season records the high number of delays and diversions due to Low Level Cloud, followed by the dry winter season. During the morning peak time period (04H30-08H30), the category Low level cloud is the second responsible of aviation delays and diversions. Noting that Low Level Clouds and Fog/Mist categories are in charge of the uppermost frequency of combined-delay/diversion time per combined-delay/diversion event, it is straightforward that the simultaneous occurrence of these events are likely to give rise to huge congestion at JKIA airfield, in addition due to they take place in the course of peak time slot.

Also in the course of night Off-peak time slot (23H00-04H30), category Low level cloud is the second responsible of aviation delays and diversions. Low level cloud category causes a departure delay time of approximately 53 minutes, an arrival delay time of approximately 17 minutes, a diversion time of approximately 73 minutes, an in-flight delay/diversion time of approximately 48 minutes and a combined-delay/diversion time of approximately 49 minutes. The study finds that mean times are almost similar for the category Fog/Mist and the category Low level cloud, likely linked by the notion ‘’ceiling and visibility’’. As a premature recommendation, the study suggests that a "Ceiling and Visibility" category be created while giving this category a higher hierarchy than the category of phenomena reducing visibility and the Low Cloud category, like the predominance of the CB Cloud category over the TCU category.

Rain (not related to convective cloud)

The research found that Rain category was at fourth place as significant giver to aircraft delays and diversions due to weather at JKIA airfield.

Rain was the cause of approximately 4% of weather-related departure delay incidents (lowest contributor in departure delay incidents), approximately 9% of weather-related arrival delay incidents, approximately 3% of weather-related diversion incidents, approximately 5% of weather-related in-flight delay/diversion incidents and approximately 5% of weather-related combined-delay/diversion incidents at JKIA. Rain-related delay and diversion events occur either in January, April, July, October, November or December; months of November and December, on average, having the topmost amount of delay and diversion events.

OND rainy season records the high number of delays and diversions due to Rain, followed by the MAM season, especially the month of April. Rain was third most important phenomena in the course of morning off-peak time slot (08H30-13H00).

During the evening peak time period (13H00-23H00), the category Rain (not related to convective cloud) is the second responsible for the majority of aviation delays and diversions, Rain category causes a departure delay time of approximately 29 minutes, an arrival delay time of approximately 21 minutes, a diversion time of approximately 60 minutes, an in-flight delay/diversion time of approximately 32 minutes and a combined-delay/diversion time of approximately 32 minutes.

Wind Change Category

The research found that Wind change category was the fifth important giver to aircraft delays and diversions due to inclement weather at JKIA airfield. Wind change was the cause of approximately 18% of weather-related departure delay incidents, approximately 7% of weather-related arrival delay incidents, approximately 1% of weather-related diversion incidents, approximately 3% of weather-related in-flight delay/diversion incidents and approximately 4% of weather-related combined-delay/diversion incidents at JKIA.

According to the data, Wind Change can cause delays and diversions throughout the year with exception of the month of April and December. The month of June had the highest number of delay and diversion events on average. Dry winter season records the high number of delays and diversions due to Wind change, followed by the OND season. Wind change category was the third most important phenomena in the course of morning peak time slot (04H30-08H30).

During morning off-peak time period (08H30-13H00), the category Wind change is the second responsible of aviation delays and diversions. Wind change category causes a departure delay time of approximately 70 minutes, an arrival delay time of approximately 12 minutes, a diversion time of approximately 60 minutes, an in-flight delay/diversion time of approximately 25 minutes and a combined-delay/diversion time of approximately 30 minutes.

4.4.2 Forecast Analysis

The study was interested in determining the percentage of TAFs success issued at JKIA airport on the foundation of accumulated dataset over ten years during occurrences of departure delays, arrival delays and diversions. The assessment of TAF precision was conducted by use of reports, namely METARs and SPECIs. The evaluation considered the amended TAFs. If an amended TAF was issued at least six hours before the delay or diversion event, then it is used in the evaluation. Except for the category Wind change, all phenomena responsible for delays and diversions are assessed.
After evaluating the accuracy of the TAFs, the study proceeded to count the TAFs passed and the TAFs missed for each year. Finally the annual percentage of success and failure of the precision of the TAFs is determined.
METAR reports are issued regularly, every one hour, at JKIA. SPECIs are issued whenever weather conditions allow for a significant change in accordance with the criteria set out in annex 3. TAFs at JKIA weather service are issued by a forecaster with a 30h validity.

