THE IMPACTS OF WEATHER ON AVIATION DELAYS AT O.R. TAMBO INTERNATIONAL AIRPORT, SOUTH AFRICA

By

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Submitted in accordance with the requirements for the degree of

MASTER OF SCIENCE

In the subject

GEOGRAPHY

at the

University of South Africa

Supervisor: Dr D.W. Hedding

November 2015

The impacts of weather on aviation delays at O.R. Tambo International Airport, South Africa

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Abstract

Weather-related delays in the aviation sector will always occur, however, through effective delay management and improved weather forecasting, the impact and duration of delays can be reduced. The research examined the type of weather that caused departure delays, due to adverse weather at the departure station, namely O. R. Tambo International Airport (ORTIA), over the period 2010 to 2013. It was found that the most significant weather that causes such delays are thunderstorms, followed by fog. Other noteworthy elements are rainfall, without the influence of other weather elements, and icing. It was also found that the accuracy of a weather forecast does not impact on the number of departure delays, and thus departure delays due to weather at the departure station are largely unavoidable. However, the length and impact of such delays can be reduced through improved planning. The study highlights that all weather-related delays can be reduced by improved weather forecasts, effective assessment of the weather forecast, and collaborative and timely decision making. A weather impact index system was designed for ORTIA and recommendations for delay reductions are made.

Keywords: Delays, Weather, Aviation, O.R. Tambo International Airport, South Africa, Forecasting

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Declaration

I declare that “The impacts of weather on aviation delays at O.R. Tambo International Airport, South Africa” is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

Signature:

Date:

01/09/2015

Acknowledgments

"In the Lord, put your trust" Psalm 1:11

I would like to express my sincere gratitude to my supervisor, Dr David Hedding, for your excellent guidance and support. Thank you for leading me down the academic road.

A very special thank you to Mr Bradley Stalls from Airports Company South Africa. Without your assistance in data, the research would not have even begun. Thank you for all of your help regarding the data and communication at the airport.

Thank you to The South African Weather Service who provided invaluable data and information.

A big thank you to Mr Trevor Kell from The National Center of Meteorology and Seismology (UAE) for your advice and excellent expertise in aviation.

And lastly, thank you to my family and friends for your kind words of encouragement, and to my wonderful husband for your unwavering belief in me.

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Assumptions

The following assumptions can be made throughout the dissertation:

- All times, unless otherwise stated, are in South African Standard Time (SAST).

Acronyms

- AHPS - Atlantic High Pressure System
- AMC - Airport Management Centre
- ATC - Air Traffic Control
- ATFM - Air Traffic Flow Management
- ATM - Air Traffic Management
- CAMU - Central Airspace Management Unit
- CB - Cumulonimbus Cloud
- IATA - International Air Transport Association
- ICAO - International Civil Aviation Organization
- IHPS - Indian High Pressure System
- ILS - Instrument Landing System
- METAR - Meteorological Aerodrome Report
- NWP - Numerical Weather Prediction
- ORTIA–Oliver Reginald Tambo International Airport
- RVR - Runway Visual Range
- SAST - South African Standard Time
- SAWS - South African Weather Service
- SFO - San Francisco International Airport
- SPECI - Special Weather Report
- TAF - Terminal Aerodrome Forecast
- TCU - Towering Cumulus Cloud
- VFR - Visual Flight Rules

Definitions

- 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).
- 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).
- Hydroplaning (aka aquaplaning)- When a tire rolls over a wet surface, it squeezes water from underneath the footprint. This process generates water pressure on the surface of the tire footprint. At a critical speed, the tire will completely separate from the ground surface by a film of water, known as hydroplaning (Van Es, 2001). This results in a decrease in braking and steering effectiveness.
- 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. ICAO classifies ILS approaches into three categories, as per Table 1.

Table 1:Instrument landing system approach categories.

Category	**Decision Height (DH) ***	**RVR Minimum**	**Visibility Minimum**
Category I	200 ft	550 m	800 m
Category II	100 ft	370 m	None
Category IIIA	No DH	210 m	None
Category IIIB	No DH	46 m	None
Category IIIC	No DH	No RVR	None

** DH (Decision Height) is the altitude where the pilot must obtain visual contact with the runway and decide if the landing will continue or if a missed approach will be initiated.*

- <u>METAR (Meteorological Aerodrome Report)</u> - 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 standardised 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.
- <u>Off-block</u> - The actual time that the aircraft pushes back/vacates the parking position.
- <u>On-block</u> - The actual time that the aircraft arrives in the parking position.
- <u>Payload</u>-Payload in aviation is the carrying capacity of an aircraft, usually measured in terms of weight. Depending on the nature of the flight, the payload may include cargo, passengers, flight crew, munitions, scientific instruments or experiments, or other equipment (Wikipedia)
- <u>Runway Threshold</u> - The runway threshold is an allocated area at the beginning and the end of the designated space on a runway for landing and take-off of aircraft under non-emergency conditions.
- <u>Runway Visual Range (RVR)</u> - The runway visual range is the horizontal distance that a pilot of an aircraft which is on the centreline of the runway can see the runway surface markings and lights. This distance is normally measured in feet or meters.
- <u>SPECI (Special Weather Report)</u>- A SPECI is an observation report just like a METAR but is only issued when significant changes in the weather occur. These changes can be an improvement or deterioration in the weather since the previous METAR or SPECI was issued. The criteria used for the issuance of a SPECI are regulated by ICAO.
- <u>TAF (Terminal Aerodrome Forecast)</u> - A TAF is a coded weather forecast for an aerodrome, used for aviation purposes. The forecast includes weather variables such as wind speed and direction, precipitation and other weather, horizontal visibility, vertical visibility when needed, and cloud height, amount and type. The forecast generally covers a 30 hour period at major aerodromes and is globally disseminated and updated every 6 hours. If the forecast changes significantly in between issue times, an amended TAF can be issued. The TAF is a standardised report and is regulated by ICAO.

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Chapter 1: Introduction

1.1. Introduction

The aviation industry and associated operations is significantly influenced by weather. Aviation safety, efficiency and capacity are sensitive to weather, and adverse weather can have negative impacts to the sector (Sasse&Hauf, 2003). The increase in aviation demand can push an airport's capacity to its limits, and even a small weather change can lead to a reduction of the airport capacity (Markovic *et al*., 2008). Weather conditions affect all aspects of aerodrome operations such as aircraft fuelling, cleaning, baggage handling, catering, aircraft maintenance, and the actual scheduled flights. The operational capacity of airports, and even a region's entire airspace, can be significantly reduced due to bad weather, resulting in delays, diversions and cancellations of flights (Sasse&Hauf, 2003).

On average, weather accounts for nearly 75% of global aviation delays (Abdelghany *et al*., 2004).There are various definitions to describe an aviation delay. The definition adopted for this study is that of the actual off-block/on-block time of an aircraft relative to the operator's published schedule (Cook *et al.,* 2004). The projected flight time as per the schedule assumes a completely efficient operation of the airspace system, with all coping mechanisms in place and an accurate weather forecast (Robinson, 1989). Delays not only have local implications, but also affect flights downstream due to the ripple effect and tight airline schedules (Allan *et al*., 2001). Adverse weather conditions at one airport can create disturbances in the traffic flow throughout the entire airspace system (Allan *et al*., 2001). Delays trigger additional costs such as extra airport charges, maintenance and crew costs and passenger compensation (Pejovic *et al.,* 2009).

Many studies have shown how aviation delays can have a significant financial impact to the sector. According to Evans (1995), 65% of the delays experienced by US domestic airlines are attributable to adverse weather, with estimated costs of US$3 billion per year. The National Oceanic and Atmospheric Administration (NOAA) reported that US$600 million per year could be saved from improved winter weather forecasting and icing diagnostics at U.S. airports (Klein *et al*., 2009). NavCanada estimated that the use of 100% accurate terminal aerodrome forecasts at Canadian airports would result in a saving of US$12.5 million annually, as a conservative number (Klein *et al*., 2009). Another example of the financial impacts is the approximately US$250,000 of economic loss that Frankfurt airport undergoes per fog hour experienced (Möller *et al*., 2001).

A response to adverse weather for aviation is that of hazard mitigation. Aviation weather mitigation can be realised through two avenues. The first covers measures to improve the aircraft or aerodrome to be better suited for adverse weather. In the last century, the operational capabilities of aircraft and aerodromes have undergone continual improvements (Stough, 2007). Such mitigation examples include instrument landing systems, autopilots and auto-throttles, de-icing fluids, grooved runways, anti-lock braking systems, electrical hardening, gyroscopic instruments, crosswind landing gear and pressurised cabins (Stough, 2007). The second mitigation avenue is to enhance the operational decision-making process regarding the adverse weather. The availability of affordable and high-performance data processing systems and high-capacity digital data links has facilitated in the improvement of weather information systems, thereby enhancing weather-related decisions. Stough (2007) characterises aviation weather mitigation as a continuum with the need to avoid all adverse weather at one extreme and the ability to safely operate in all weather conditions at the other extreme. Realistic aviation capabilities would fall somewhere between these two extremes. Avoidance of adverse weather is dependent on weather observations, accuracy of forecasts, timely dissemination and presentation of these weather datasets to all the relevant parties, and the integration of the information into the flight management decision process.

A decrease in the number of delays to an airline would lead to significant financial savings. On-time performance of airlines is a key factor in maintaining current customer satisfaction and attracting new customers (Abdelghany *et al*., 2004). Disruptions in a planned flight schedule also impact the availability of crews and aircrafts for future flights (Abdelghany *et al*., 2004). For example, if a flight is delayed, crewmembers may misconnect their next scheduled flight. Therefore, a decrease in delays would lead to a positive effect for the air carriers, airport operators and passengers (Markovic *et al*., 2008). Therefore, mitigation cannot only decrease the notable financial losses of adverse weather, but also address operational losses. Reducing these losses would bring obvious benefits to the aviation industry but every mitigation activity has a cost that must be considered. Rose *et al*., (2007) propose a benefit-cost analysis to assess mitigation suitability.

The operational response to a delay often varies, even under similar weather and traffic conditions, due to the multitude of factors that influence the response. Such factors include the accuracy of terminal and en-route weather forecast products, airspace design and traffic flow management, scheduling times and over-scheduling by airlines, airport procedures and constraints and so on (Klein *et al*., 2009). Delays can be divided into avoidable and unavoidable. Unavoidable delays are directly related to the severity of the weather and the airspace procedures and regulations (Klein *et al*., 2009). The avoidable portion of delays is related to many factors, but typically is related to the accuracy of a weather forecast (Klein *et al*., 2009). An over-forecast may lead to unnecessary ground delay programs, and an under-forecast can lead to last-minute air traffic flow management (ATFM) actions such as unplanned delays and re-routes, which can cause a significant ripple effect throughout the national airspace (Klein *et al*., 2009). According to the National Center of Atmospheric Research (NCAR), as much as 60% of today's delays and cancellations due to weather, and particularly convective weather, are potentially avoidable (Klein *et al*., 2009).

Despite modern avionics on-board aircraft, and automated instrumentation on the ground assisting aerodrome operations, weather is still a vital part of aircraft operations' decision making, and affects the safety and efficiency of flying (Dalton, 1992). The pilot needs, at all stages of a flight, accurate and up-to-date information concerning the weather. National weather services, as well as air traffic control (ATC) staff, are responsible for providing weather information to the aviation industry. The information is used by aircraft operators and ATC centres to contribute to efficient aircraft operations. The management of aircraft around a major international airport is very demanding, and any weather hazard that may cause disruption can cause havoc both on aerodrome operations, as well as on en-route flights (Dalton, 1992). ATC services are very sensitive to weather hazards, specifically thunderstorms, fog and snow, and require expert advice from weather forecasters during critical conditions (Dalton, 1992).

The operating costs for aircraft being held at the departure gate are significantly lower than active aircraft. Therefore, it would be economically viable to hold the aircraft at the departure gate until a normal, un-delayed flight path to the destination is available (Robinson, 1989). Therefore, an accurate forecast of the ending-time of a delay-causing weather phenomenon, would improve operational efficiency by allowing for maximisation of gate times and minimisation of flight times (Robinson, 1989). However, even with an accurate forecast, other factors such as gate availability and airspace crowding can also hinder effective operations. Nevertheless, an increase in forecast accuracy would allow airlines and ATC to schedule flights that would decrease overall delay time (Robinson, 1989). Robinson (1989) researched how improvements in weather forecasts of the dispersal time of fog at Atlanta Hartsfield International Airport, resulting in the reduction of a flight's delay time by say 1 minute, would ultimately result in an annual saving of US$68 000 per-minute increase in forecast accuracy, for this one situation alone (Robinson, 1989). Accurate forecasts, specifically of convective weather, would result in better route planning and ground delay management, with estimated potential benefits of hundreds of millions of dollars annually (Klein *et al.*, 2009).

Airports and air traffic service providers adjust their scheduled throughput according to the forecasted weather conditions. For example, if a thunderstorm is expected, an airport's throughput can be systematically reduced by up to 75% to prevent additional delays and flight cancellations (Pejovic *et al.,* 2009). Such techniques help to minimise such a weather impact. However, when unexpected events occur, there is far less ability to adjust operations, and thus the impact is more severe. Therefore, weather and weather forecasts are critical components of aviation operations, and gaining a better understanding of both elements at an aerodrome is crucial in order for aviation operations to run with fewer disruptions. Through the use of geography, the examination of weather (a branch of physical geography) can be used to tailor solutions to economic and transportation issues in an environmental context, with a marked planning approach.

1.2. Motivation

O.R. Tambo International Airport (ORTIA) is the busiest airport in South Africa, if not Africa (Peck & Hedding, 2014) and is a major regional hub in the aviation industry. It is also located where significant weather, such as thunderstorms and fog, are frequent occurrences and, thus, weather, as a geographic phenomenon, is a critical aspect of its' aviation operations. It is, therefore, an ideal airport to base a study regarding adverse aviation weather and its impacts on aviation operations, with specific reference to delays.

Determining the causes of aviation delays is essential for formulating and evaluating approaches to reduce them (Allan *et al.,* 2001). According to Allan *et al*. (2001), in order for traffic planning tools, which are intended to reduce delays, to be effective, the tools must be tailored to incorporate the specific type of adverse weather which is affecting the problem area.Thus, obtaining a detailed understanding of the type of weather that influences airport operations at O.R. Tambo International Airport is vital in order to develop or contribute to traffic planning tools in order to reduce these delays.

Many challenges have faced the aviation industry over the last few years, including increasing jet fuel prices, and the notion of cost cutting to reach levels of efficiency and long-term sustainability has become vital to many airlines. Frankfurt airport undergoes an economic loss of about US$250,000 per fog hour experienced (Möller *et al*., 2001). This example displays the negative economic impacts that adverse weather can have on an aerodrome. Therefore reducing aviation delays due to adverse weather could be considered as part of cost cutting solutions.

There is growing concern that an increase in the severity and/or frequency of severe weather patterns, a possibility due to climate change, may affect future air transport operations (Pejovic *et al.,* 2009). Therefore, negative weather impacts on the aviation industry may increase in the future, and solutions should be tailored now. Evans (1995) determined that part of reducing adverse weather impacts on aviation lies with accurate forecasts of the adverse weather phenomena, followed by ATC centres effectively using the information. It must first be determined the existing accuracy of forecasts, and only then can improvements be made.

Delays are highly sensitive to the time of day affected by adverse weather, as the greatest amount of delays occur during the highest demand periods (Allan *et al.,* 2001). Thus, identifying a trend or pattern in flight delays can help airport authorities and airline scheduling to develop an effective strategy to reduce flight delays (Abdel-Aty *et al.,* 2007).Therefore, gaining a thorough understanding of weather induced aviation delays at ORTIA, could lead to formulating approaches to reduce such delays. This type of research has never been conducted at ORTIA before, and is the first of its kind.

1.3. Background

Most aviation accidents occur during the take-off climb or the descent-approach-landing phases of the flight (Mahapatra, 1991). This statement is reflected in Figure 1, which displays the phase of flight for global aviation accidents during the year 2013. Therefore, most aviation accidents, regardless of the cause, occur within the aerodrome area. Additionally, weather accounts for 10-15% of all aviation accidents (Wan & Wu, 2004). In order to attempt to decrease this percentage, it is important to identify and understand the specific types of weather that are hazardous to aviation operations. This section gives a general overview of the types of weather phenomenon that pose as hazards to the aviation industry. After an understanding of the general types of hazardous weather, one can examine the specific weather hazards directly over the aerodrome in order to gain an understanding of the weather impacts on flight delays at an aerodrome.

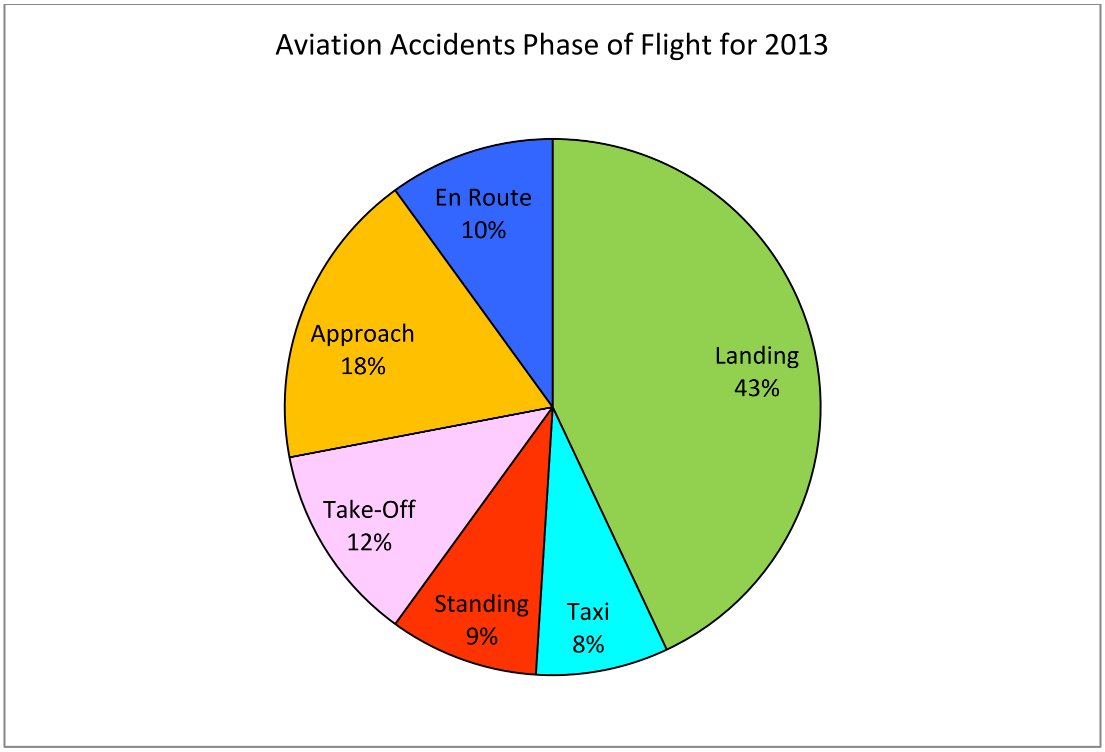

Figure 1: Global aviation accidents by phase of flight for the year 2013 (ICAO, 2014).