The category Fog/Mist through assessment on associated visibility values is an element for which the study registers lowest success percentage (6%) that do not reach the required minimum (80% of cases). The success percentage of visibility forecast is problematic. The category Rain had 50% and was therefore below the required minimum for precipitation (80% of cases). If the success percentage was evaluated entirely, not only situations were delays and diversions occurred, the computed forecast accuracy of Fog/Mist category and Rain category for the given period of study would be different. The majority of dates were not considered as there was comparatively few days of delays and diversions. Therefore, the analysis does not reflect the overall forecast accuracy, as not every TAF that was issued during the 4-year period has been examined i.e. TAFS not associated with delays and diversions. The remaining categories namely CB Cloud category and Low level cloud category are above the minimum required percentage of success rate.

Figure 46 indicates the connections that exist between the combined-delay/diversion number of incidents and the accuracy of TAF from the year 2006 to 2009. The number of combined-delay/diversion incidents increased sharply from year 2006 to year 2007 as shown by the steepness of the line, dropped moderately from 2007 to 2008 and then dropped sharply from 2008 to 2009. The forecast accuracy dropped substantially from 2006 to 2007, increased moderately from 2007 to 2008, and finally increased slightly from 2008 to 2009. Thus the study finds that, in this research, there is strong connections between the number of combined-delay/diversion incidents and the Terminal Aerodrome Forecast accuracy.

It can be seen that:

When the percentage of TAF accuracy is high (above 65%), the decrease in combined-delay/diversion incidents begins. Also when the percentage of TAF accuracy is beyond 67% to reach 73%, the number of combined-delay/diversion incidents decreases and drops sharply to only 11. Therefore, improving the forecast accuracy at JKIA results in enhancing the aviation safety, improves the airport capacity and an orderly flow, reduces the delays and diversions with effect to improve the finances of the airlines operating at JKIA.

When the percentage of TAF accuracy is low (48%), the combined-delay/diversion incidents is very high (79 incidents). Any slight increase in TAF accuracy from 48% until 65% leads to a slight decrease in combined-delay/diversion incidents. Therefore, a deterioration in TAF accuracy at JKIA results in decreasing the aviation safety, reduces the airport capacity, increases the delays and diversions with effect of income loss to the airlines operating at JKIA.

From visualization of the figure, the fact that the number of combined-delay/diversion curve is above zero line, meaning that inclement weather conditions will generate delays and diversions in spite of the accuracy of a TAF. This figure also reveals the relevance of ICAO regulations which require 80% of forecasts to be successful.

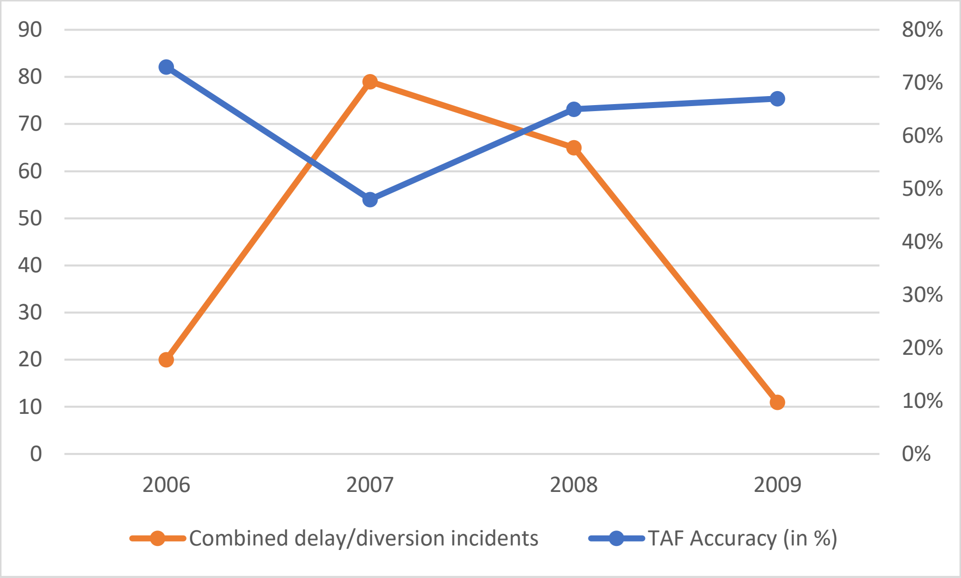


Figure 46: The number of delays and the TAF accuracy (%) over the period 2006 to 2009

TAF and Uncertainty

The notion of uncertainty and shakiness underlies Terminal Aerodrome Forecast about atmospheric processes. If atmospheric processes were constant, describing them mathematically would be very easy. Terminal Aerodrome forecasting would therefore be easy and meteorology would be a very boring subject. The atmosphere exhibits variations and fluctuations that are irregular; it is uncertain.

The uncertainty of the atmosphere is the driving force behind the collection and analysis of large datasets in this study and in general in meteorology.

Terminal Aerodrome Forecasts are therefore inescapably uncertain. The weather forecaster predicting a particular temperature on the following day is not at all surprised if the subsequently observed temperature is different by a degree or two.