1.3.1 General Weather Hazards to Aviation

The typical weather, but not inclusive of all weather, that affect aviation operations includes thunderstorms, turbulence, wind shear and wind gusts, snow, aircraft and runway icing, low visibility due to fog, mist and haze and low cloud ceilings. Weather-related delays can be caused by such weather found at the departing or destination aerodrome and en-route the flight path.

Thunderstorms are responsible for the majority of weather-related aircraft accidents and incidents, and a significant fraction of delays (Mahapatra, 1991). Thunderstorms are born from cumulonimbus clouds (CB), and thus are termed as convective weather. The aviation hazards that are associated with thunderstorms include severe turbulence, lightning, hail, heavy precipitation and severe icing. It is most often the turbulence that poses the most significant threat to aircraft. Turbulence can be in the form of erratic winds, intense updrafts and downdrafts, wind shear, microbursts, macrobursts, gustfronts and strong low-level winds (Kulesa, 2003). It is near the ground i.e. during landing, take-off and on final approach that is the most difficult time to handle and encounter thunderstorms (Buck, 2013). This is due to the fact that there is no altitude buffer in which to recover from the turbulent motions (Buck, 2013). An uncontrolled altitude loss close to the ground can result in disaster. Severe turbulence can cause injuries to passengers, which can also result in costly compensation claims (WMO, 2007). Winds within and close to a thunderstorm are unpredictable in direction and can cause significant, sometimes violent gusts. Therefore, landing and take-off in such erratic winds would be injudicious. Even with sophisticated radar technologies, wind shear detection is not good enough to show the sharp demarcation between smooth and turbulent air (Buck, 2013).

The typical wind scenario that an aircraft would encounter when approaching and flying through a downburst is displayed in Figure 2. The diagram shows a violent downward motion of air from a thunderstorm, which upon hitting the ground, spreads radially outwards. An aircraft within such a scenario would first encounter a headwind, thus lifting the aircraft up, followed by a sudden and intense downdraft, and then a strong tailwind. These winds can result in a substantial loss of height if not counterbalanced (WMO, 2007).

Thunderstorms and its' related phenomena can close airports, degrade airport capacities for acceptance and departure, and can hinder or stop ground operations (Kulesa, 2003). Lightning discharges are generally a minor danger to aircraft (Buck, 2013), but a major danger to ground operators, resulting in fuelling and engineering activities to cease. Hailstones of a sufficient size can cause damage to the propeller and engine blades, and the skin of the aircraft, which may alter the aerodynamics of the aircraft and can even shatter windscreens (WMO, 2007). Small hail will have little effect on the structure of an aircraft; however it can have significant negative effects on visibility. Lightning and hail damage to aircrafts can also remove aircraft from operations, resulting in both revenue loss and excessive maintenance costs (Kulesa, 2003).

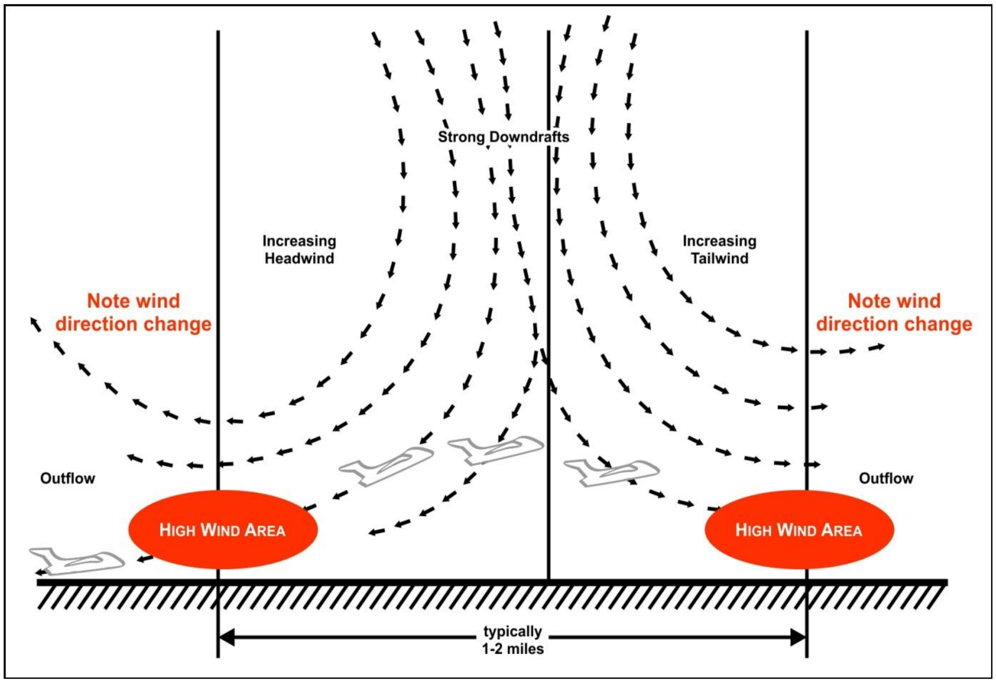

Figure 2: A downdraft scenario depicting the flight path of an aircraft and the associated wind regime(NOAA, 2010).

Towering cumulus cloud (TCU) is the first stage of thunderstorm formation. This type of cloud is therefore also convective in nature, and hence contains unstable air. Due to this, significant turbulence and icing may be present, together with showers of rain. Therefore, even though TCU may not appear to be as dangerous as CB clouds, they still pose significant threats to aviation, and should be avoided.

Non-convective turbulence poses another major aviation hazard, and all aircraft are vulnerable to turbulent motions in one way or another. Non-convective turbulence can occur at any altitude, and is often experienced in clear skies, known as clear-air turbulence. The effects of turbulence range from a jostling of the aircraft that is mildly discomforting for the passengers and crew members, to sudden accelerations that can result in serious injury and temporary loss of aircraft control. Turbulence can be the cause of flight delays, resulting in major impact on the efficiency of flight operations (Kulesa, 2003). Wake turbulence is another form of non-convective turbulence and is found at all aerodromes. This type of turbulence is a result of the vortices formed in the wake of an aircraft (WMO, 2007). Due to this phenomenon, there must be a separation time between two aircrafts in the wake of one another. This separation time depends on the aircraft type, as wake turbulence is a function of the weight, size and the aerodynamic properties of an aircraft (WMO, 2007).

Another type of weather hazard to aviation is that of low cloud ceilings and poor visibility. Pilots who are not rated for such conditions, or aircraft that are not equipped with the necessary instrumentation, should not encounter these conditions. An extreme reduction in visibility, such as that associated with fog, can have a profound effect upon air transportation (Mitchell & Suckling, 1987). The degree to which an airline would be affected by poor visibility depends largely on its technological capabilities and the airport's Instrument Landing System (ILS). However, despite modern equipment and systems, there are still limitations in ground traffic control, and as a result, the time between two aircraft movements must be enlarged during times of poor visibility (Möller *et al.*, 2001). Also, ground operations such as baggage and refuelling may also be affected by poor visibility, and vehicular movement during fog conditions will be slowed. Therefore, these conditions can lead to numerous airborne and ground delays, often resulting in cancellations, diversions and missed connections (Kulesa, 2003).

Aircraft on the ground during periods of freezing precipitation and other icing conditions are susceptible to the build-up of ice on the control surfaces, instrument orifices, propellers, and engine inlets (Kulesa, 2003). Aircrafts moving along taxiway and runway surfaces in standing water with near-freezing conditions are also susceptible to surface icing, even after precipitation has ceased. Even a very small amount of ice on a wing surface can increase drag and reduce airplane lift by 25% (Kulesa, 2003). Runways and taxiways can also become slippery from snow accumulation or icing, (Mahapatra, 1991) and can significantly degrade braking action. Snow accumulations can also obscure runway lights and markings (WMO, 2007). Therefore, ice or snow on runways, taxiways, and aircraft must undergo de-icing, often resulting in delays and airport operational capacities can be sharply reduced (Kulesa, 2003). Even slight rates of snowfall can have a serious effect on visibility (WMO, 2007).

Prevailing winds is another factor which can limit airport capacity (Klein *et al*., 2009). Airports with closely-spaced parallel or crossing runways are especially sensitive to wind (Klein *et al*., 2009). Even if the wind is not particularly strong, but comes from a certain direction, it can cause a cross-wind which can lead to a suboptimal runway configuration at the airport (Klein *et al*., 2009). Changes in wind direction can also lead to a change in runway use, leading to delays.

Before take-off, calculations need to be done in order to determine the acceptable weight of the aircraft. The load amount that an aircraft can take-off with depends on the air temperature, the wind vector and the atmospheric pressure. Aircraft performance is degraded under conditions of high temperatures and low density (WMO, 2007). A pilot or airline will typically use 'Take-Off Data' that a designated weather centre will prepare for the aerodrome. This data is a forecast of the above mentioned weather variables that is then used to calculate an acceptable payload. However, if the forecast of any of these variables become significantly out of sync with the actual weather conditions, delays can occur. An aircraft that is loaded and ready for take-off must either wait for conditions to become more favourable, for example waiting for the temperature to drop by a degree or two, as often is the case, or the airline must offload cargo to an acceptable take-off weight. Either way, this can cause significant delays.

Rain is often a meteorological condition that is overlooked as an aviation hazard. However, rain can result in unfavourable flying conditions, often yielding delays. Firstly, rainfall can cause a significant reduction in visibility, often affecting VFR flying. Rainfall also results in wet runways, which will influence an aircraft's take-off and landing performance. If a runway receives over 3 mm of accumulated water, an aircraft will encounter the 'hydroplaning' or 'aquaplaning' phenomenon (Wan & Wu, 2004). This phenomenon leads to an increase in the likelihood of an aircraft sliding, and ultimately dramatically increasing the required runway length for take-off or landing (Wan & Wu, 2004). Research by Wan & Wu (2004) reveals results of significant aerodynamic performance loss when encountering heavy rain. Rainfall can also effect ground operations such as baggage handling, catering etc. Heavy rain will slow all vehicular movement and foot traffic on the airfield.

1.4. Aims and Objectives of the Study

The aim of the study is to produce a comprehensive understanding and examination of the weather that impacts aviation activities, with specific reference to aviation delays, at a significant location, namely O.R. Tambo International Airport, South Africa. By applying the gathered geographical knowledge, recommendations can be formulated to reduce the impacts of weather on the sector, with a key reference to weather forecasting, in order to assist with the operations at the airport.

The study has the following objectives:

1.) To conduct an examination of the actual weather that occurred at ORTIA, and the surrounding region, over the study period (i.e. 2010 to 2013)
2.) To analyse the delay incidents associated with weather phenomena over time
3.) To analyse the delay hours associated with weather phenomena
4.) To establish a temporal (diurnal and monthly) analysis of the weather-related delays
5.) To analyse the weather forecast accuracy over the study period
6.) To develop a weather impact index for ORTIA
7.) To develop recommendations for delay reduction at ORTIA

Chapter 2: Literature Review

Weather impact studies at airports have been done predominantly in the US (Robinson, 1989; Mitchell & Suckling, 1987; Evans, 1995 & 1997; Allan *et al*., 2001;Klein *et al*. 2009; Reynolds *et al*., 2012; Kulesa, 2003) with fewer similar studies in Europe (Sasse&Hauf, 2003; Pejovic *et al.,* 2009). There has been no such research conducted in Africa, including South Africa. This literature review will examine some of these key studies, giving an overview of the research and some of the key findings. Additionally, two studies have been included with specific reference to weather mitigation.

Robinson (1989) analysed the influence of weather on flight operations at Atlanta Hartsfield International Airport, U.S.A. Data was collected from three years, 1977, 1978 and 1983. Results revealed that weather induced delays at this airport cost one airline US$6 million annually. The study examined weather-related delays at various phases of aircraft operation namely taxi-in, taxi-out, airborne and flight preparation stages. The adverse weather was categorised into specific weather types i.e. heavy fog, fog, smoke and haze, and thunderstorms. The time and duration of each weather event was also determined. The study compared 'clear weather day' delays to weather-related delays. Clear weather days were defined as days with no rain, a minimum temperature of above freezing and no weather types as mentioned above. The clear weather day data created a baseline upon which the effects of weather induced delays could be determined. The mean and standard deviation for each weather-related delay was determined and a Student's *t*-test was used to assess the significance of the variation from the clear day values (Robinson, 1989). It was found that taxi-in weather delays were mostly due to fog, whereas taxi-out weather delays were mostly due to thunderstorms (Robinson, 1989). Both fog and thunderstorms created significant delays in the airborne flight phase which can be attributed to landing problems. The weather-related aircraft preparation delays were associated mainly with fog, as fog would create a visibility problem in servicing aircraft (Robinson, 1989). Thunderstorms did also contribute to these delays, however only a small number of aircraft preparation operations were affected during the short time of the storm. During the three year analysis of Robinson (1989), three major snowstorms occurred at Atlanta Hartsfield International Airport. Due to this small sample size, the events were considered separately to the other weather-related delays. Two of the three snowstorm events occurred in the early morning, allowing for cancellation of flights and resulting in the delay pattern to be similar to that of clear days. However, the third snowstorm event occurred rapidly, resulting in little forecast lead time, and daily operations were well underway, with inbound aircraft already en-route, resulting in numerous delays (Robinson, 1989).

The research also examined the economic consequences of weather events. It was found that the total excess daily delays due to weather ranged from 450 minutes when only haze was present to over 2500 minutes due to heavy fog (Robinson, 1989). Robinson (1989) furthermore states the total operating cost of a typical jet airliner such as a Boeing 727 to be about US$37 per minute, thence the later type delays increase operating costs by US$92 000 for a single day. Robinson (1989) furthermore concludes that over 165 000 minutes of delay can be attributed to the weather annually, costing an airline in excess of US$ 6 million in annual operating expenses at Atlanta. Airborne weather-related delays decreased by 30% over the three years that were analysed, and Robinson (1989) suggests that improvements in forecasts over the three years can be responsible for at least 10% of these improvements, therefore saving at least US$1.5 million per year.

Mitchell & Suckling, 1987, examined the impact of winter fog on commercial air transportation at Sacramento Metropolitan Airport, California. Sacramento experiences a considerable amount of fog in the months of December and January, with an average of 9 and 10 days of fog respectively, often characterised by long periods of continuous fog (Mitchell & Suckling, 1987). The research determined the number of cancelled, diverted, or delayed flights during the December 1984 to January 1985 fog season. During this period, 11% of all scheduled flights were cancelled, diverted or delayed due to fog-impaired visibility conditions (Mitchell & Suckling, 1987). During this period, 21 severely foggy days were identified, which resulted in 23.1% of affected flights during these days. Emory Air Freight experienced 8 delayed flights out of 21 flights during January 1985. This resulted in the company reverting to trucking their freight during the fog season, instead of using air transportation. Mitchell & Suckling (1987) further investigated fog impacts on general aviation at Sacramento Executive Airport. Due to the smaller nature and type of flights that occur at this airport, statistics on flight delays, diversions and cancellations did not exit, however records on daily fuel loading were used. The effects of fog were determined by means of comparing average number of fuel loadings on fog days and non-fog days using the Student's *t*-test (Mitchell & Suckling, 1987). It was found that fuel loadings were on average 48% less on fog days than on non-fog days. This displays the profound effect of fog on general aviation activities. The paper shows how fog can negatively influence both commercial and general airport operations, as displayed at

Sacramento Metropolitan Airport and Sacramento Executive Airport, respectively. When comparing the two airports, the impact of fog at Sacramento Executive Airport was far greater due to the landing system at the airport, and the type of aircraft using the airport. Executive's runway number 2 is equipped with an instrument landing system that allows for landings and take-offs with 0.8 km visibility (Category I instrumentation). However, runway number 1 is not equipped with such a landing system, and thus normal flight operations require 5 km visibility. Both runways at Executive Airport do not meet the sophistication that Metropolitan Airport has with the minimum runway visibility of 365 m (Category II instrumentation). Equipment to improve the minimum runway visibility requirement at Executive Airport was not planned. Capital investment in on-board and ground-based instrument landing systems can overcome the problems associated with fog as was the endeavour at Sacramento Metropolitan Airport. However, due to the nature of the airport, most aircraft operators would not make such an investment. Therefore, no mitigation techniques were planned, and the fog problem will most likely persist indefinitely. Metropolitan Airport is currently upgrading its instrument landing system to Category III (which would allow for operations in zero visibility). This would completely mitigate the fog problem. By contrast, the Sacramento Executive Airport is profoundly affected by fog, and according to airport management, the problem will not be mitigated in the foreseeable future due to the high costs of advanced avionic systems. The two Sacramento airports show the effects of adverse weather and subsequent mitigation methods to address the problem.

The percentage of flight delays at New York's Newark International Airport ranks amongst the highest of all airports in the USA, with the vast majority of these delays being attributed to adverse weather. Due to this, Allan *et al*. (2001) investigated two specific airport delay factors, namely convective weather occurring away from the airport's location, and high winds occurring in otherwise fair weather, factors which had not been considered before. The study used data covering the period September 1998 through to August 2001. It was established that gate and taxi-out delays accounted for the largest portion of airport delays, particularly from convective weather. It was found that in general, convective weather poses a more difficult problem for the aviation industry than low cloud ceilings or high surface winds, because convection not only affects the departure and arrival frequency, but also flight routes in the region (Allan *et al*., 2001). Convective weather both inside and outside Newark International Airport's airspace accounted for approximately 41% of all arrival delays. Low cloud ceiling and poor visibility was ranked as the second category of weather to effect delays, and high wind days ranked third on the list in terms of average delay per event.

Sasse&Hauf (2003) investigated the impact of thunderstorms on flight landing operations at Frankfurt Airport, Germany. The study compared days without thunderstorms at Frankfurt Airport to days when thunderstorms passed over the airport region. Five thunderstorm days and five non-thunderstorm days were selected in the summer months of the years 1997 and 1998 (Sasse&Hauf, 2003). The difference in delay times between a thunderstorm day and a non-thunderstorm day was determined on an hourly basis, from hourly flight data obtained from the German ATC authority. Various weather data, provided by The German Weather Service, was used to define the thunderstorm days and the non-thunderstorm days. Each selected event was analysed. Results showed that for the 10 thunderstorm days selected, there was a clear increase in delay minutes by a certain factor. This factor depends on the intensity and duration of the thunderstorm event, and the instant capacity of the airport. For the non-thunderstorm delay days, a linear relationship was found between delay and the number of aircraft, whereas for the thunderstorm days, a non-linear relationship was found (Sasse&Hauf, 2003). The research concluded that of the 10 thunderstorm events selected, 100 arriving aircraft were impacted, resulting in 1000 total delay minutes, approximately 750 minutes more than the non-thunderstorm delay days (Sasse&Hauf, 2003).

Klein *et al*. (2009) investigated the role that terminal weather forecast accuracy has on air traffic arrival delays in the U.S. due to inclement weather. The objective of the research was to estimate avoidable delays and costs that can be attributed to terminal weather forecast inaccuracy. The study focused on 35 commercial U.S. airports with significant activity during 2008. Four different hourly arrival rates were compared, namely the scheduled arrival rate, the actual arrival rate, a model-generated arrival rate based on actual weather data, and a model-generated arrival rate based on forecast weather data. Analysis of the relationship between these four different arrival rates can provide an indication of avoidable delays. From these computations, an estimate of the benefit pool of improved terminal weather forecast accuracy was given. Results revealed that there was 81,429 hours of arrival delays during 2008 that were indeed avoidable, yielding an avoidable cost of over US$258 million (Klein *et al.*, 2009). The percentage of avoidable delays attributable to terminal weather forecast inaccuracy amounted to 12.2% (Klein *et al.*, 2009). The research also established that inaccurate forecasts of low cloud ceilings, visibility and heavy rain was the largest contributor to avoidable delays, followed by significant wind (speed or gusts > 15Kt).

Reynolds *et al*. (2012) investigate how improved forecasts of the clearing time of low clouds over the approach area of San Francisco International Airport (SFO) reduces aircraft arrival delays and provides substantial monetary savings to the airlines. SFO is one of the highest delay airports in the US National Air Space, due to the presence of low-ceiling stratus cloud in the approach zone. SFO has two pairs of closely spaced parallel runways that perform dual approaches to the airport, maximizing arrival rates (Reynolds *et al*., 2012). However, when stratus cloud moves in, the phenomenon can reduce the airport's arrival capacity by half. These delays led to the development of the Marine Stratus Forecast System (MSFS), intended to improve the daily forecast of stratus clearing to help air traffic managers more efficiently manage arrival demand (Reynolds *et al*., 2012). During the warm season, stratus clouds form and dissipate on a daily cycle due to marine air advection, impacting operations on approximately 50-60 days each year. The stratus dissipates between midmorning and early afternoon, coinciding with the morning arrival push of aircraft into the airport. When stratus is forecasted and is expected to persist, traffic managers often implement a Ground Delay Program by holding a portion of upstream aircraft on the ground to reduce the flow of incoming traffic (Reynolds *et al*., 2012). This significantly reduces the risk of excessive airborne holding and diversions. The research examined the benefits of incorporating skilful forecasts, using the MSFS, into the issuance of Ground Delay Programs. It was found that by utilising the current operational MSFS from 2008 to 2010, approximately US$0.85 million had been saved annually (Reynolds *et al*., 2012). It was further examined how applying the Ground Delay Parameters Selection Model (GPSM), an additional 25-30% reduction in delays could have been realised, resulting in US$11 million in potential savings per stratus season.

The Federal Aviation Administration (FAA), the national aviation authority of the U.S.A., operates the Aviation Weather Research Program. This program's goal is to relieve weather impacts on the national airspace's safety, capacity and efficiency (Kulesa, 2003). Part of this program is the National Convective Weather Forecast product, operationally used by the National Weather Service of the US. This product is designed specifically to minimise delays caused by convective weather by providing locations of significant convection one hour in the future, with updates every 5 minutes (Kulesa, 2003). Part of this product includes a one hour terminal convective weather forecast. The product provides an extrapolated position of storms, together with storm growth and decay (Kulesa, 2003). Benefit analysis of the terminal convective weather forecast product was conducted at New York airports (Kennedy, LaGuardia and Newark), and the total benefit was estimated at US$80 million annually for these New York airports (Kulesa, 2003). A national benefit analysis was estimated at US$524 million annually (Kulesa, 2003). Another product that was developed by the Aviation Weather Research Program is the Terminal Ceiling and Visibility Product. This product was specifically designed for San Francisco International Airport, although a national product was also developed. San Francisco International Airport is adversely affected by low clouds and poor visibility due to its location along the coast (Kulesa, 2003). Aircraft are often assigned to holding patterns or are prevented from taking off en-route to the airport until the weather clears. The product entails a 1-6 hour forecast of when conditions will improve and simultaneous parallel approaches can be made to the airport so that the aircraft arrival rate matches the acceptance rate. The benefit analysis of this marine stratus forecast can potentially provide a benefit of US$5.45 million annually in arrival and departure delay savings (Kulesa, 2003). Many other products have been developed by the Aviation Weather Research Program such as the In-Flight Icing Product, the Turbulence Product, the Winter Weather Research Product, the Oceanic Weather Product and the Quality Assessment Product (Kulesa, 2003).

Carn *et al.,* (2009) researched mapping and tracking volcanic eruption clouds for aviation hazard mitigation. The last three decades have shown that all major eruptions produce large amounts of SO_2 allowing volcanic clouds to be tracked long distances from their sources using satellite measurements. Even intermediate-scale eruptions would reach the stratosphere at all latitudes, and thus satellite-based detection of these frequent, smaller eruptions is essential for effective aviation hazard mitigation. Rising volumes of aircraft traffic over the past three decades have led to an increase in the number of aircraft flying in proximity to active volcanoes, aircraft encounters with volcanic eruption clouds, and consequentially an increased awareness of volcanic ash hazards to aviation (Carn *et al.,* 2009). The fine-grained rock, mineral fragments and glass shards found in airborne volcanic ash, are widely acknowledged to be the primary aviation hazard in volcanic clouds. These materials are capable of abrading surfaces of aircraft, disrupting avionics and navigation systems and impairing engine performance. The results of encounters range from minor superficial damage to airframes, to full flame out and engine shutdown. Volcanic clouds are gas-rich with the dominant gases being water vapour, carbon dioxide and sulphur dioxide. Of these gases, SO_2 is by far the easiest to measure using remote sensing techniques (Carn *et al.,* 2009).The concentration of volcanic ash that constitutes a threat to aircraft is currently unknown, and thus, all plumes are regarded as a potential hazard to aviation (Carn *et al.,* 2009). Indeed, many airlines operate a zero tolerance policy with respect to volcanic ash. Operational mitigation of the volcanic ash hazard is typically achieved by tracking airborne ash using satellite sensors. The 'typical' techniques for tracking ash (using IR channels at 11 and 12 μm) can often fail to detect ash if the volcanic ash is opaque (often in the early phase of many eruptions), if there is insufficient thermal contrast between the volcanic cloud and the underlying surface (i.e. if a cold volcanic cloud drifts over snow or ice), or if the ash is encased in ice (Carn *et al.,* 2009). The authors explore recent developments in space-based SO_2 monitoring, and focus on daily, global ultraviolet measurements by the Ozone Monitoring Instrument on NASA's Aura satellite. The Ozone Monitoring Instrument has high sensitivity to SO_2, and thus provides a new tool to detect and track volcanic clouds. The research displays numerous case studies demonstrating the ability of the Ozone Monitoring Instrument and other sensors to track volcanic clouds. The research also highlights these improved mitigation techniques of volcanic cloud hazards to aviation. Carn *et al.,* (2009) propose a future challenge to combine these advanced satellite measurements into an effective aviation hazard warning system as the next step in the mitigation process.

Rose *et al.,* (2007) conducted a benefit-cost analysis of hazard mitigation grants from the Federal Emergency Management Agency (FEMA). Mitigation decreases the losses from natural hazards by reducing the frequency and magnitude of them. In a world of limited resources, the costs of mitigation must be considered. A benefit-cost analysis would be an appropriate tool to use. Billions of dollars are used on programs aimed to mitigate risks from natural hazards. In light of these expenditures, the U.S. Congress directed FEMA to conduct an independent study to assess the future savings resulting from mitigation activities. Three hazards were identified, namely earthquake, flood and wind (including hurricanes, tornados and other windstorms). The authors identified various hazard mitigation benefits such as reduced direct property damage, reduced direct and indirect business interruption loss, reduced environmental damage, reduced other nonmarket damage, reduced societal losses and reduced emergency response (Rose *et al.,* 2007). FEMA recognised the value of loss estimation modelling as a key hazard mitigation tool. The organisation consequently developed a standardised loss estimation model called Hazards US-Multihazard which was used extensively in the study. It was found that according to standard benefit-cost analysis, earthquake project grants are cost effective, with a ratio of 1.4:1. Thus, earthquake projects are estimated to save $1.40 in reduced future losses for every $1 spent. Results showed that benefit-cost analysis for wind project grants is a ratio of 4.7:1. Thus, every $1 spent on wind project grants is estimated to save almost $5. Similarly, the benefit-cost ratio for flood project mitigation activities is 4.8:1, i.e. every $1 spent on flood project grants is estimated to save almost $5. The conclusion of the research was that the present value net benefits to society from 5,479 FEMA grants between mid-1993 and mid-2003 for flood, wind and earthquake hazard mitigation is $10.5 billion, and thus Americans benefit greatly from FEMA's investment in adverse weather mitigation (Rose *et al.,* 2007).

These highlighted studies, ranging from 1987 to 2012, display how adverse weather has always been a significant factor for aviation operations at major international airports, and still is today. The studies show how delays due to adverse weather can cost airlines substantial monetary amounts. Improved weather forecasts, as part of a mitigation plan, have the potential to reduce these costs significantly. Once the type of weather phenomena that causes delays has been established, specific weather programs that specifically address the identified phenomena can be implemented, in order to aid in the forecast.

Chapter 3: Study Area and Methodology

3.1 Study Area

3.1.1 Background

O.R. Tambo International Airport (ORTIA)is located at 26º 08’ 01.30”S; 28º 14’ 32.34”E, at an altitude of 1694 m (5,558 feet) above mean sea level. It is situated 20 km east-north-east of the city of Johannesburg and 40 km south of Pretoria. The airport opened on 1 September 1953, and has become the busiest airport in Africa. Similar to other international airports, ORTIA has two distinct morning and evening peaks. The low demand hours are between 07:00 in the morning until 19:00 in the evening (Tilana, 2011). It has the capacity to handle up to 28 million passengers annually, with a current demand of 51 aircraft movements per peak hour, and 40 aircraft movements per non-peak hour (Tilana, 2011). This demand is expected to grow to approximately 80 peak hour movements and 65 non-peak hour movements by the year 2022 (Tilana, 2011). ORTIA is classified as a Category II airport, which permits flight operations in reduced horizontal visibilities as low as 300 m.

3.1.2 The Runways

ORTIA has two parallel north-south runways. The western runway, 03L/21R is over 4400 m long, and the eastern runway, 03R/21L is 3400 m long. Due to the high altitude of the airport, and hence thinner air, the western runway is one of the world’s longest international airport runways. The runways are equipped with Instrument Landing Systems (ILS) and Approach Lighting Systems. Weather readings of temperature, wind speed and direction, humidity, rainfall, cloud height and Runway Visual Range (RVR) are recorded next to the runway threshold of runway 03L. Temperature, RVR, wind speed and direction are also recorded at the thresholds of runways 03R, 21L and 21R.Furthermore, RVR is also captured at the centre point of both runways (SAWS, 2012).

Figure 3: Aerial view of the runways at O.R. Tambo International Airport (Earth Science and Remote Sensing Unit).

3.1.3 Weather Variables

3.1.3.1 Surface Winds

Surface winds from all directions occur at the airfield of ORTIA during the year, depending on the synoptic situation, however northerly to north-westerly winds tend to dominate the area. The average hourly wind speed is approximately 4,2 m/s (SAWS, 2012). Wind speeds display a definite diurnal variation, with calmer winds at night which rise during the morning to reach a maximum during the early afternoon. Stronger winds generally occur in summer during the late afternoon, and are mainly associated with thunderstorms.

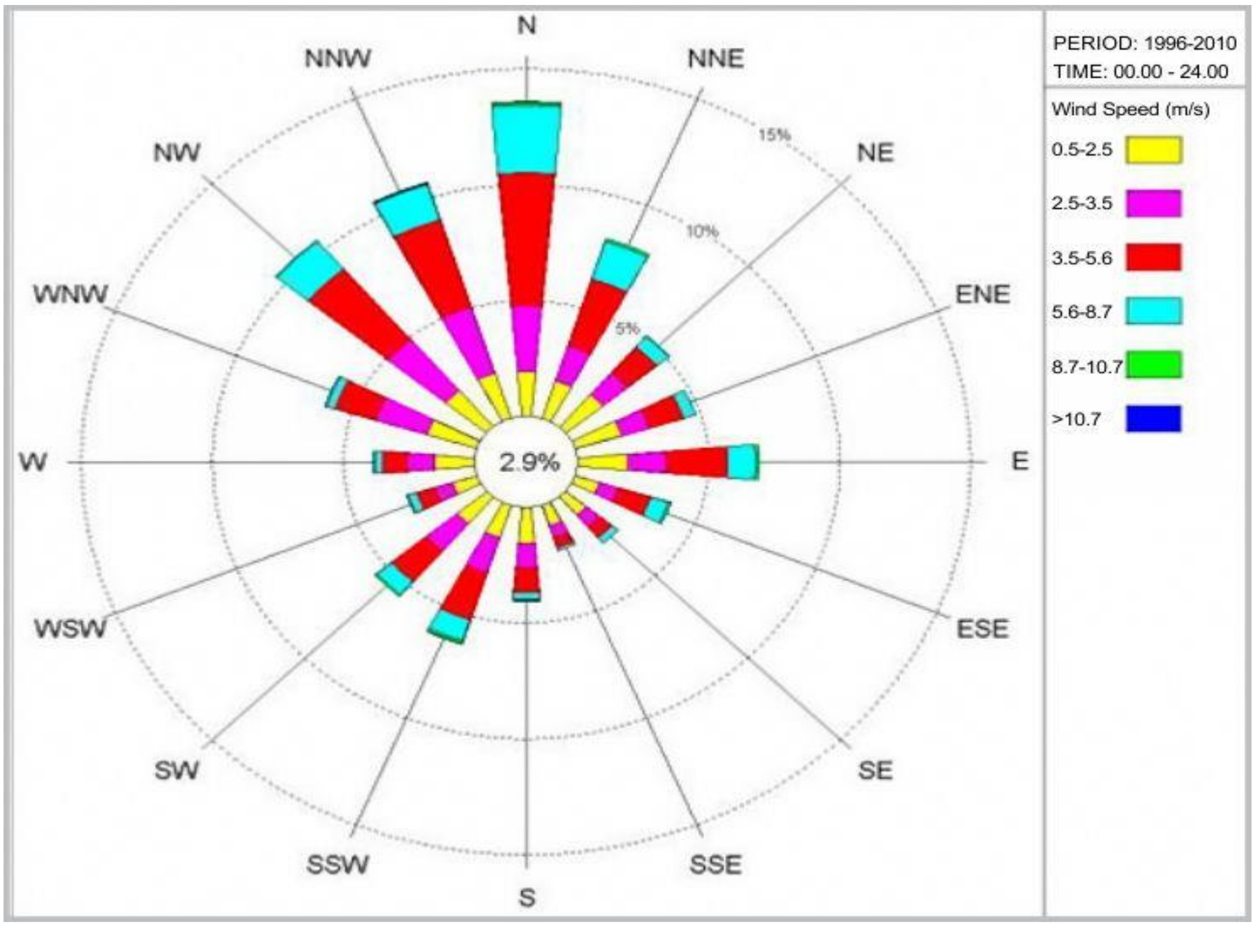

Figure 4: Wind rose for the average annual wind at O.R. Tambo International Airport (SAWS, 2012).

3.1.3.2 Visibility

Fog, mist, haze and smog are all phenomena that can lead to a reduction in visibility at the airport. Both advection and radiation fog occurs at ORTIA with an average occurrence of around two to three days per month. March and April have the greatest fog frequencies of around four to five days per month (SAWS, 2012). Advection fog usually rolls in from the east and north-east, due to ridging anticyclones. Low cloud is often advected into the aerodrome and is observed as fog due to the high altitude of Johannesburg. The frequency of fog is greatest between 04:00 am and 07:00 am in summer, and between 05:00 am and 08:00 am in winter. Fog typically starts clearing about an hour after sunrise and is rare to persist after 10:00 am (SAWS, 2012).

ORTIA is located within a built up, mainly industrial, urban area, and, therefore, is prone to smog. Smoke and other pollutants in the area often get ‘trapped’ near the surface of the ground due to temperature inversions that generally occur during winter in the early morning. The temperature inversion usually ‘breaks’ after sunrise due to surface heating, leading to improved visibilities.

3.1.3.3 Low Cloud

Clouds with low bases (generally below 2000 m) such as Stratus and Stratocumulus clouds, can pose significant problems for low flying aircrafts which are VFR rated. The incidence of low clouds at ORTIA is high, generally due to the high altitude of the airport. Most low clouds at the airfield form between midnight and 08:00 am, with a clear trend for cloud bases to be higher after 06:00 am (SAWS, 2012). More than 80% of low cloud clears before noon.

The simultaneous occurrence of low clouds and poor visibility can cause significant aviation complications. ORTIA often experiences this simultaneous occurrence during the early hours of the morning (generally before 07:00 am), during the late-spring, summer and autumn months (SAWS, 2012).

3.1.3.4 Thunderstorms

ORTIA experiences an average of around 80 thunderstorms per year, with around 90% of them occurring between September to April (SAWS, 2012). Many severe thunderstorms, such as squall lines, can impact the airport. These squall lines are commonly aligned from north-west to south-east, and move across the airport from the south-west or south, such as the example found in Figure 5. Thunderstorms at ORTIA usually occur between 14:00 and 22:00, but mostly around 17:00 (SAWS, 2012). Hail is observed on average about 5 days per annum (SAWS, 2012).