To quantitatively deal with uncertainty in the atmosphere, meteorology employs probability; the mathematical language of uncertainty.

The atmosphere is never completely observed. Hence it is not possible to initialize a mathematical model in exactly the same state as that of the real system (METAR and SPECI and that is the reason behind why METAR/SPECI are used to assess Terminal Aerodrome Forecast accuracy). This leads to the uncertainty in the forecasts.

Deterministic forecasts of future atmospheric behavior will therefore always be uncertain. Hence probabilistic methods are needed to describe adequately the behavior of the atmosphere and the projection and planning of aviation operations by users.

All meteorological prediction problems, from weather forecasting to climate change projection, are essentially probabilistic; they are uncertain. For instance the fog or any other event and its impacts on aviation operations that will occur tomorrow at Jomo Kenyatta International Airport is a random event. It can only be estimated in terms of probability. But data-based statistical analysis of inclement weather and their associated impacts (arrival delays, departure delays, diversions, cancellations and costs induced) on aviation operations records at JKIA would yield relative frequencies of these inclement weather elements and other related independent variables from impacted operations. The outcome from the data analysis will then provide substantial information about tomorrow's inclement weather at JKIA.

Reducing uncertainty about random meteorological events is the purpose of weather forecasting.

The developing of the weather impact index at JKIA is fundamentally concerned with uncertainty. Evaluating and quantifying uncertainty including making inferences and forecasts in the face of uncertainty are all parts of this weather impact index on aviation delays and diversions for JKIA.

The field of statistics therefore has many roles to play in the atmospheric sciences which are full of uncertainties.

Many people are fascinated by weather forecasting which remains interesting precisely because of the uncertainty that is intrinsic to it. If it were possible to make perfect forecasts into the future then the practice of meteorology would be very dull.

4.5 Results on the Development of Weather Impact Index Models

4.5.1 Need of Assessment and Management of Weather-Related Risks

According to Eurocontrol (2014), it is possible to reduce delays caused by bad weather if the following criteria are put in place:

1.) A robust, accurate weather forecast;
2.) A proper assessment of weather-related risks;

3) Well-timed, collaborative decision-making based on delay impact assessment simulations.

According to FAA, two defining elements of Aeronautical Decision Making (ADM) are hazard and risk. Hazard is a real or perceived condition, event, or circumstance that a pilot encounters. When faced with a hazard, the pilot makes an assessment of that hazard based upon various factors. The pilot assigns a value to the potential impact of the hazard, which qualifies the pilot's assessment of the hazard—risk. Therefore, risk is an assessment of the single or cumulative hazard facing a pilot.

FAA stated that risk management is the responsibility of everyone involved in aviation. The flight operations manager, for example, who is faced with the decision as to just how hard to push a pilot to go, becomes a party to the risk management process. It is understandable from an economic point of view that the mail, checks, boss, passenger, whatever, must get through. This question ‘’is the success of the task worth the risk?’’ must always be kept in mind during decision making.

A good tool to use in making good aeronautical decisions is the Decide Model. The Decide Model is comprised of a six step process:

1) Detect. The decision maker detects the fact that change has occurred.
2) Estimate. The decision maker estimates the need to counter or react to the change.
3) Choose. The decision maker chooses a desirable outcome (in term of success) for the flight.
4) Identify. The decision maker identifies actions which could successfully control the change.
5) Do. The decision maker takes the necessary action.
6) Evaluate. The decision maker evaluates the effect(s) of his action countering the change. (FAA, Circular 60-22).

Building upon the foundation of conventional decision-making, ADM enhances the process to decrease the probability of human error and increase the probability of a safe flight.

Risk management, as an important component in Aeronautical Decision Making (ODM), allows for reducing or even eliminating the inherent risk in a flight.

While poor decision-making in everyday life does not always lead to tragedy, the margin for error in aviation is thin (FAA, Aviation Handbook).

4.5.2 Weather Impact Index System

Weather related delays and diversions of aircrafts constitute a real problem of great importance to airports, airlines and passengers. Hence the need to develop and use a weather impact index as a predictive model for estimating delays and diversions induced by weather phenomena, that can be used as a decision-making tool. Klein *et al.* (2010) developed a predictive model for estimating delays using data from weather forecast products.

The model was based on an existing model called the Weather Impacted Traffic Index (WITI).

WITI has three components namely the en-route component (E-WITI examines the impact of convective weather on routes connecting major airports), the terminal component (T-WITI captures capacity degradation resulting from surface weather impact) and the queuing delay component (Q-DELAY measures the cumulative effect of traffic demand in excess of capacity). The terminal component processes METAR data and determines the dominant weather at the terminal. The expected capacity degradation is measured by the scheduled air traffic against the dominant weather. From this, WITI-FA was developed which uses TAF reports to determine the impact that forecast weather is expected to have on scheduled air traffic.