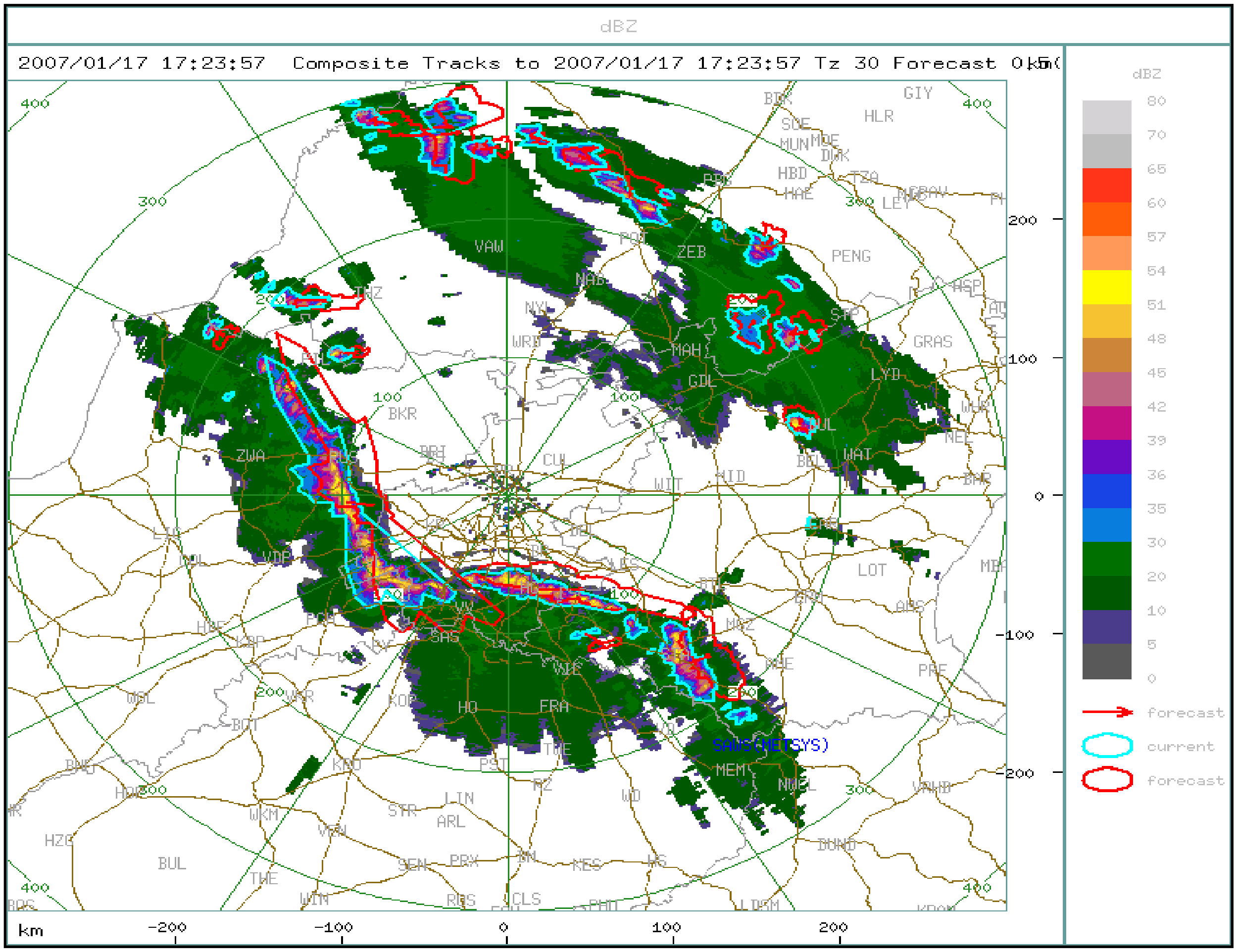

Figure 5: Radar image of a squall line approaching O.R. Tambo International Airport from the south-west and south (Date: 2007/01/17).

3.1.4 Topography

Figures 6 and 7 show that the surrounding areas of ORTIA are mostly built up, urban land cover, with hilly topography. The highest terrain lies within a radius of 40 km to the south of the airport.

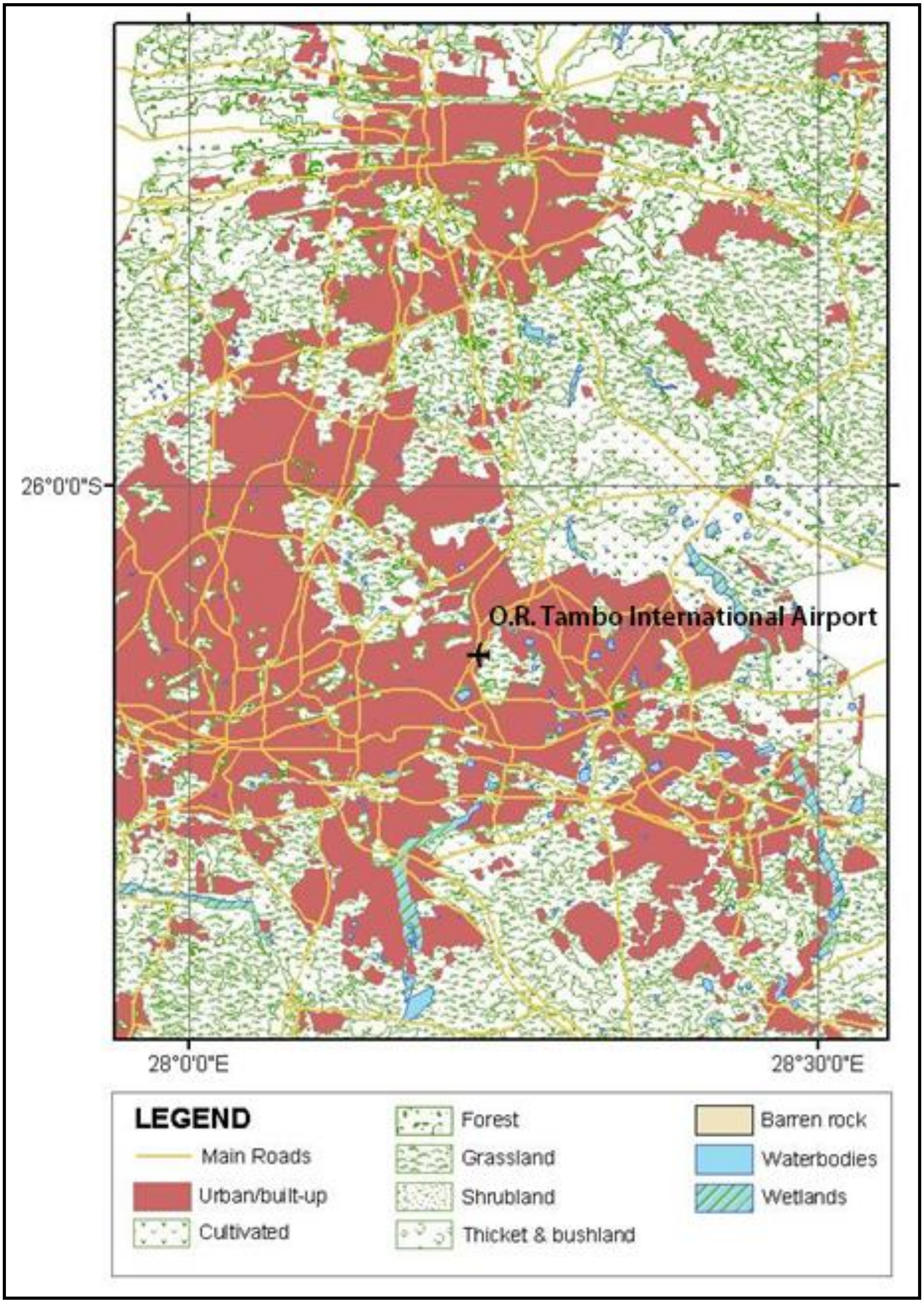

Figure 6: Land cover in the vicinty of O.R. Tambo International Airport (SAWS, 2012).

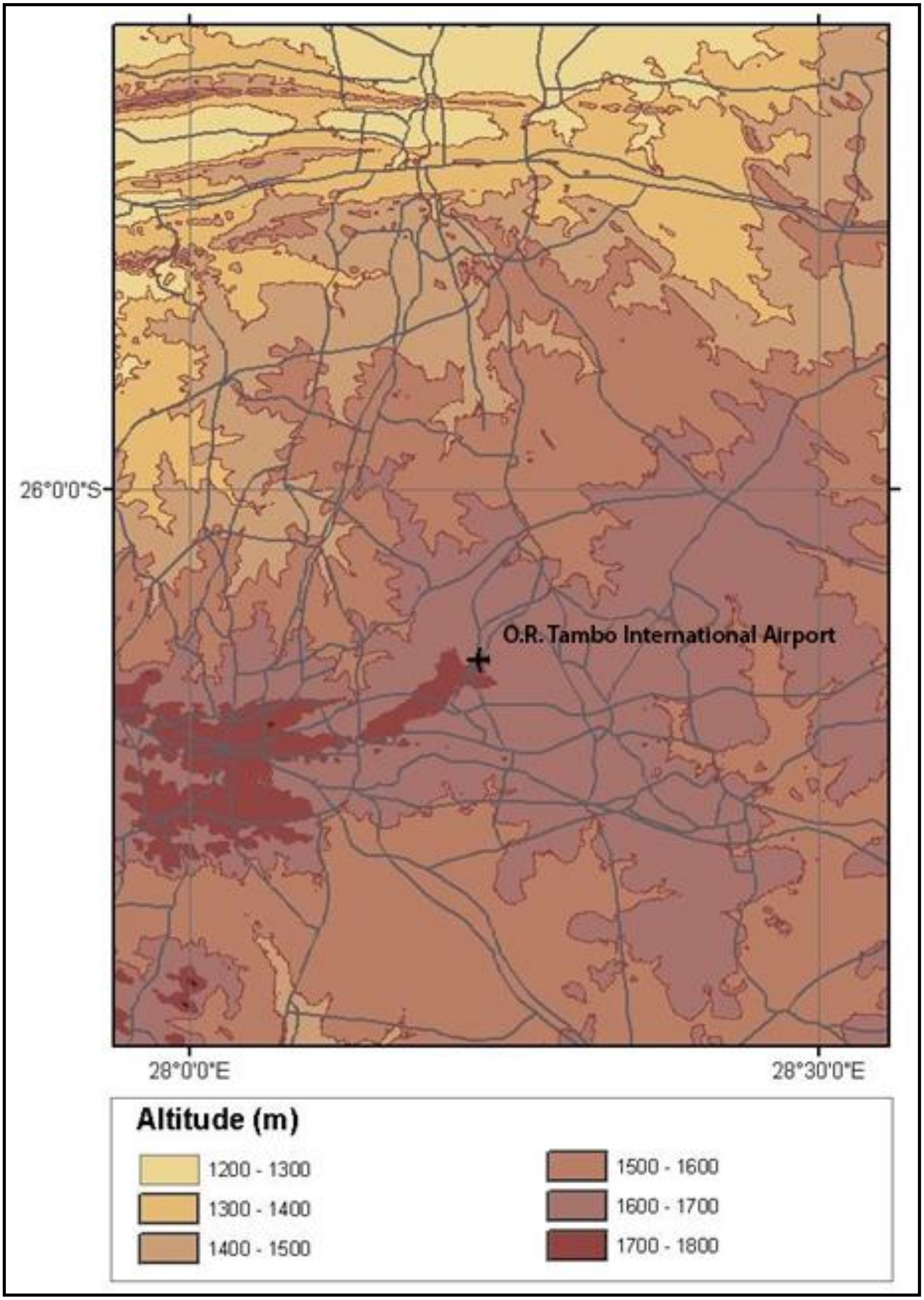

Figure 7: Topography in the vicinty of O.R. Tambo International Airport (SAWS, 2012).

3.2 Methodology

Identifying an aviation delay by comparing the actual flight time to that of the scheduled flight time is the most commonly adopted method in the industry, and is by far the easiest method to quantify. Therefore, the definition of an aviation delay within this paper, can be expressed through this method. Furthermore, the research did not define a minimum delay time, and therefore all delays were examined. This section outlines the methodology used during each step of the delay analysis.

3.2.1 Data

Before 2009, there was no mechanism in place at O. R. Tambo International Airport for measuring and monitoring delays (Tilana, 2011). Since then, the Aviation Management Centre (AMC) at the airport has formulated ways to capture such data. Four years of delay data, from 2010 through to 2013, was obtained from the AMC at ORTIA. The data obtained lists all aircraft ***departure*** delays at the airfield due to weather phenomena. The delay data captured is specific to scheduled flights, and weather delays effecting un-scheduled flights is not in the scope of the research. Only four years of data were readily available in this format. The delay data contained specific information for each delay such as (but not limited to): the carrier code, the flight number, the scheduled date and time, the flight type (i.e. regional, international or domestic), the flight nature (i.e. passenger or cargo), the delay duration, delay comments and the IATA irregularity description. The IATA irregularity description describes the reason for the delay (See Appendix A – IATA Delay Codes (code 7 for weather)).

Table 2 displays the number of weather delays and the associated delay hours for each year for the original data received. It also displays the amount of weather delays and the associated delay hours after filtering the original data (see Methodology section). The filtered dataset was used for the research. The delay data did not capture the specific weather phenomenon that induced the delay. Therefore, historical records from the South African Weather Service(SAWS) were used to enhance the dataset. METARS and TAFS were added to the dataset to link the weather phenomena to the delay (see Methodology section).

Table 2: The amount of weather delays and associated delay hours per year for the original dataset and the filtered dataset.

Year	Original Data		Filtered Data	
	Number of Weather Delay Incidents	Delay Hours	Number of Weather Delay Incidents	Delay Hours
2010	877	424	621	278
2011	852	506	583	288
2012	780	466	574	281
2013	1082	815	824	578

3.2.2 Data Filtering

The research examines what type of weather phenomena at ORTIA causes aviation delays. Therefore, only weather events over the aerodrome itself were examined. The original dataset encompassed delays due to poor weather at ORTIA, poor weather in the vicinity of ORTIA, poor weather en-route to or from ORTIA, late arrival at ORTIA due to poor weather at the departure station, late departure from ORTIA due to poor weather at the destination station, and lastly, delays due to a runway change, resulting from a wind change, at ORTIA.A filtered dataset was therefore needed in order to extract all delays that were captured due to poor weather that did not occur at ORTIA aerodrome itself. The new dataset therefore contained only aviation delays caused by weather at ORTIA. This data filtering process was conducted manually by noting the International Air Transport Association (IATA) irregularity code and the delay comments (see the data section).

3.2.3 METAR and TAF Selection

Once the filtered dataset was completed, METARS and TAFS were selected from The SAWS's historical database. The time of the scheduled flight as per the delay records, was assumed to be the time of the delay due to inclement weather. Therefore, the METAR (or in some instances, the SPECI) that recorded the most inclement weather within two hours before the delay time was captured. Weather that occurred after the delay time was not used. If the METAR did not reflect any poor weather for a specific delay entry, then that entry was deleted from the dataset. Possible reasons for these occurrences are that the delay was captured incorrectly as a weather-related delay, or the poor weather did not occur directly over the aerodrome, and was therefore not reflected in the METAR.

In order to evaluate the weather forecast valid for the time of delay, TAFS were selected and analysed. The TAF that was issued a minimum of six hours before the delay time was selected. Six hours was deemed as a sufficient time for appropriate flight planning and airport capacity planning to occur. Each and every delay was therefore allocated a relevant METAR and TAF, and hence many delay incidents assumed the same METAR and TAF if the incidents were in close proximity to one another.

3.2.4 Weather Categories

In order to identify the type of weather phenomenon that leads to aviation delays, weather categories were designed. Ten main weather categories were identified as significant weather phenomenon influencing aviation operations at ORTIA. Table 3 displays these categories and sub-categories. These categories were selected due to the hazards that they pose to aviation as outlined in the background section.

Often, more than one type of weather is reported in a single observation report. In order to simplify the delay analysis, a hierarchy method was implemented. The weather categories as listed in Table 3 are in order of importance. Therefore, if more than one type of weather was reported in a METAR, the weather type categorised as most significant would have been analysed. For example, if CB and TCU were reported in a single METAR, the delay would have been categorised as a CB event. The categories “rain”, “mist” and “rain and mist”, were categorised separately. The purpose of this was to identify the effect of each phenomenon individually.

It is well documented that convective cloud, specifically thunderstorms, is a significant aviation hazard. In light of this, sub-categories were formulated for both the CB category (category 1) and TCU category (category 2), in order to analyse these phenomena further. Within these sub-categories, reduction in horizontal visibility was examined. If more than one visibility was reported in the METAR, the worst visibility was captured for analysis. Each METAR representing the aircraft delay was therefore categorised as per Table 3, using Excel programming.

Table 3: Weather phenomenon categories and sub-categories.

Main Category	Sub-Category	Comments
1.) Cumulonimbus (CB) Cloud	1.1.) CB with Thunderstorm (TS) 1.1.1.) CB with TS, no precipitation 1.1.2.) CB with TS, precipitation, no reduction in visibility 1.1.3.) CB with TS, precipitation, and a reduction in visibility: 1.1.3.1.) < 1000 m 1.1.3.2.) 1000 m - < 3000 m 1.1.3.3.) 3000 m - 5000 m 1.2.) CB without Thunderstorm (TS) 1.2.1.) CB without TS, no precipitation 1.2.2.) CB without TS, precipitation, no reduction in visibility 1.2.3.) CB without TS, precipitation, and a reduction in visibility: 1.2.3.1.) < 1000 m 1.2.3.2.) 1000 m - < 3000 m 1.2.3.3.) 3000 m - 5000 m	• Strong winds (20kt or greater), may or may not have been reported with the CB cloud.
2.) Towering Cumulus (TCU) Cloud	2.1.) TCU, no precipitation 2.2.) TCU, precipitation, no reduction in visibility 2.3.) TCU, precipitation, and a reduction in visibility: 2.3.1.) < 1000 m 2.3.2.) 1000 m - < 3000 m 2.3.3.) 3000 m - 5000 m	
3.) Fog		
4.) Mist		• Low cloud may or may not have been reported with the mist.
5.) Rain		• Rainfall not associated with any convective cloud i.e. CB or TCU. • Drizzle is included in this category.
6.) Rain and Mist		• Drizzle reported with mist is included in this category.
7.) Wind Change		• A wind change causing a runway change.
8.) Icing		• This category includes delays due to: ▪ Removal of runway icing ▪ Aircraft de-Icing ▪ Snow
9.) Temperatures		
10.) Low Cloud		• Only low cloud reported i.e. no reduction in visibility from fog, mist or rainfall.

3.2.5 Temporal Analysis

In order to perform a temporal analysis, the data had to be further categorised into monthly and diurnal categories. The months of the year were used in order to examine monthly frequencies of the delay events. In order to examine the time-of-day when delay events occurred, four diurnal categories were allocated, as per Table 4. The time slots were designed around the morning and evening peaks at ORTIA.

Table 4: The time-of-day categories.

Time Period	**Name of Category**
07:00 – 12:00	Morning Off-Peak
12:00 – 19:00	Afternoon Off-Peak
19:00 – 00:00	Night Peak
00:00 – 07:00	Morning Peak

3.2.6 TAF Evaluation Technique

Each METAR was compared to the selected TAF through a manual comparison, and the forecast was determined either as a hit or a miss. The following criteria were designed and used to classify the TAF as a hit or a miss:

- The time of the inclement weather was correctly forecasted.
- The type of weather as per the main categories of Table 3 was correctly forecasted.
- The forecasted horizontal visibility was in line with Table 5.

This evaluation technique is displayed in Figure 8. As can be seen, if any of the evaluation criteria are not met, the TAF is regarded as a missed forecast.

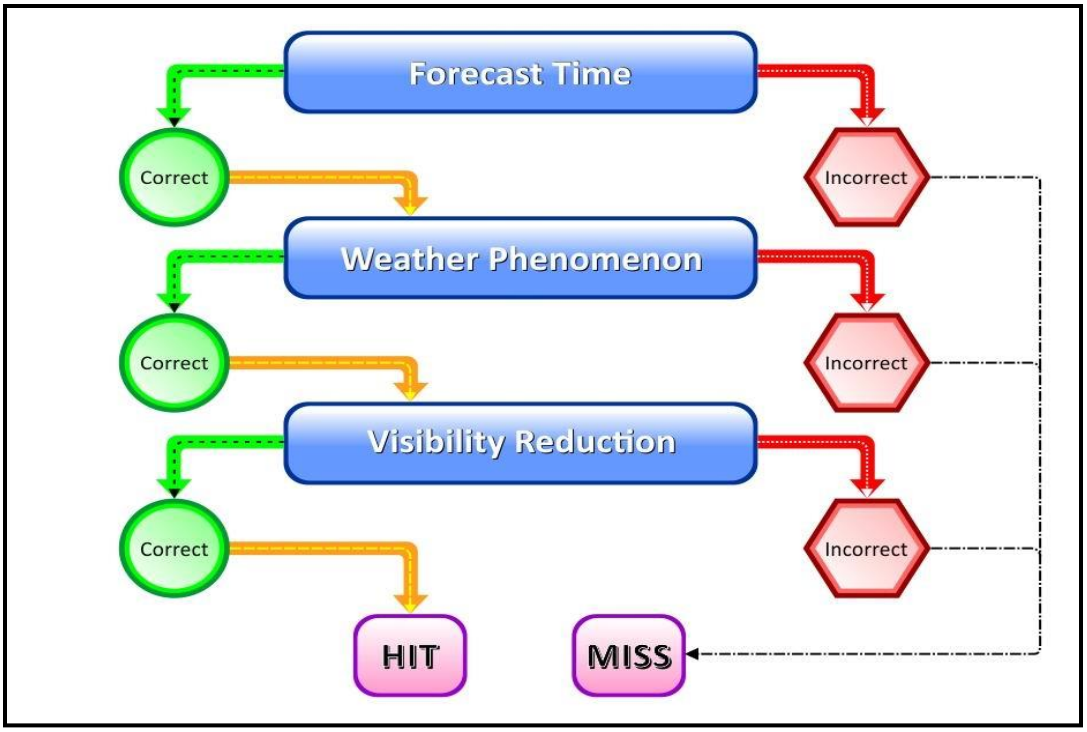

Figure 8: Terminal Aerodrome Forecast (TAF) evaluation technique flow chart.

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 organisations. As per this documentation, the forecast of horizontal visibility should be forecasted within specific ranges, as set out in Table 5. Therefore, if the reported visibility lies within a group that is less than the forecasted visibility, the forecast will be regarded as a missed forecast.

Table 5: Horizontal visibility groups (Adapted from ICAO, 2013).

Horizontal Visibility Groups
150 m – 350 m
350 m – 600 m
600 m – 800 m
800 m – 1500 m
1500 m – 3000 m
3000 m – 5000 m

An over-forecast was classified as a hit. (An over-forecast can be classified as a forecast that projects the weather situation to be worse than that which occurred). An under-forecast was classified as a miss. (An under-forecast can be classified as a forecast that projects the weather situation to be better than that which occurred.)

The TAFS associated with delays due to the categories wind change, icing and temperatures, did not undergo TAF evaluation, and were eliminated from the TAF evaluation dataset. This is due to the fact that hourly temperature and hourly wind forecasts are not relayed through a TAF message. These forecasts are generally relayed through another type of forecast product i.e. “Take-Off Data”, and are therefore not in the scope of this research. Surface icing is not an element that is forecasted for ORTIA aerodrome, and therefore this variable cannot be evaluated. Therefore, in total, 2386 TAFS were evaluated after eliminating 217 TAFS from the dataset, as displayed in Table 6.

Table 6: The number of Terminal Aerodrome Forecasts that were not evaluated and the number that were evaluated per year.

Year	**Number of TAFS Not Evaluated**	**Number of TAFS Evaluated**
2010	65	556
2011	80	503
2012	21	554
2013	51	773
Total	217	2386

3.2.7 Data Analysis

Once all of the data was captured and categorised as above, analysis methods were implemented. Quantitative and statistical analysis was used on the data. A classification method was used (as per Table 3), and therefore a data correlation technique was not implemented, as each variable was analysed individually. The law of averages was used on the data, specifically using the mean as per the following equation:

$$\overline{X} = \frac{\sum X}{n}$$ [Equation 1]

where,

$\overline{X}$ is the symbol for the mean,
Σ is the Greek symbol sigma and denotes to sum or add up,
X refers to each of the individual values that make up the dataset,
n is the number of values that make up the dataset.

The mean was used per weather category over the four years of data, and was used in order to eliminate any extreme conditions within the dataset. Bar graphs were chosen to represent the analysis and data.

Chapter 4: Results and Discussion

4.1. Results

Before reviewing the delay results, an overview of the weather conditions that occurred during the study period must be established in order to determine the general pattern and whether or not the weather was abnormal during the study period. Once an understanding of the background weather conditions is developed, an interpretation of the results can be made. Appendix 2 summarizes the most significant weather that occurred in the general Johannesburg region during the study period.

4.1.1 Weather Variables During the Study Period

Weather conditions, namely the number of thunderstorm days, the number of fog days, the average daily temperature and the recorded rainfall, recorded at ORTIA, over the period 2010 to 2013, together with the climatic average (the average over the period 1961 to 1990) are summarised in Appendix 2. Figure 9 displays the annual number of thunderstorm and fog days reported at ORTIA for the period 2010 to 2013. The horizontal green and yellow lines represent the annual climatic average of 73 thunderstorm days and 35 fog days, respectively. The years 2010 and 2012 experienced above average thunderstorm days, whereas 2011 and 2013 recorded average thunderstorm days. From Table 24 in Appendix 3, January of both 2010 and 2012 had a particularly high number of thunderstorm days, as well as September of 2012 and December of 2010. The number of fog days recorded over the period was well below the average number of fog days, particularly for 2012.

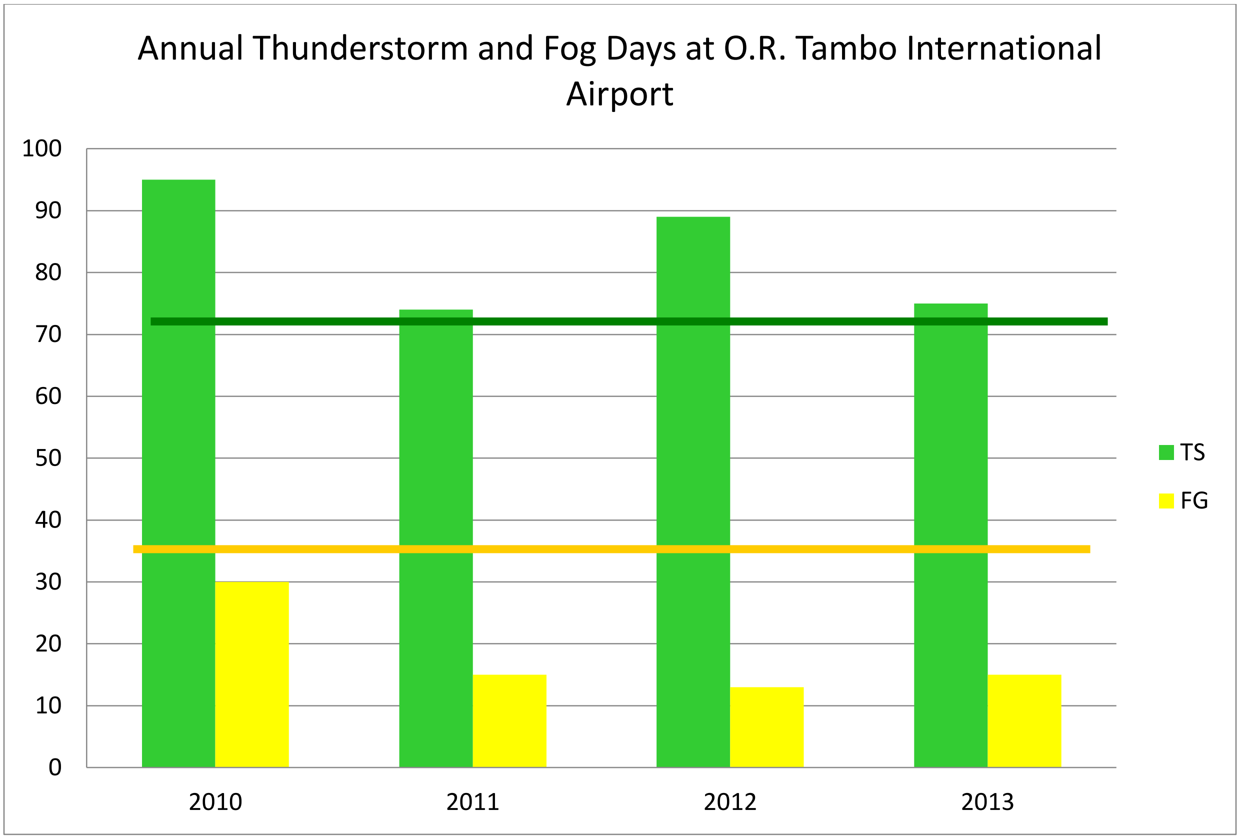

Figure 9: The annual number of thunderstorm (TS) and fog (FG) days reported at O.R. Tambo International Airport for the period 2010 to 2013. The horizontal lines indicate the average number of thunderstorms (green) and fog days (yellow); based on SAWS climate data (1961-1990).

Figure 10 displays the monthly average temperature at ORTIA during the study period, and the climatic average. Referring to Figure 10 and Table 26 in Appendix 3, it can be seen that the study period was, on average, slightly warmer than the climatic average. However, July of 2011 was the coldest month recorded during the period, and was 1°C cooler than the climatic average for that month.

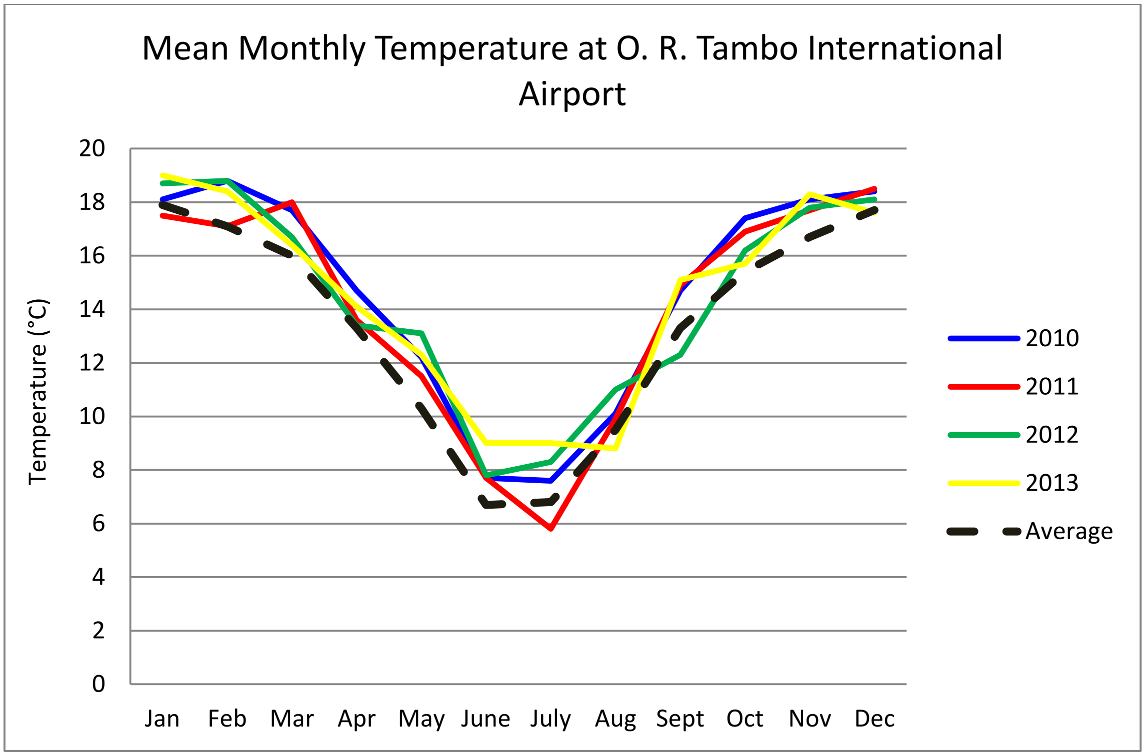

Figure 10: The mean monthly temperature (measured at 0800) at O.R. Tambo International Airport for the period 2010 to 2013 and climatic average based on SAWS climate data (1961-1990).

Figure 11 displays the monthly rainfall that occurred at ORTIA over the study period and the climatic average. As per Table 27 in Appendix 3 and Figure 11, 2010 and 2011 were well above the annual average of 713 mm, with 982 mm and 845 mm respectively. These high rainfall years can be attributed to the La Niña weather cycle phenomenon that occurred over Southern Africa during these years. The year 2012 recorded an annual rainfall of 666 mm, indicating a below average annual rainfall, while 2013 yielded a more average rainfall of 707 mm. January of 2010 was a particularly wet month with a recorded rainfall (269 mm) of more than double the climatic average of that month. Rainfall during this month was the highest recorded during the study period. Widespread and slow-moving thunderstorms, resulting from an intense surface and upper-air trough, were responsible for these dramatic rainfall amounts, with severe thunderstorms effecting ORTIA on the 20th January 2010 (Mduduzi, 2013). Flooding occurred in the Greater Johannesburg Region, resulting in extensive evacuations. Similarly, January of 2011 also received high rainfall amounts (170 mm). During this time, Johannesburg was declared one of many disaster areas as flash floods led to over 100 deaths and at least 8,400 people were displaced from their homes in South Africa (Smith, 2011).

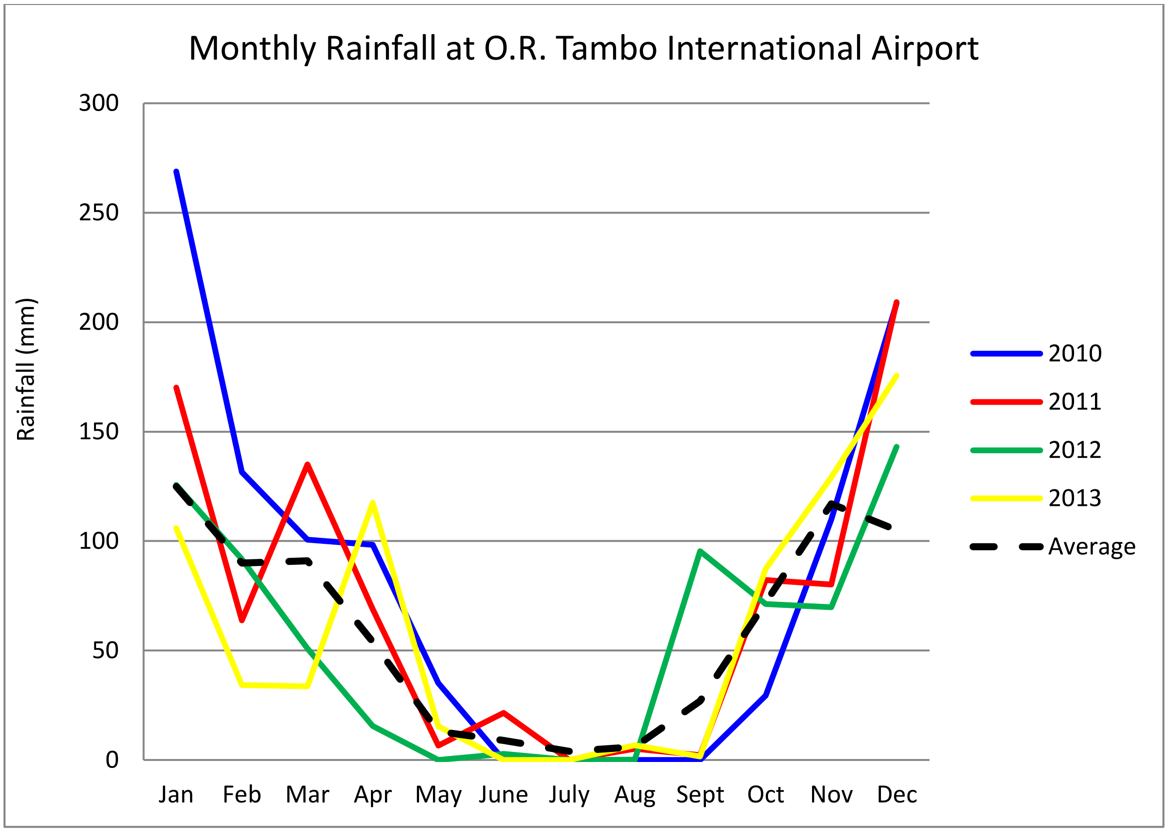

Figure 11: The monthly rainfall at O.R. Tambo International Airport for the period 2010 to 2013 and climatic average; based on SAWS climate data (1961-1990).

4.1.2 Analysis of Delay Incidents

After reviewing the general weather conditions that affected ORTIA during the study period, an analysis of the weather-related delays can now be performed. This section examines the number of delay incidents that occurred and the type of weather phenomenon that led to the delay incident. It should be noted that many delay incidents can occur in one day, and even one weather event can lead to numerous delays. Analysis of the duration of delay and the temporal aspects of the delay are examined later in this section.

The number of delay incidents per weather phenomenon for each year of data, and the overall totals are displayed in Table 7. It also displays the percentage contribution to the annual number of delays and the rank from highest to lowest contribution over the four years. Figure 12 displays the contribution of each year to the overall number of delays over the four-year study period. Over the four-year study period, 2602 weather-related delays occurred at ORTIA, with the year 2013 recording the highest number of delays, namely 824. As has been reviewed, 2013 recorded a below average number of fog days, an average number of thunderstorm days and an average annual rainfall. Therefore, the 10% delay increase from the previous year of 2012 cannot be attributed to an anomalistic weather year. Furthermore, the number of annual aircraft movements steadily declined over the four-year study period. Therefore, this distinct increase in the number of delays during 2013 could possibly show an increasing trend in the number of weather-related delays, however, this trend can only be established with subsequent years of data, and is highly hypothetical.

Table 7: The number of delay incidents per weather phenomenon (and percentage contribution to the overall number of incidents per year) for years 2010 to 2013 with rank from highest to lowest frequency.