The implementation of weather impact scoring or index would be advantageous for JKIA which does not use at the moment any system based on the principals of WITI for better operational and financial decisions.

4.5.3 Weather Impact Index Users

1) Kenya Civil Aviation Authority (KCAA)

KCAA would be best suited to use Weather Impact Index for planning purposes at JKIA, as a component in ATFM system.

Kenya Civil Aviation Authority (KCAA) was established on 24th October 2002 by the civil aviation (Amendment) act, 2002 with the primary functions towards; regulation and oversight of aviation safety and security; economic regulation of air services and development of civil aviation; provision of air navigation services, and training of aviation personnel KCAA; as guided by the provisions of the convention on international civil aviation, related ICAO standards and recommended practices (SARPs), the Kenya Civil Aviation Act, 2013 and the civil aviation regulations.

KCAA has dual functions:

1- Regulator
2- Service provider

As service provider

Responsible for the management and operation of air traffic services and search and rescue within Nairobi Flight Information Region (FIR).

Service offered; En-route, Approach and Aerodrome Control, Search and Rescue and Air Traffic Flow Management (ATFM).

Air Traffic Flow Management (ATFM) is the process that enables smooth and efficient flow of air traffic in relation to capacity and demand, in-accordance with *ICAO Doc 9971: Manual on Collaborative ATFM*.

The fundamental concept of ATFM is the balancing of air traffic demand and capacity. ICAO Annex 11 states that ‘air traffic flow management (ATFM) shall be implemented for airspace where air traffic demand at times exceeds, or is expected to exceed, the declared capacity of the air traffic control services concerned’.

ATFM is a key enabler for safety, efficiency, cost-effectiveness, and reduction of environmental impact of ATM. Its objective is to balance the demands of all airspace users against airspace and airport capacity.

ATFM offers the following benefits (CANSO, 2020):

1. Reduction of ground and en-route delays
2. Maximisation of capacity and optimisation of the flow of air traffic
3. Enhancement of operational safety
4. Improvement in operational efficiency

5. Provide an informed choice between departure delay, re-routing and/or flight level selection
6. Alleviate unplanned in-flight re-routing; and assist ATS Units in planning for and managing future workload in the light of forecast increased traffic flows within the region.
7. Assessing the impact of FUAs, UAVs and RPAS operations on the air traffic control systems
8. Provide improved solutions around predicted severe weather
9. Balance the demand and capacity of ATC sectors
10. Determine the necessity for an airspace/ground delay program and other traffic management initiatives (TMls) and enact them
11. Enabling aircraft operators to operate as close to their preferred trajectories
12. Balance airspace capacity impact through collaboration with UTM (unmanned aircraft systems management) initiatives and seamless integration including the UAV surveillance to ATM
13. A functional ATFM system enhances situational awareness

The ATFM process consists of five phases – planning, strategic, pre-tactical, tactical, and post-operations analysis These phases should be thought of as a continuous planning, action and review cycle that is fully integrated with the ATM planning and post-operations processes. The individual phases can be found in *ICAO Doc 9971: Manual on Collaborative ATFM.*

2. The model can also be used for Airline operations and by Airline dispatchers.

An airline dispatcher assists in planning flight paths, taking into account aircraft performance and loading, en-route winds, thunderstorm and turbulence forecasts, airspace restrictions, and airport conditions.

An aircraft dispatcher runs airline operations and ensures that pilots and their passengers can travel safely to their destination. Flight plans, airspace restrictions, airport conditions, safety briefings, and weather conditions (enroute winds, thunderstorm and turbulence forecasts etc) are all part of the job a dispatcher does. Airline dispatchers, in majority, have as much – if not more – knowledge than pilots, which allows them to come up with flight plans that are the best choice for weather conditions, mechanical issues, or other issues that may arise. A dispatcher has the authority to do any of the following to a plan: to divert, to cancel, to delay or to change a flight. He also advices pilot when the weather changes. The dispatcher uses extensively weather forecasts.

3. General Aviation Pilots

The model can be used by General Aviation Pilots.

Weather forecast is one of the variable used by a pilot to make decisions as weather can easily make the difference between a safe and smooth flight to a dangerous one if it is not paid attention to. Taking into account the weather forecast and current conditions will allow pilots and air traffic controllers to make the best decisions to ensure safety of the flight.

Weather phenomena like thunderstorms, fog among others will have an influence over how flights will operate on a daily basis, and before a flight takes off, the pilot will need to be aware of the weather, so they can make the best decisions or even alterations regarding the flight.

There are lots of different weather conditions for a pilot to consider when they are flying a plane, but being aware of any potential hazards and threats ensures that the pilot can make the right decisions to keep everything running smoothly.

If the weather has become too dangerous to fly in, Pilots may have to divert from their flight path. (Roger, Website Pilot School)

4.5.4 Computation of the Weather Impact Index at JKIA

Two weather impact index models were created more precisely for JKIA using data over ten years. In-flight delay/diversion model is developed for aircrafts arriving at JKIA.

The combined-delay/diversion model is developed to take into account the departure delay, the arrival delay, the diversion and cancellation assuming the number of diversion minutes and incidents are similar to those of cancellation based on the assumption that the average rate of arriving aircrafts equals the average rate of departing aircrafts. The developed weather impact index models are based on the selected weather categories in this study. The index models are established on the following scoring system:

Frequency Score + Duration Score = Weather Impact Score [Equation 2]

The sum of the two variables, namely frequency score and duration score gives the total impact score.

Frequency score indicates how often a weather category induces delays. Tables 10 and 11 record respectively the number of in-flight delay/diversion incidents and combined delay/diversion incidents over the 10-year period per weather phenomenon. The frequency score utilizes the percentage participation of each weather category to the total amount of weather delay/diversion incidents over the 10 years.

Frequency score for in-flight delay/diversion Weather Impact Index model:

Frequency Score of Fog/Mist is 66%

Frequency score of CB Cloud is 15%

Frequency Score of Low Level Clouds is 11%

Frequency score of Rain is 5%

Frequency Score of Wind Change is 3%

Frequency score for combined delay/diversion Weather Impact Index model:

Frequency Score of Fog/Mist is 62%

Frequency score of CB Cloud is 17%

Frequency Score of Low Level Clouds is 12%

Frequency score of Rain is 5%

Frequency Score of Wind Change is 4%

For in-flight weather impact index model, the duration score means the mean duration of in-flight delay/diversion event as a percentage of an hour. For combined-delay/diversion model, it means the mean duration of combined-delay/diversion event as a percentage of an hour. These scores come from the averaged total minutes of each weather phenomenon as per table 20 and table 21 respectively for the two models.

Duration score based on annual average for in-flight delay/diversion Weather Impact Index model

Duration score based on annual average total minutes for Fog/Mist is 78%

Duration score based on annual average total minutes for Low Level Clouds is 81%

Duration score based on annual average total minutes for CB Clouds is 57%

Duration score based on annual average total minutes for Rain is 53%

Duration score based on annual average total minutes for Wind Change is 41%

Duration score based on annual average for combined delay/diversion Weather Impact Index model

Duration score based on annual average total minutes for Low clouds is 82%

Duration score based on annual average total minutes for Fog/Mist is 78%

Duration score based on annual average total minutes for CB Clouds is 60%

Duration score based on annual average total minutes for Rain is 53%

Duration score based on annual average total minutes for Wind Change is 50%

The mean of the two scores (duration and frequency) gives the total impact score as a percentage. Tables 37 and 38 display the total impact score of the two models

Table 37: Total impact scores per weather category of in-flight delay/diversion WITI model for JKIA

Weather Phenomena	Total Impact Score
Fog/Mist Category	72%
CB Cloud Category	36%
Low Level Cloud Category	46%
Rain Category	29%

Table 38: Total impact scores per weather category of combined-delay/diversion WITI model for JKIA

Weather Phenomenon	Total Impact Score
Fog/Mist Category	70%
CB Cloud Category	39%
Low Level Cloud Category	47%
Rain Category	29%

An adjustment of the total impact score is done to mirror the anticipated or current air traffic, by multiplying the score with a coefficient X. The weather impact index is thus based on the total impact score and an air traffic coefficient as shown in Equation 3.

Total Impact Score * Traffic Coefficient = Final Weather Impact Index [Equation 3]

An adjustment of this coefficient is possible each day or hour depending on the context. Its predetermination is on the responsibility of ATM Centre at JKIA.

For illustration purpose, from a point of view of general peak traffic, the dissertation uses the following coefficients contained in table 39.

Table 39: Proposed traffic coefficients based on peak and off-peak traffic periods

Time Period	Traffic Coefficient

Morning Peak (04:30Z to 08:30Z)	1.3
Morning Off-Peak (08:30Z to 13:00Z)	1.2
Evening Peak (13:00Z to 23:00Z)	1.6
Night Off-Peak (23:00Z to 04:30Z)	1.1

The range of traffic coefficient should be between 1.0 to 1.6, where 1.0 would typically be used in normal or below capacity traffic, and 1.6 in high traffic situations. The final weather impact index will give a percentage score. The higher the index is, the higher the probability of disruption to air traffic due to the adverse weather.