Weather Phenomenon	**2010**	**2011**	**2012**	**2013**	**Total/Rank**
CB	383 (61.67%)	349 (59.86%)	412 (71.65%)	**493** (59.83%)	1636 (62.87%)
Fog	**94** (15.14%)	72 (12.35%)	72 (12.52%)	52 (6.31%)	290 (11.15%)
Rain	16 (2.58%)	25 (4.29%)	8 (1.39%)	**124** (15.05%)	173 (6.65%)
Wind Change	59 (9.50%)	43 (7.38%)	13 (2.26%)	41 (4.98%)	156 (6.00%)
TCU	31 (4.99%)	20 (3.43%)	27 (4.70%)	47 (5.70%)	125 (4.80%)
Mist	24 (3.86%)	24 (4.12%)	27 (4.70%)	33 (4.00%)	108 (4.15%)
Icing	6 (0.97%)	**33** (5.66%)	5 (0.87%)	7 (0.85%)	51 (1.96%)
Low Cloud	7 (1.13%)	9 (1.54%)	6 (1.04%)	5 (0.61%)	27 (1.04%)
Rain and Mist	1 (0.16%)	4 (0.69%)	2 (0.35%)	**19** (2.31%)	26 (1%)
Temperature	0 (0%)	4 (0.69%)	3 (0.52%)	3 (0.36%)	10 (0.38%)
Total	621	583	575	824	2602

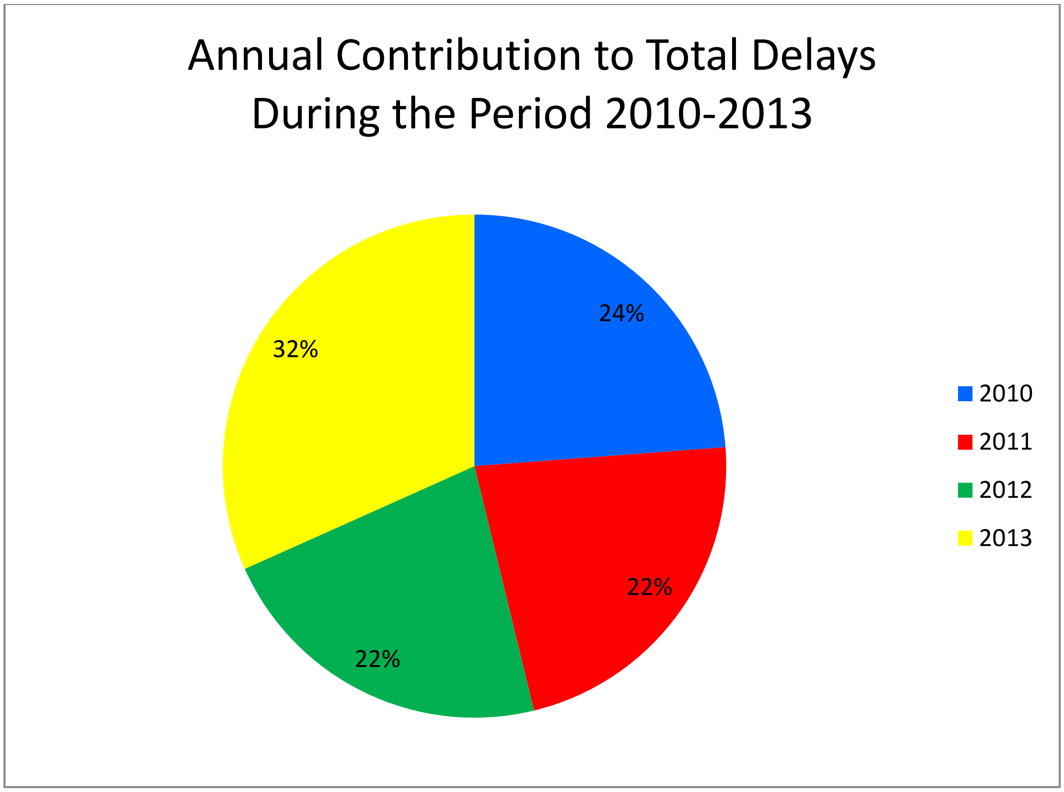

Figure 12: The annual contribution to the total number of delays during the period 2010-2013.

The year 2010 had the second highest number of delays during the four-year study period. This year was, however, an abnormal weather year, with well above average rainfall being recorded. When comparing the data in Table 7, distinctive extremes can be detected, as shown in bold. First, the number of delay incidents due to cumulonimbus clouds (CB) in 2013 was well above the number of incidents of the other years. In fact, there were over 100 more delay incidents due to CBs in 2013 compared to 2010 and 2011, resulting in a 9% increase from 2011. This was unexpected, as 2013 had a below average number of thunderstorm days when compared to 2010 which exceeded the average. Second, 2010 recorded a significantly higher number of delay incidents due to fog than the other years. This is to be expected, as 2010 recorded double the number of fog days than every other year. Another significant observation is the number of delay incidents due to rain and rain and mist during 2013. This year recorded a dramatic difference compared to the other years, however, once again, it only received an average annual rainfall. The reason for this could possibly have been that the number of recorded delays due to these phenomena occurred in a very short time frame, for example over one or two days, and possibly other delay factors occurred simultaneously, resulting in a cumulative delay effect, instead of occurring steadily throughout the year. Lastly, 2011 recorded a marked difference in icing incidents compared to other years. This can be attributed to the fact that 2011 had a relatively cold July month.

The category CB is by far the highest contributor to weather-related delays at ORTIA, followed by fog. Surprisingly, rain (from non-convective cloud), without the influence of other weather phenomenon such as mist or fog, is the third highest contributor to weather-related delays at ORTIA. The influence of high temperatures caused the least amount of weather-related delays over the four years.

4.1.3 Analysis of Delay Hours

Table 8 displays the total number of delay hours caused by each weather phenomenon for each year of data. It can be seen that over the four year study period, 1425 hours of weather-induced delay time was recorded, yielding an average of 356 hours per year, or 14.8 days per year. Therefore, on average, nearly half a month each year is lost due to weather induced delays over the airfield. Expectedly, the rank of each phenomenon is similar to that of Table 7, with the categories CB, fog and rain as the top three highest contributors to delay hours. This is due to the fact that the more incidents per category, the higher the number of delay hours. It is, therefore, important to analyse the average delay time per single delay event in order to establish what type of weather phenomenon is causing the longest delay times during a single delay event.

Table 9 displays the average delay time in minutes per single delay event. The average over the four years was calculated, and the table is displayed from highest average delay time to lowest. Icing has the highest average delay time, per single delay event. On the other end of the scale, a wind change causes the lowest average delay time per single delay event. Note that the categories of mist and rain share the same average delay time. A comparison can now be performed between weather phenomenon causing frequent delay incidents, to weather phenomenon causing large average delay time, as per Table 10. This comparison is significant as it suggests that the weather phenomenon accountable for the most number of weather delay incidents is not necessarily the same phenomena accountable for the highest amount of average delay time.

Table 8: The number of delay hours per weather phenomenon for years 2010 to 2013 (and percentage contribution to the overall number of hours per year) with rank from highest to lowest frequency.

Weather Phenomenon	**2010**	**2011**	**2012**	**2013**	**Total/Rank**
CB	210 (75.54%)	188 (65.28%)	222 (79.00%)	428 (74.05%)	1048 (73.54%)
Fog	25 (8.99%)	29 (10.07%)	24 (8.54%)	14 (2.42%)	92 (6.46%)
Rain	3 (1.08%)	7 (2.43%)	3 (1.07%)	74 (12.80%)	87 (6.11%)
TCU	16 (5.76%)	13 (4.51%)	15 (5.34%)	24 (4.15%)	68 (4.77%)
Icing	6 (2.16%)	22 (7.64%)	2 (0.71%)	15 (2.60%)	45 (3.16%)
Mist	5 (1.80%)	15 (5.21%)	8 (2.85%)	7 (1.21%)	35 (2.46%)
Wind Change	10 (3.60%)	8 (2.78%)	2 (0.71%)	7 (1.21%)	27 (1.89%)
Temperature	0 (0%)	2 (0.69%)	3 (1.07%)	4 (0.69%)	9 (0.63%)
Low Cloud	2 (0.72%)	3 (1.04%)	2 (0.71%)	2 (0.35%)	9 (0.63%)
Rain and Mist	1 (0.36%)	1 (0.35%)	0 (0%)	3 (0.52%)	5 (0.35%)
Total	278	288	281	578	1425

Table 10 reveals that fog and wind changes have the shortest average delay time than any of the other weather phenomenon categorised. However, these two categories rank relatively high as weather phenomenon responsible for the number of delay incidents. Therefore, even though fog and wind changes are accountable for numerous delay incidents (frequency) in a year, on average, the incident is short-lived (duration), and has a short delay time. Alternatively, CBs are responsible for a significant amount of delay incidents and, generally, a significant amount of average delay time. Consequently, CB is the most significant weather phenomenon at ORTIA in terms of weather-induced delays. Interestingly, icing and temperatures appear to be two of the more insignificant weather phenomena when analysing contributions to delay incidents. However these phenomena are the most significant when analysing contributions to average delay time. Table 9 shows that a single icing event causes, on average, a one hour delay. Similarly, even though high temperatures resulting in delays occur very infrequently, they cause, on average, a delay of approximately 50 minutes, yielding a relatively high delay time period.

Table 9: The average number of delay minutes per single weather delay event in order from highest to lowest.

Weather Phenomenon	**2010**	**2011**	**2012**	**2013**	**Average Total Minutes**
Icing	57	39	20	130	61.50
Temperature	none	30	50	72	50.67
CB	33	32	32	52	37.25
TCU	31	38	34	30	33.25
Rain and Mist	53	14	12	8	21.75
Mist	14	37	19	13	20.75
Rain	10	17	20	36	20.75
Low Cloud	14	23	23	22	20.50
Fog	16	24	20	16	19.00
Wind Change	11	10	10	10	10.25

Table 10: A comparison of the weather phenomenon contributing to delay incidents and contributing to delay time, in order of priority.

Weather phenomenon responsible for delay incidents	**Weather phenomenon responsible for average delay time**
CB	Icing
Fog	Temperature
Rain	CB
Wind Change	TCU
TCU	Rain and Mist (one phenomenon)
Mist	Mist and Rain (as two separate phenomena) – joint 6th place
Icing	Low Cloud
Low Cloud	Fog
Rain and Mist	Wind Change
Temperature	

4.1.4 Temporal Analysis

4.1.4.1 Monthly Analysis

The number of delay days in a month and the number of delays in a month differ greatly. Table 11 displays the number of delay days that were recorded per month during the study period and the number of delay incidents recorded per month.

Table 11: The number of delay days and the number of delay incidents per month for the period 2010-2013.

	2010		**2011**		**2012**		**2013**	
Month	Number of Delay Days	Number of Delay Incidents	Number of Delay Days	Number of Delay Incidents	Number of Delay Days	Number of Delay Incidents	Number of Delay Days	Number of Delay Incidents
January	12	66	10	85	10	83	7	39
February	9	42	11	53	10	47	7	39
March	4	11	9	65	10	68	9	85
April	10	65	9	84	4	11	8	72
May	3	36	2	5	4	14	2	3
June	3	12	3	13	0	0	6	12
July	3	12	11	57	3	14	6	51
August	5	22	6	46	4	7	4	5
September	1	15	2	9	9	79	5	11
October	10	60	9	65	10	94	10	160
November	10	190	9	57	9	85	13	224
December	10	90	12	44	11	73	11	123
Total	80	621	93	583	84	575	88	824

Over the four-year period, the annual average is 86 days with delay. The month that recorded the highest number of delay days was November of 2013; with 13 delay days documented. In 2010, January recorded the highest number of delay days, of 12 days, whereas in 2011 and 2012, December had the most number of delay days, of 12 and 11 days respectively. Therefore, it is evident that the period November to January (summer) is most at risk for delay days. Similarly, when reviewing the number of delays per month, the period October to January records the highest number of delays. November of 2013 recorded the highest number of delays in one month, with 224 delays. The average number of delay incidents per month can now be examined from the four years of data. Figure 13 shows the average monthly frequency of delays over the four year period. The months October to December are the months with the highest number of delay incidents on average, with November holding the highest frequency. Based on averages, the month with the least number of aviation delay incidents is June.

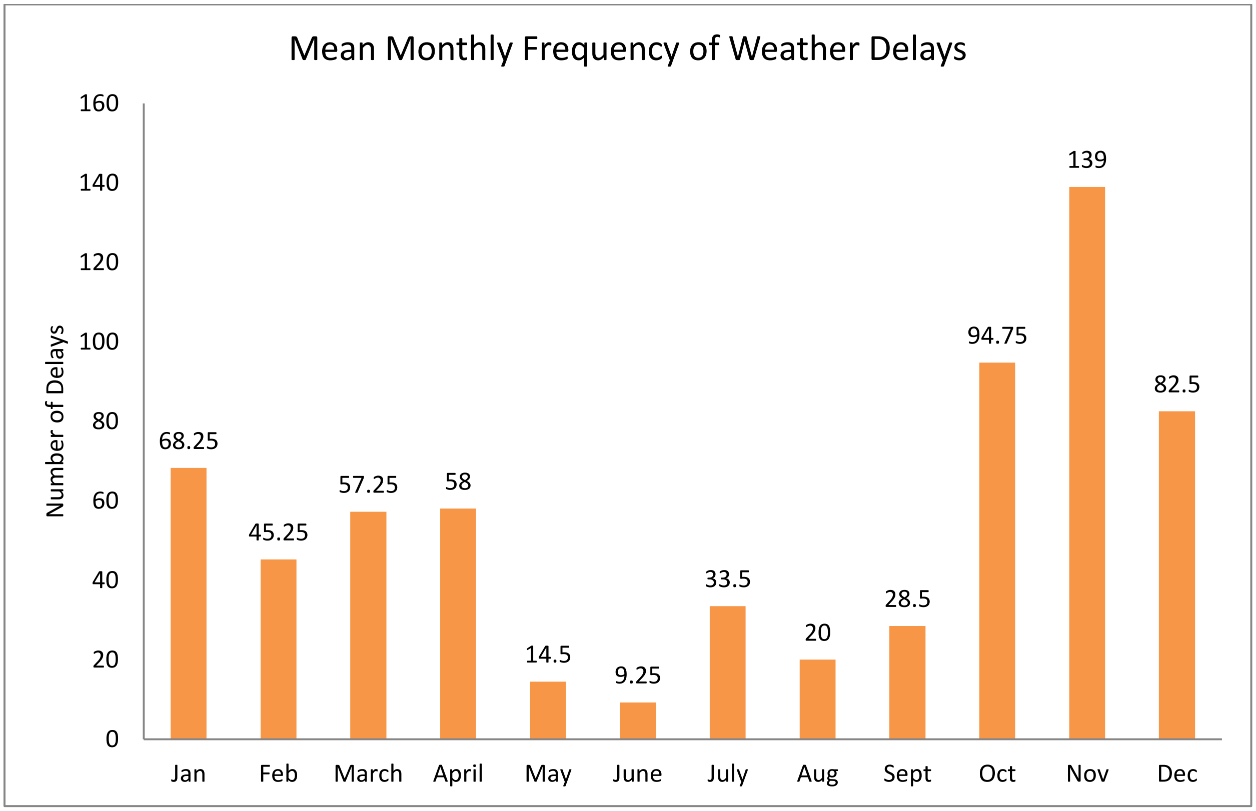

Figure 13: The mean monthly frequency of weather-related delays.

The average monthly frequency of delays can be classified per weather phenomenon. Figure 14 shows the average monthly frequency of weather-related delays per weather phenomenon. According to the data, towering cumulus cloud (TCU) can cause delays during most months of the year, with the exception of June and July. The most frequent months for TCU to cause delays are April and November. Naturally, CBs cause delays most often in the summer months, namely October to January. Fog and mist can cause delays throughout the year; however, they are most common in July. March, April and May are other frequent months for delays due to fog or mist. On average, rain (with no influence of other weather) causes delays most often in October, whereas rain and mist together, cause delays most often during February, March and April. Delay events due to icing occur either in June, July or August, with July having the highest number of events on average. The effects of low cloud can be felt throughout the year, with the exception of May and July, and is most frequent in April.

4.1.4.2 Diurnal Analysis

Table 12 classifies the number of delay incidents into specific time periods of the day for each year of data and the overall totals of the four years. It can be seen that the vast majority of weather-related delays during the entire study period occured during the afternoon off-peak times. The second time frame when most weather-related delays occured is during the morning off-peak period. Therefore, the data shows that 71% off all weather-related delays occured during the least busiest hours at ORTIA, i.e. between 07:00 and 19:00. Thus, the busiest hours at ORTIA, categorised as night peak and morning peak, accounts for only 29% of all weather-related delays.

Table 12: The number of weather-related delay incidents during defined time periods of the day.

Time Period	**2010**	**2011**	**2012**	**2013**	**Totals**
Morning Off-Peak (07:00 – 12:00)	132	147	125	138	542
Afternoon Off-Peak (12:00 – 19:00)	309	269	326	411	1315
Night Peak (19:00 – 24:00)	114	93	61	206	474
Morning Peak (00:00 – 07:00)	66	74	63	69	272

Figure 15 examines the type of weather phenomeona responsible for aviation delays during the four allocated time periods of the day. The figure displays the total delay incidents of the four years of study. It is clear that during the morning off-peak time period (07:00 – 12:00), fog is responsible for the majority of aviation delays, with CBs coming in second. Noteworthy, wind changes is the third most significant weather phenomena during this time period. Therefore, the majority of runway changes occurred due to a wind change, thus inducing delays, take place during the times 07:00 to 12:00.

CBs, as expected, are responsible for the majority of delays during the afternoon off-peak times and night peak times, with more delays during the afternoon times. TCU are more frequent during the afternoon off-peak times than any other time. Surprisingly, rain (not related to convective cloud) occurs more frequently during the afternoon. Of the few isolated events when high temperatures have caused delays, 90% of these events occurred during the afternoon, attributable to the hottest time of the day.