4.5.5 Applying the Weather Impact Index to TAFS

By converting a TAF into a set of hourly forecasts, each hour can be assigned the weather impact index. As TAFs do not include forecasts of wind changes resulting in runway changes, the index can only assess the risk of disruption to air traffic based on the weather categories of Table 37 (Total impact scores per weather category of in-flight weather impact index model for JKIA) and Table 38 (Total impact scores per weather category of combined-delay/diversion weather impact index model for JKIA)

4.5.6 Weather Impact Index Examples

Training Period

4.5.6.1 Case Study 1: 14/07/2008

A low level cloud event on the 14th of July 2008 at JKIA, led to nine (9) reported diversion incidents, with a total of 473 diversion minutes. The diversions occurred from 0509Z to 0751Z. The forecasts and diversions and the associated weather impact index coefficients and index score is as shown in Table 40.

The following TAF was issued on 13th July 2008 at 2200Z

TAF HKJK 132200Z 140024 04005KT 9999 SCT020 BKN090

TEMPO 0006 VRB05KT FEW005 BKN015

BECMG 0811 16010KT BKN025

TEMPO 1218 -SHRA FEW020CB BKN020 BKN080
BECMG 1922 06005KT SCT020 BKN09

Table 40:Forecasts, diversions and the associated coefficients and index score

Hour	Forecast	Index	Coefficient	Final Index Score	Diversions
23Z (13-07-2008)	Fine	0	1.1	0	No
00Z (14-07-2008)	Low Clouds	47	1.1	52	No
01Z	Low Clouds	47	1.1	52	No
02Z	Low Clouds	47	1.1	52	No
03Z	Low Clouds	47	1.1	52	No
04Z	Low Clouds	47	1.1	52	No
0430Z	Low Clouds	47	1.3	61	No
05Z	Low Clouds	47	1.3	61	Yes
06Z	Low Clouds	47	1.3	61	Yes
07Z	Low Clouds	47	1.3	61	Yes

4.5.6.2 Case Study 2: 02/06/2009

A thunderstorm event on the 2nd of June 2009 at JKIA, led to 5 reported arrival delays and diversions, with a total of 285 delay and diversion minutes. The delays and diversions occurred in the evening with the first at 1435 Z, and the last at 1649 Z, with the remaining 3 delays and diversions falling in between.

The following TAF was issued at 0430Z

HKJK 020430Z 0206/0312 07010KT 9999 BKN025
TEMPO 0212/0218 VRB10KT -TSRA/SHRA FEW023CB BKN024 BKN080
BECMG 0219/0222 05005KT SCT018
TEMPO 0300/0306 VRB05KT FEW007 BKN016
BECMG 0308/0311 08010KT SCT025=

Combined-delay/diversion weather impact index model for JKIA

By applying the combined-delay/diversion Weather Impact Index model for JKIA for the 2nd of June 2009, as displayed in Table 41, the index scoring system revealed that potential disruption to air traffic could be around 47% at noon, increasing to 62%. Five delay and diversion incident did occur during this time, and thus, by using the index, appropriate traffic planning and management as mitigation measures could potentially have reduced the extent and duration of delays.

Table 41: The forecasts and diversions and the associated weather impact index coefficients and index score valid for 25/01/2013

Hour	**Forecast**	**Index**	**Coefficient**	**Final Index Score**	**Delay/Diversion Impacts**
11Z	Fine	0	1.2	0	No
12Z	Thunderstorm	39	1.2	47	No
13Z	Thunderstorm	39	1.6	62	No
14Z	Thunderstorm	39	1.6	62	Yes
15Z	Thunderstorm	39	1.6	62	Yes
16Z	Thunderstorm	39	1.6	62	Yes
17Z	Thunderstorm	39	1.6	62	Yes
18Z	Thunderstorm	0	1.6	0	No
19Z	Thunderstorm	0	1.6	0	No

Verification Period of Weather Impact Index Models for JKIA

4.5.6.3 Case study 3: 21-08-2012

Table 42 shows the METARS issued on 21/08/2012. The TAF below was issued at 2230Z
HKJK 202230Z 2100/2206 24005KT 9999 SCT017

TEMPO 2100/2106 VRB05KT -DZ FEW006 BKN017
BECMG 2108/2111 15010KT SCT023
TEMPO 2112/2118 VRB10KT FEW022CB BKN023
BECMG 2120/2123 23005KT SCT020
TEMPO 2200/2206 VRB05KT -DZ FEW005 BKN015=

Table 42: METARS issued on 21/08/2012

HKJK	METAR	2012-08-21 0100	HKJK 210100Z 00000KT 9999 SCT015 14/13 Q1023 NOSIG
HKJK	METAR	2012-08-21 0130	HKJK 210130Z 36003KT 0900 FG SCT006 14/13 Q1023 TEMPO 0500 FG SCT005 SCT015
HKJK	METAR	2012-08-21 0200	HKJK 210200Z 01003KT 0400 FG FEW005 13/13 Q1023 TEMPO 0500 FG SCT005 SCT015
HKJK	METAR	2012-08-21 0230	HKJK 210230Z 00000KT 0500 FG FEW002 SCT120 13/13 Q1023 BECMG 0800 FG SCT015
HKJK	METAR	2012-08-21 0300	HKJK 210300Z 00000KT 0400 FG SCT002 13/13 Q1023 BECMG 0800 FG SCT015
HKJK	METAR	2012-08-21 0330	HKJK 210330Z 28003KT 0400 FG FEW003 SCT120 13/13 Q1023 BECMG 0800 FG FEW005 SCT017
HKJK	METAR	2012-08-21 0400	HKJK 210400Z 19003KT 2000 MIFG FEW015 13/12 Q1023 TEMPO 0800 BCFG SCT016

The TAF, evaluated on the basis of actual conditions within the METARs, illustrates the difficulty of forecasting fog. Using METARs, our model will show the following weather impact index values for the fog event, contributing in bad visibility and ceiling conditions.

Table 43 shows the use of in-flight delay/diversion WITI model for JKIA

Table 43: Forecasts, actual impact and the weather impact index coefficients and index score

Hour	METAR	Index	Coefficient	Final Index Score	Actual impact over JKIA
0100Z	Fine	0	1.1	0	Weather Good for Normal Operations
0130Z	Fog	72	1.1	79	Diversions, ILS Landing only
0200Z	Fog	72	1.1	79	Diversions, Airport closed
0230Z	Fog	72	1.1	79	Diversions
0300Z	Fog	72	1.1	79	Diversions continue
0330Z	Fog	72	1.1	79	Diversions continue
0400Z	MIFG	72	1.1	79	Airport opened after signs of weather improving

4.5.6.4 Case study 4: 16-07-2012

The MEATARS issued on 16.07.2012 is shown in Table 44. The below TAF was issued on 2300Z (15-07-2012)

TAF HKJK 152300Z 1600/1706 VRB05KT 9999 FEW008 BKN015
BECMG 1608/1611 15010KT FEW024CB BKN025
BECMG 1620/1623 SCT020
BECMG 1700/1703 FEW00 8 BKN015=

The TAF shows that fog was not forecasted. Forecasts, actual impact and the weather impact index coefficients and index score are shown in Table 50

Table 44: METARS issued on 16/07/2012

HKJK	METAR	2012-07-16 0330	HKJK 160330Z 21006KT 9999 SCT009 BKN016 13/12 Q1022 NOSIG
HKJK	METAR	2012-07-16 0400	HKJK 160400Z 21006KT 3000 BR BKN002 13/12 Q1022 TEMPO 0600 9999 BKN017
HKJK	METAR	2012-07-16 0430	HKJK 160430Z 22005KT 0700 FG BKN001 13/13 Q1023 TEMPO 0630 9999 BKN018
HKJK	METAR	2012-07-16 0500	HKJK 160500Z 24004KT 9999 SCT006 BKN017 14/13 Q1023 NOSIG

Table 45: Forecasts, actual impact and the weather impact index coefficients and index score

Hour	METAR	Index	Coefficient	Final Index Score	Actual impact over JKIA
0330Z	Fine	0	1.1	0	Normal weather but shows signs of deteriorating
0400Z	Fog	72	1.1	79	Aircrafts put on hold (arrival delays), Diversions: Airport closed due to bad weather
0430Z	Fog	72	1.3	94	Aircrafts diverted
0500Z	Fine	0	1.3	0	Weather clears. Some of the aircrafts on diversion turn back (expensive)

4.5.6.5 Case study 5: 20-07-2012

The METARS issued on 20/07/2012 is shown in Table 46. Forecasts, actual impact and the weather impact index coefficients and index score is shown in Table 47.

Table 46: METARS issued on 20/07/2012

HKJK	METAR	2012-07-20 0300	HKJK 200300Z 22007KT 9999 BKN015 13/12 Q1022 NOSIG
HKJK	METAR	2012-07-20 0400	HKJK 200400Z 19008KT 4000 BCFG SCT003 OVC015 13/12 Q1023 TEMPO 0530 9999 FEW006 BKN016
HKJK	METAR	2012-07-20 0430	HKJK 200430Z 18007KT 0600 FG SCT001 BKN015 12/12 Q1023 TEMPO 0600 9999 FEW006 BKN016
HKJK	METAR	2012-07-20 0500	HKJK 200500Z 19008KT 0800 FG SCT001 BKN015 12/11 Q1024 TEMPO 0630 9999 FEW006 BKN016
HKJK	METAR	2012-07-20 0530	HKJK 200530Z 20005KT 2000 BR BKN001 BKN016 12/11 Q1024 TEMPO 9999 BKN018
HKJK	METAR	2012-07-20 0600	HKJK 200600Z 21006KT 4000 BR BKN003 BKN016 13/12 Q1025 TEMPO 9999 BKN018