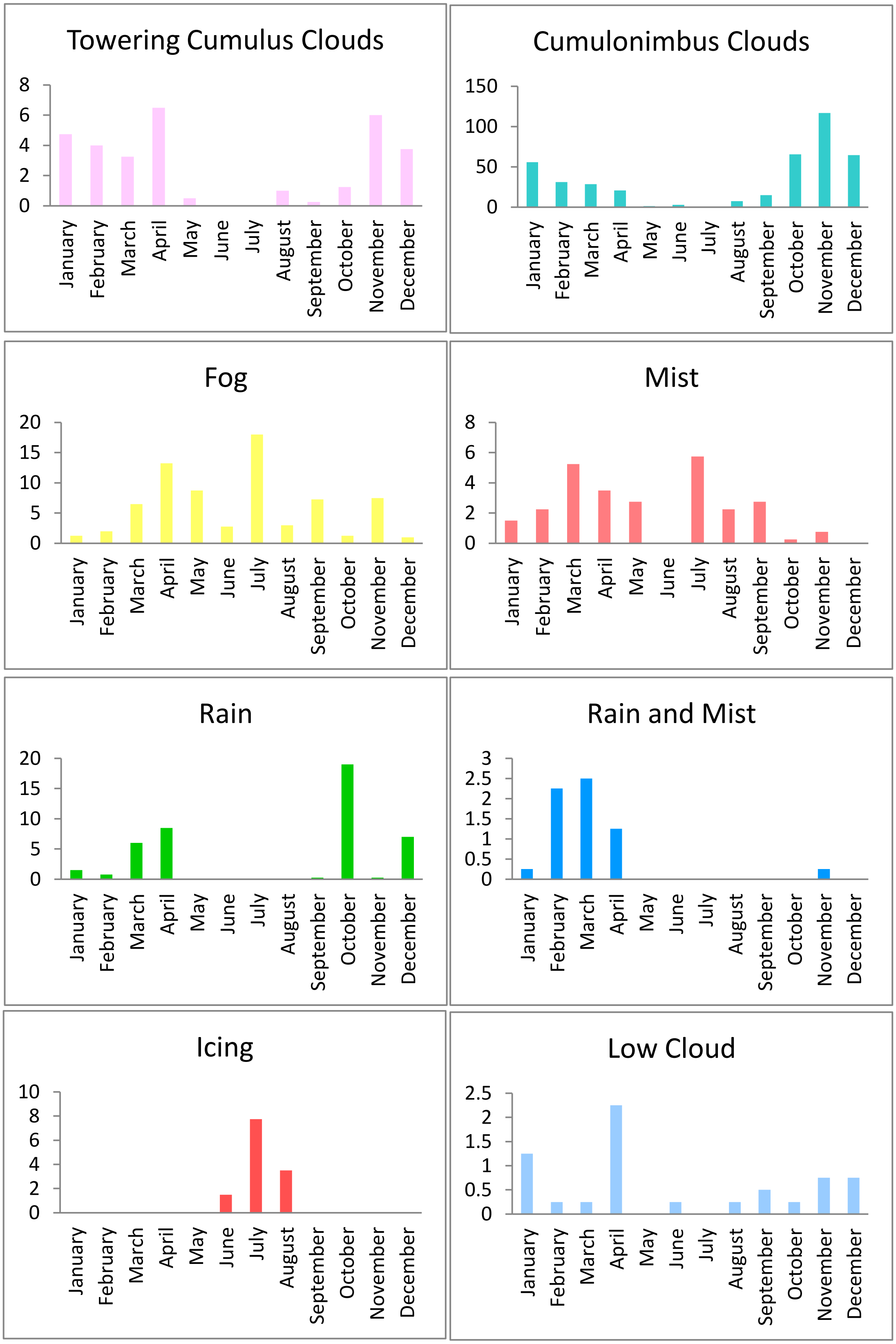

Figure 14: The average monthly frequency of weather-related delays per weather phenomenon.

During the morning peak time period, fog is responsible for the vast majority of delays. Mist is more common during this time period than any other time period but it only ranks second. Icing occurs most frequently during the morning peak time. This is of significance, since icing is accountable for the highest amount of delay time per delay event. Therefore, an icing event could result in heavy congestion at the airfield, as it occurs during a busy peak time.

4.1.5 Cumulonimbus Analysis

As the weather category CB is the most significant contributor to weather-related delays at ORTIA, the category is analysed in greater detail. Table 13 indicates that there is no evidence that a CB event with precipitation, or visibility reduction, causes any more delay time than a CB event without precipitation or visibility reduction. Therefore, any CB event causes delays, regardless of the intensity of the event. A single CB event with TS, regardless of intensity, generally causes a delay time of approximately 37 minutes. A single CB event without TS, regardless of intensity, generally causes a delay time of approximately 31 minutes. Therefore, on average, a CB event with TS will induce a slightly lengthier delay time than an event without TS.

Table 13: The average number of delay minutes per delay event due to cumulonimbus clouds (CB), with and without thunderstorms (TS) reported, during the period 2010 to 2013, and the average total.

	2010	**2011**	**2012**	**2013**	**Average Total**
CB with TS					
No precipitation occurred	34	39	20	57	37.5
Precipitation occurred, but no reduction in visibility	30	34	38	46	37
Precipitation and a reduction of <1000 m in visibility	20	65	44	21	37.5
Precipitation and a reduction of 1000 m - < 3000 m in visibility	28	29	26	47	32.5
Precipitation and a reduction of 3000 m – 5000 m in visibility	34	29	30	72	41.25
CB without TS					
No precipitation occurred	33	35	38	65	42.75
Precipitation occurred, but no reduction in visibility	67	21	24	20	33
Precipitation and a reduction of <1000 m in visibility	*No Events Observed*				
Precipitation and a reduction of 1000 m - < 3000 m in visibility	4	20	0	0	12
Precipitation and a reduction of 3000 m – 5000 m in visibility	7	48	0	19	24.67

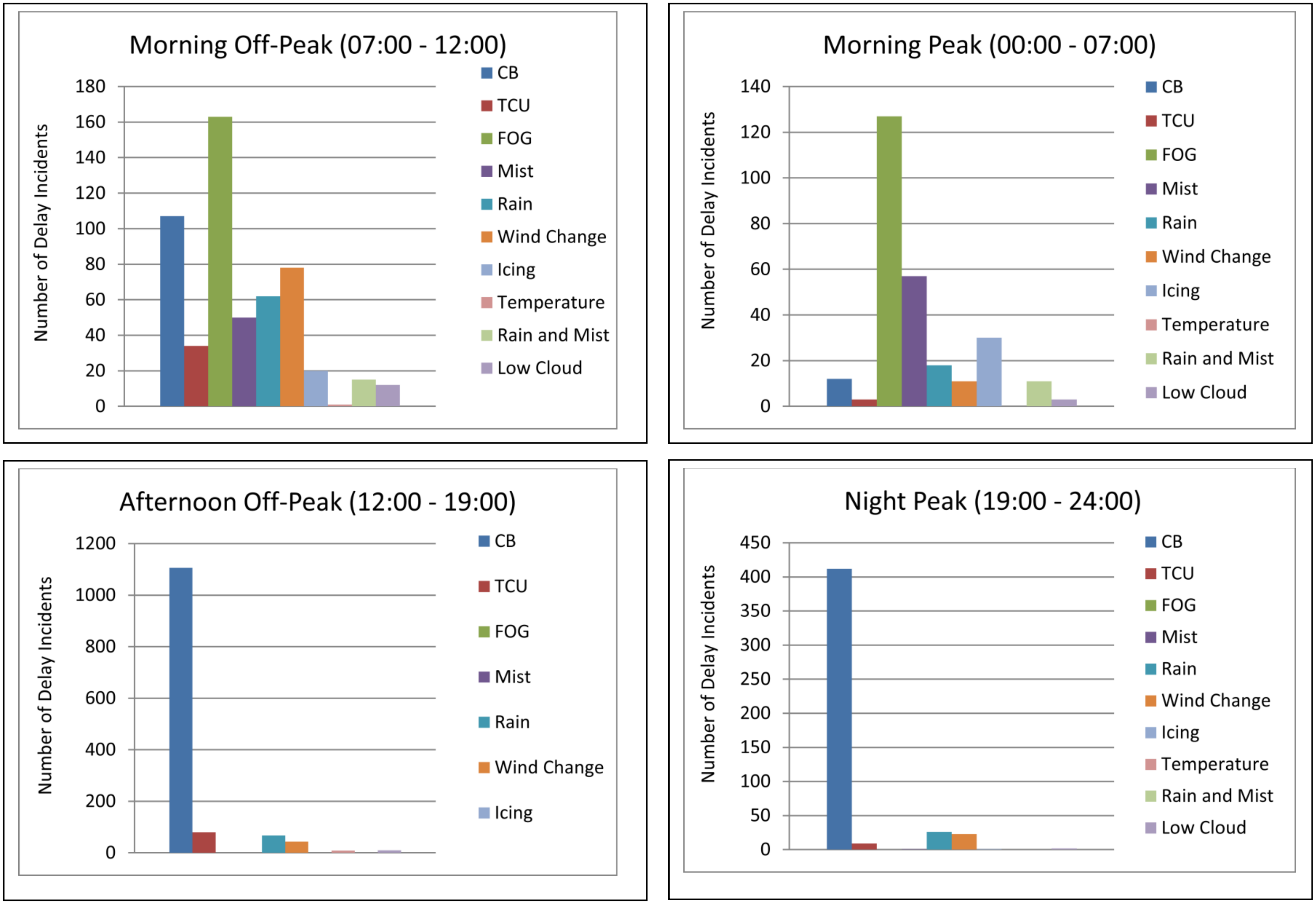

Figure 15:The total number of delay incidents over the period 2010 to 2013 per weather phenomenon during four time periods of the day.

4.1.6 Towering Cumulus Analysis

Table 14 shows the average delay times per single TCU event, with different characteristics of the weather phenomenon. The data indicates that TCU events cause delays regardless of the intensity of the event. Events with no precipitation or visibility reduction caused greater delay times than those with precipitation or visibility reduction. A single TCU event, regardless of intensity, causes on average, a delay time of around 26 minutes.

Table 14: The average number of delay minutes per delay event due to towering cumulus clouds (TCU), for the years 2010 to 2013, and the average total.

Towering Cumulus	**2010**	**2011**	**2012**	**2013**	**Average Total**
No precipitation occurred	24	60	38	62	46
Precipitation occurred, but no reduction in visibility	39	10	16	13	19.5
Precipitation and a reduction of <1000 m in visibility	*No Events Observed*				
Precipitation and a reduction of 1000 - < 3000 m in visibility	10	0	0	0	10
Precipitation and a reduction of 3000 – 5000 m in visibility	5	0	28	12	15

4.1.7 Forecast Analysis

An analysis of the forecast accuracy of the weather categories per delay event was conducted. Table 15 displays the overall results of the forecast analysis. For the period 2010 to 2013, the year 2013 had the highest Terminal Aerodrome Forecast (TAF) accuracy of 66% with 2011 exhibiting the lowest level of accuracy at 48%. The forecast accuracy from the year 2011 fell by 14% from the previous year. However, the accuracy steadily improved after this dip. The overall accuracy over the four year period was 59%.

Table 15: Terminal Aerodrome Forecast (TAF) accuracy during the period 2010-2013.

Year	**TAF Accuracy**
2010	62%
2011	48%
2012	59%
2013	66%
Overall	59%

Table 16 displays the annual average forecast accuracy for each weather phenomenon and the overall average from the period 2010 to 2013, in order of highest to lowest overall accuracy. Figure 16 presents the overall average graphically. It can be seen that the category low cloud has the highest forecast accuracy of 75%, whereas fog has by far the lowest forecast accuracy of only 5%. This is a significant result as fog causes the second highest number of weather-related delays at ORTIA. During the year 2013, the fog forecast had a 0% hit rate, even though there were 52 recorded delay incidents due to fog. The category rain and mist had highly contrary levels of forecasting accuracy over the four years. The years 2010 and 2012 had a 100% hit rate, whereas 2011 and 2013 had a 0% and 5% hit rate respectively.

Table 17 presents the average number of delay minutes per correct forecast and per missed forecast for each weather category. The majority of weather-related delays where the weather phenomenon was correctly forecasted experienced a longer average delay time than those delays where the weather phenomenon was not forecasted correctly. The only exceptions are those in bold on the table, namely fog, mist, mist and rain, and low cloud.

Table 16: TAF accuracy (in %) of weather parameters during the period 2010-2013, with the overall average, in order of highest to lowest overall accuracy.

Weather Phenomenon	**2010**	**2011**	**2012**	**2013**	**Average**
Low Cloud	71	67	83	80	75
Rain	75	36	88	94	73
TCU	84	60	56	85	71
CB	70	60	68	70	67
Rain and Mist	100	0	100	5	51
Mist	71	13	67	21	43
Fog	14	3	3	0	5

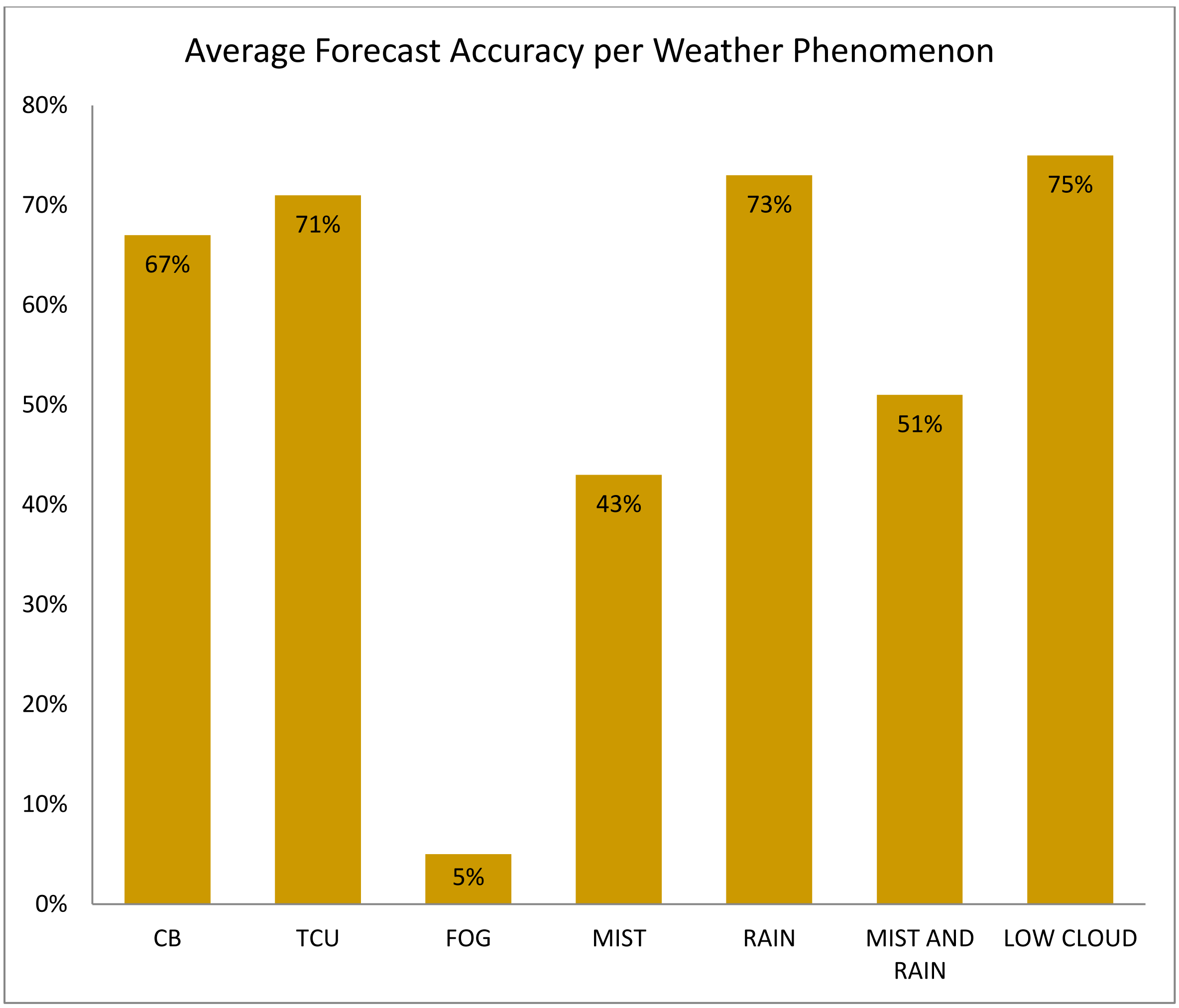

Figure 16: The average forecast accuracy per weather phenomenon (2010-2013).

Table 17: The average number of delay minutes per correct forecast (hit) and per incorrect forecast (miss) over the period 2010 to 2013.

Weather Phenomenon	**2010**		**2011**		**2012**		**2013**	
	HIT	MISS	HIT	MISS	HIT	MISS	HIT	MISS
CB	35	29	32	33	33	31	57	42
TCU	33	25	48	23	45	20	30	31
Fog	**12**	17	**7**	25	19	20	N/A	16
Mist	**11**	20	**18**	40	**16**	24	**10**	14
Rain	11	6	27	12	21	12	37	12
Mist and Rain	53	N/A	N/A	14	12	N/A	**4**	8
Low Cloud	15	13	**17**	35	26	8	25	8

4.2 Discussion

4.2.1 Weather Variables and Phenomena

Thunderstorms are perhaps the most hazardous weather phenomena to aviation as they can generate severe turbulence, severe icing, lightning, poor visibility, hail, heavy precipitation and strong, squally winds. Thunderstorms could, therefore, result in significant departure delays especially due to windshear and crosswinds generated by cells over or close to the aerodrome. Also, when lighting is evident, fuelling of aircraft is stopped immediately, together with other functions such as baggage. The research found that thunderstorms were the cause of the vast majority (63%) of weather-related delays at ORTIA, and consequently, delays occur most often during the summer months of October to January (with the majority recorded in November). Furthermore, delays occur more frequently during the afternoon and early evening, namely between 12:00 and 19:00. This coincides with the off-peak times of the day, and therefore the current scheduling of flights is appropriate. The second time period when thunderstorms most often occur is between 19:00 and 24:00, which is a peak period, and thus thunderstorms would cause most disruption between these hours. There is no clear evidence that the intensity of a cumulonimbus(CB) event (where intensity is measured by the reduction of visibility) influences the length of the delay time. A CB event with thunderstorms (TS) will extend the average delay time by only 6 minutes than an event without TS. Therefore all CB events, regardless of the intensity will cause a significant delay (and thus the term thunderstorms can be used to categorize all CB events from here on for ease of reference). A single delay event due to thunderstorms is on average 37 minutes. However, the longest single delay event due to thunderstorms over the 4 year period was 1079 minutes (around 18 hours). This particular event was the product of a severe hailstorm over the airfield, which produced golf ball sized hail. The significant length of the delay could have potentially been due to aircraft damage. This event shows the ability of thunderstorms to cause extremely significant delays.

Towering cumulus clouds (TCU) are not as hazardous as thunderstorms, but are still significant especially for light aircraft. TCU can also produce lightning, windshear and crosswinds on the runway, which would result in departure delays. Also, precipitation from TCU may lead to a reduction in visibility, which could also lead to delays, especially for VFR flights. The research found that TCU events without precipitation resulted in a longer delay time than those with precipitation. A possible reason for this is that precipitation from TCU is generally light (in comparison to a CB), and perhaps any visibility reduction is short lived within the TCU event, and hence negligible. Delays due to TCU resulted in only around 5% of all the weather-related delays. However, the average length of time of a single delay due to TCU is 33 minutes, only 4 minutes shorter than a thunderstorm delay. The longest single TCU delay over the 4 year period was recorded at 235 minutes, roughly 4 hours. Thus even though TCU does not often result in aviation delays, when they do, the delay can be relatively lengthy.

Icing can be a very hazardous phenomenon which could lead to numerous departure delays. Icing can change the performance and aerodynamics of an aircraft, and thus de-icing is needed before take-off, usually a timely procedure. Icing events at ORTIA are infrequent, however when they do occur, the event is lengthy (on average just over one hour) and occurs during a busy time period of the day, namely the morning peak hours between 00:00 – 07:00. The longest single icing event over the 4 year period was 245 minutes (around 4 hours). Again, this shows the potential that icing can have on substantial delays. This particular event occurred in June 2013, when winter temperatures were well above the climatic average, indicating that a significant delay can occur under average weather conditions.