Table 47: Forecasts, actual impact and the weather impact index coefficients and index score

Hour	**METAR**	**Index**	**Coefficient**	**Final Index Score**	**Actual impact over JKIA**
0300Z	Fine	0	1.1	0	Normal weather for take-off and landing
0400Z	Fog	72	1.1	79	Delay and diversion; Aircrafts landing on threshold weather conditions
0430Z	Fog	72	1.3	94	Diversions: Airport closed
0500Z	Fog	72	1.3	94	Aircrafts diverted: Airport closed
0530Z	Fog	72	1.3	94	Continued diversions
0600Z	Fog	72	1.3	94	Delays and diversions: Airport opens for ILS

In all these last three examples, for aircrafts on ground, the impact would be cancellations of departure flights, and to a lesser extent very long and lengthier delay times than arriving aircraft which are equipped with landing instruments.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the identified research problem, the formulated research questions, the set objectives, and the detailed data and methods, the main conclusion from the study is that it is possible to implement a weather impact index on aviation delays at JKIA as a decision-making support tool for better operational and financial decisions. The other specific conclusive findings drawn from the study include: Over the ten-year period, when examining the total number of in-flight delay/diversion incidents per month, the month of April records the highest total number, namely 75 whereas the months of August and September have the least total number with respectively 9 and 3 total numbers. The month of April 2005 (with 21) has the highest number of in-flight delay/diversion incidents, followed by the month of May 2002 (16).

For the case of weather-related in-flight delay/diversion minutes, conclusion can be made that the more incidents per category, the higher the number of in-flight delay/diversion minutes. The year 2007 recorded the largest in-flight delay/diversion minutes, followed by the year 2001 and 2002. When the percentage of TAF accuracy is high (above 65%), the decrease in combined-delay/diversion incidents begins. Also, when the percentage of TAF accuracy is beyond 67% to reach 73%, the number of combined-delay/diversion incidents decreases and drops sharply to only 11. Therefore, improving the forecast accuracy at JKIA results in enhancing the aviation safety, improves the airport capacity and an orderly flow, reduces the delays and diversions with effect to improve the finances of the airlines operating at JKIA. The study reveals the relevance of International Civil Aviation Organization (ICAO) regulations which require 80% of forecasts to be successful.

5.2 Recommendations

1) **Implementation of weather impact index**

Based on the identified research problem, the formulated research questions, the set objectives, and the detailed data and methods, the conclusions drawn, the main recommendation from the study is that the Kenya Meteorological Department should consider the development and use of a weather impact index on aviation delays and diversions at JKIA for implementation as decision making support tool by the Kenya Civil Aviation for better aerodrome operational and financial decisions. It is important to note that the total impact scores per weather category of the developed models are based on annual average, i.e the reason why the total impact score remains constant for each weather category. The total impact scores per weather category can be developed as a function of months and further as function of time of day to be more effective for use in operation planning and management.

2.) Improving fog forecast quality

It is a fact that fog represents one of the most difficult meteorological weather variable to forecast accurately.

Quality of forecasting fog in TAF at JKIA is very low, almost nonexistent. Thus, filling in this gap becomes necessary for aviation safety and for economy of airlines operating at JKIA. It is known from literature that several satellite products are available for monitoring and forecasting of specific weather elements, like rainfall e.g., TRMM (Tropical Rainfall Measuring Mission), and CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations) etc.

Satellite can be used to fill gaps in the fog forecasting. The decisions-makers however must apply some criteria in identifying the most appropriate products. They can rely on criteria that depends on the following:

a) Have the products been validated i.e., ground trothed with local country or regional observational datasets?
b) What will be the skills of such products in forecasting over Nairobi County or Kenya country. Such metrics as Root Mean Square Error (RMSE), Mean Absolute Error (MAE) etc can be used to test the skill
c) At what level of processing are the products available? Raw, pre-processed or processed? The level of uncertainty is dependent on the level of processing
d) Are the products freely available or commercially available? If they advocate for freely available products, this should however not be at the cost of quality.
e) Are the products packaged and availed in a user friendly manner? Depending on the personnel capacity at JKIA meteorological forecasting office, the products ought to be an

easy to use manner. If not, they would therefore also advocate for forecasters to be trained on such skills.

f) Do the products have the temporal and spatial relevant resolution? These resolution characteristics affects the accuracy and scope of monitoring and forecasting. Since they depend on the orbital properties of satellites, either geostationary or polar orbiting satellite products will be chosen with fine temporal and spatial sensor resolution

g) At what remote sensing channels are the products collected by the satellite sensors? Common channels are the VIS, IR, MW and RGBs.

h) Are the products from passive or active remote sensing systems? Although the passive remote sensing systems are cheap, they are only available during the day. When there is need to monitor and forecast fog at night, products collected by active remote sensing systems will be desired.

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