Rainfall does not only reduce visibility, but can also result in slippery runways and taxiways. This could delay operations such as baggage handling and catering, resulting in departure delays. According to ICAO (Annex 3), precipitation should be forecasted when it is expected to be moderate or heavy. This results in operational aviation forecasters to generally forecast rain when the visibility is expected to be less than 5 000 m (such as in the case of moderate or heavy rain). It has been noted during the research that even light rain, or rain that did not cause a reduction in visibility of 5000 m or less, still initiated delays. Light rain (without reduction in visibility) is not operationally significant to flight, however the research shows that it can be operationally significant to the aerodrome, by impacting the apron conditions. When reviewing the delay comments regarding the delay due to rain, the following remarks were highlighted:

“Only 1 step operation due to wet/rainy weather”
“Adverse weather prohibiting rear disembarkation and boarding”
“Congestion in shuttle due to weather”

These comments display that during rainy conditions, delays can occur during the disembarkation and boarding phases of flights when steps and shuttles are being used for passengers. Other aspects such as baggage handling can also cause delays during rain.

Therefore rain in itself, without other poor weather factors such as low clouds or poor visibilities, can cause delays.

Rain and mist was often reported together, and hence the three categories, ‘rain’, ‘mist’ and ‘rain and mist’ was classified in order to truly evaluate the effects of rain on delays without the influence of another type of weather, such as mist. The average delay time for all 3 categories was approximately 21 minutes, and therefore there was no significant difference when comparing the average delay time. However, when comparing the number of delay incidents, rain was the third highest contributor of aviation delay incidents during the study period, after thunderstorms and fog. The longest recorded single delay event due to rain over the 4 year study period was 121 minutes, around 2 hours. Therefore, rain by itself (without the impact of other weather variables), is a weather element that contributes to delays, and should therefore not be overlooked, as perhaps previously done.

Fog is one of the biggest hazards to aviation due to the remarkable reduction in visibility. The degree to which an airline can operate in fog depends on the skill of the pilot, the equipment of the aircraft, the instrumentation at the aerodrome and the landing/take-off criteria of the airport. Ground operations during fog will be severely slowed if not ceased all together, resulting in delays. Fog causes 11% of all aviation delays at ORTIA, and is therefore a significant weather variable. However, the average delay time per fog delay is only 19 minutes, but the longest recorded fog delay was 206 minutes (over 3 hours).

4.2.2 Forecast Analysis

The average forecast accuracy over the four year period was 59%. The forecast analysis examined the accuracy of the TAFS that were associated with the delays. 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. In addition to this, many delays can occur in rapid succession of one another. Therefore, the same TAF would have been analysed several times in such a situation. Therefore this accuracy is not a true reflection of the overall accuracy of the weather office. However, when reviewing the forecast accuracy of the TAFS that were examined, the forecast accuracy is poor. The weather variable with the lowest forecast accuracy is fog, with an accuracy of only 5%. Fog remains to be one of the most significant weather hazards to aviation worldwide.

The number of weather-related delays increased from 621 delays in 2010 to 824 delays in 2013, and the forecast accuracy improved over this time, from 62% to 66%. Figure 17 shows the relationship between the number of delays compared to the TAF accuracy over the 4 year period. The number of delays dropped slightly over the first 3 years, and then increased substantially within the fourth year. The forecast accuracy dropped dramatically in the first year, then increased in the third and continued to increase in the fourth year. This result shows that, in this research, there is no relationship between the number of delays when compared to TAF accuracy. Adverse weather will generate delays despite the accuracy of a TAF. It is important to recognize that this result is with respect to *departure* delays due to adverse weather at the departure station. When considering departure delays due to adverse weather at the destination station, and arrival delays due to adverse weather at the destination station, the result could be, and most likely would be, significantly different.

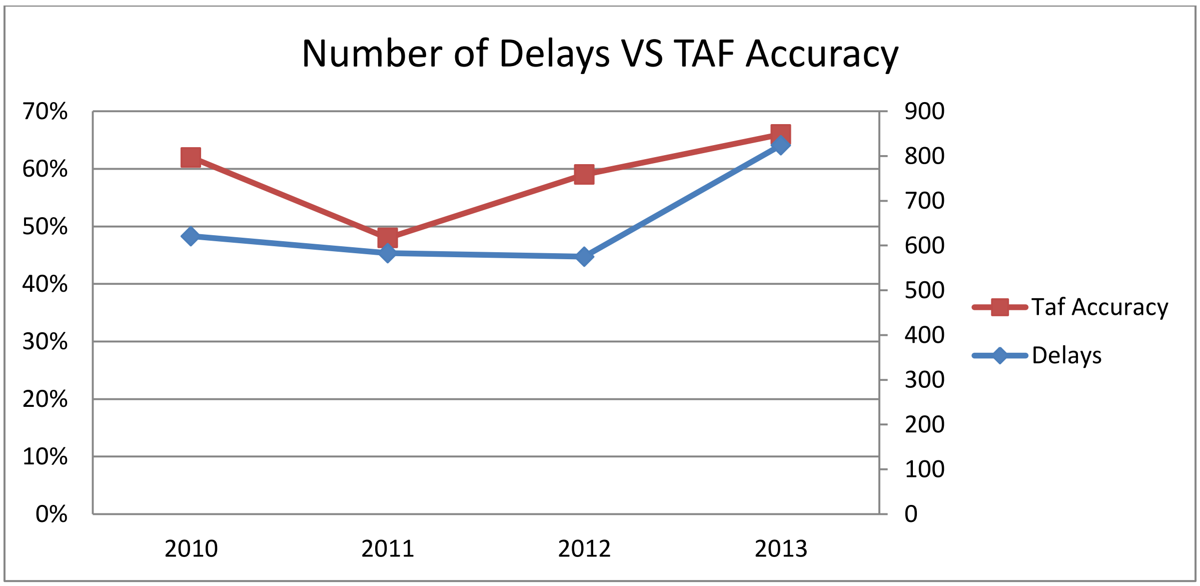

Figure 17: The number of delays and the TAF accuracy (%) over the period 2010 to 2013.

Many airlines rely on TAFS during flight planning. One of the main decisions made when considering the TAF, is determining whether to carry extra fuel for possible diversion to an alternate airport in the case of adverse weather. Inaccurate TAF information may mean that additional fuel is carried unnecessarily (Leigh *et al.,* 1997). All flights are legally bound to carry an alternate fuel supply, and the decision to load more fuel on top of the alternate fuel supply will be made with reference to the TAF. If no additional fuel is loaded, and the weather conditions at the destination airport are poor, the aircraft must make an en-route diversion (a substantial financial loss). However, if the aircraft is carrying additional fuel, and the weather conditions at the destination airport are poor, the aircraft can attempt a landing due to the additional fuel on-board. The landing will either be successful (in which case a costly diversion was avoided), or landing is aborted and a diversion is made. However, if the flight is loaded with extra fuel, and the weather conditions are acceptable for normal landing approaches, the flight will be laden with unnecessary fuel.

Leigh *et al.,* (1997) conducted a study on the economic value of TAFS, with reference to Sydney Airport and Qantas Airways Limited airline. Based on the case study conducted by Leigh *et al.,* (1997), which examined Qantas international flights into Sydney, improvements in TAF accuracy would yield significant positive benefits to airlines. The study concluded that the economic benefit of a hypothetical increase in TAF accuracy of 1% is approximately A$ 1.2 million per year. The calculations were based only on the additional fuel decision, and not on other important operational decisions, and therefore the estimated figure was deemed as a minimum value (Leigh *et al.,* 1997). Similarly, research by Klein *et al.* (2009) revealed that there was 81,429 hours of *arrival* delays during 2008 that were indeed avoidable, yielding an avoidable cost of over US$258 million. The research further concluded that up to 60% of weather-related delays are potentially avoidable, and the avoidable portion is typically related to the accuracy of a weather forecast.

Based on these findings and previous research, an improvement of the accuracy of TAFS would be greatly beneficial to arrival delays, but would have no impact on the number of departure delays. However, even though departure delays will still occur, even with an accurate TAF, the intensity and duration of the departure delay could be minimized through planning and preparedness (through the use of TAFS).

Chapter 5: Recommendations and Conclusion

5.1 Recommendations

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.

Each one of these aspects can be addressed with possible recommendations, specifically designed for O.R. Tambo International Airport (ORTIA).

5.1.1 Weather Forecasts

5.1.1.1 Advisories

It is common practice for a weather office to distribute weather warnings, typically 2 hours in advance of the weather occurring. These warnings cover a variety of weather phenomena as set out by the International Civil Aviation Organization (ICAO). On the other hand, an advisory would be issued 12 to 48 hours before the expected weather, depending on the phenomenon, and can be taken as a weather alert. Advisories are not regulated by ICAO, and thus are not common practice for every weather office. In light of the findings, advisories are recommended for the weather office at ORTIA, in order to be used for effective planning of all operations, thereby eliminating 'last-minute planning' and reducing delays.

Light rain or rain without other significant factors such as low clouds and poor visibility is not included in Terminal Aerodrome Forecast (TAF) forecasts (as per ICAO), and therefore, can create delays as rain would not be accounted for in airport ground operations planning. Thus, it is recommended that a rainfall advisory (or similar product) is issued by the weather office for daily planning purposes. Such an advisory can be used during the planning of stand allocation (i.e. avoiding steps and using tunnels), and for baggage handling.

Similarly, advisories for icing and wind changes that will result in a runway change, can be issued for ORTIA. An advisory for icing would be particularly useful, as the average delay time of a single icing delay is approximately one hour. According to OFCM (2002), an icing advisory should be issued 12-24 hours in advance. Within this timeframe, the de-icing coordinator can plan for the availability or readiness of the de-icing equipment, supplies, and manpower. Another advisory or warning should then be issued 3-6 hours before the icing is expected. During this time, de-icing fluid can be applied to the aircraft before the precipitation begins, thereby reducing delay time.

According to OFCM (2002), a 24-hour advisory for fog (or any other weather phenomena causing significant obstruction to vision) is another recommended advisory. Within this lead time, ‘follow me’ trucks can be prepared and ready for service. The contractors of any construction projects can also be advised, and schedules amended. A 12-24 hour advisory of possible heavy rainfall is another recommended practice. Within this lead time, plans for vehicular traffic flow to bypass known trouble areas can be made. The preparation to open drainage control points and equipment and staff for sweeping or pushing standing water can also be achieved within this timeframe. An advisory for strong winds can be used to plan for more frequent ramp, taxiway, and runway inspections, in order to remove foreign object material. Lastly, an advisory for hail is also recommended. Hail can cause severe damage, resulting in significant delays, as has been examined (Chapter 1).

5.1.1.2 Improved Forecasts

When reviewing the forecast accuracy over the research period, the poorest forecasted weather element is fog. Despite the improved skill of numerical weather prediction (NWP) models, fog remains difficult to forecast, due to local and complex nature of the phenomenon. Improving fog forecasts through NWP is not in the scope of this dissertation. However, fog forecasts can be improved from a greater understanding of the phenomenon through past events. Therefore, a fog database which thoroughly captures the meteorological aspects of past fog events and their geographic distribution is advisable. Such a database can be referred to when forecasting future fog events. Once a sufficient database is established, the data can be used to develop a fog probability scoring index which can become a component in the forecasting process.

5.1.2 Assessing Weather-Related Risks

5.1.2.1 Weather Impact Index System

The use of a weather impact score or index can be used in estimating and planning for airport delays. Klein *et al.* (2010) developed a model for airport delay prediction, based on weather-impacted scenarios. 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. Klein *et al.* (2010) propose that specific weather factors should be incorporated into WITI, with the following categories to be used:

- En-route convective weather
- Local convective weather
- Wind
- Snow
- IMC (when the cloud ceiling or visibility is below airport specific minima)
- Queuing delay (no particular weather factor at the time but perhaps queuing delay from high traffic demand in the aftermath of a major weather event)
- Other (minor impacts such as light rain etc.)

ORTIA currently does not use a weather impact scoring or index system and, therefore, a system based on the principals of WITI could be beneficial. However, the system should be tailor-made to each airport (as each airport has unique weather impacts in terms of severity, space and time), and a weather impact index system would have to be designed according to the data collected and assessed for ORTIA.

5.1.2.2 The Users of a Weather Impact Index

A weather impact index would typically be used as a component or variable in an airport model. It would ultimately be used for planning purposes by the air traffic management centre of the airport. At ORTIA, that management centre is CAMU (Central Airspace Management Unit). Such a division typically manages a slot allocation program and the general use of airspace for a particular time period. CAMU is also responsible for re-routing traffic affected by adverse weather, and balances demand against capacity using an air traffic flow management (ATFM) system.

ATFM is a function of an air traffic management (ATM) system with the main purpose of balancing air traffic demand with airspace and airport capacity to ensure the most efficient use of the airspace system (ICAO, 2009). ATFM has the following objectives (ICAO, 2009):

- Reduce ground and en-route delays;
- Maximise capacity and optimise the flow of air traffic;
- Provide an informed choice between departure delay, re-routing and/or flight level selection;
- Alleviate unplanned in-flight rerouting;
- Provide improved solutions around predicted severe weather;
- Balance the demand against capacity of ATC sectors, air routes and aerodromes;
- Determine the necessity for an airspace/ground delay program;
- Enabling aircraft operators to operate as close to their preferred trajectories.

Following from these objectives, a weather impact index could be utilised as part of an ATFM system. In order to maximize the potential benefits of such an index, it should be used in the pre-planning stages of traffic management. It is, therefore, recommended to apply the index to TAFS, as a TAF covers a thirty hour forecast period.

5.1.2.3 The Weather Impact Index at ORTIA

An index was developed specifically for ORTIA, based on the weather data collected from this dissertation, and is, therefore, based on four years of historical delay data. The same weather categories as set out in this dissertation were used for the weather impact index. The index is based on the following scoring system:

$$\text{Probability Score} + \text{Frequency Score} + \text{Duration Score} = \text{Weather Impact Score} \quad \text{[Equation 2]}$$

With reference to Equation 2, the total impact score is comprised of three components, namely a probability score, a frequency score and a duration score. The probability score is based on what the probability or risk is, of adverse weather causing a delay. This score was an additional calculation to the dissertation, and was calculated by establishing the number of days in the year 2013 with adverse weather, and comparing it to the number of days of delay with the same adverse weather. Each day of 2013 was allocated a type or types of weather based on historical METARS. For example, January of 2013 recorded 10 thunderstorm days throughout the month. The number of delay days due to thunderstorms was recorded as 5, and thus, the probability of a delay occurring due to thunderstorms is 50%. The average over the year for each weather category was defined as the probability score.

The frequency score marks how often a weather type causes delays. Table 7 records the number of delay incidents over the four year period per weather phenomenon. The frequency score uses the percentage contribution of each weather phenomenon to the total number of weather delays over the four years. The duration score can be defined as the average duration of a delay event as a percentage of an hour. This score is based on the averaged total minutes of each weather phenomenon as per Table 9. The average of the three scores (probability, frequency and duration) yields the total impact score as a percentage, as displayed in Table 18.

Table 18: Total impact scores.

Weather Phenomenon	**Total Impact Score**
CB	61%
Fog	25%
Rain	27%
TCU	32%
Mist	22%
Low Cloud	13%
Rain and Mist	46%

The total impact score can be further adjusted to reflect the expected 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 per Equation 3.

$$\text{Total Impact Score} * \text{Traffic Coefficient} = \text{Final Weather Impact Index} \qquad \text{[Equation 3]}$$

The coefficient variable can be adjusted per day or per hour, depending on the situation at hand, and would be predetermined by the air traffic management centre, i.e. CAMU at ORTIA. Simply from a general peak traffic point of view, the traffic coefficient variables as per Table 19 can be used as a general guideline.

Table 19:Proposed traffic coefficients based on peak and off-peak traffic periods.

Time Period	**Traffic Coefficient**
Morning off-peak (05Z to 10 Z)	1
Morning peak (22 Z to 05 Z)	1.2
Afternoon off -peak (10 Z to 17 Z)	1
Night peak (17 Z to 22 Z)	1.4

The traffic coefficient range 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.

5.1.2.4 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 icing, wind changes resulting in runway changes, and temperatures, the index can only assess the risk of disruption to air traffic based on the weather categories of Table 18.The limitation of a weather impact index that is based on a TAF, is the index relies on the accuracy of the TAF for air traffic planning. The tool would be ineffective in the case of missed events. However, as the TAF is amended or corrected, the index can be applied again, and can still give some lead time for planning.

5.1.2.5 Weather Impact Index Examples

The following random case studies were selected in order to test the weather impact index on a post hoc basis. The examples show how the index would be applied in an operational environment. The case studies shows the skill of the index, from consecutive and lengthy delays to short, intermittent ones.

5.1.2.5.1 Case Study 1: 25/01/2013

A thunderstorm event on the 25th of January 2013 at ORTIA, led to 14 reported delays, with a total of 381 delay minutes (6 hours and 35 minutes of delay time). The delays occurred in the evening with the first delay at 1550 Z, and the last delay at 1815 Z, with the remaining 12 delays falling in between.

The following TAF was issued at 1000 Z:

TAF FAOR 251000Z 2512/2618 23010KT 9999 SCT045 PROB30 TEMPO 2513/2519 6000 –TSRA FEW040CB BECMG 2519/2521 03010KT CAVOK FM260000 03014KT 9999 SCT010 PROB40 TEMPO 2602/2606 5000 BR BKN006 BECMG 2607/2609 33015KT SCT040 PROB30 TEMPO 2613/2618 5000 TSRA FEW035CB TX30/2512ZTN16/2604Z=

By applying the weather impact index system for the 25th of January 2013, as displayed in Table 20,the applicability of such an index on a day of the adverse weather can be assessed. The index scoring system revealed that potential disruption to air traffic could be around 61% in the early evening, increasing to 85%. Several delays did occur did occur during this time, and thus, by using the index, appropriate traffic planning and management could potentially have reduced the extent and duration of delays.

Table 20: The weather impact index valid for 25/01/2013

Hour	Forecast	Index	Coefficient	Final Index Score	Delay
12 Z	Fine	0	1	0	No
13 Z	Thunderstorms	61	1	61	No
14 Z	Thunderstorms	61	1	61	No
15 Z	Thunderstorms	61	1	61	Yes
16 Z	Thunderstorms	61	1	61	Yes
17 Z	Thunderstorms	61	1.4	85	Yes
18 Z	Thunderstorms	61	1.4	85	Yes
19 Z	Thunderstorms	61	1.4	85	No
20 Z	Fine	0	1.4	0	No
21 Z	Fine	0	1.4	0	No
22 Z	Fine	0	1.4	0	No
23 Z	Fine	0	1.2	0	No
24 Z	Fine	0	1.2	0	No

5.1.2.5.2 Case Study 2: 06/09/2012

Extensive delays occurred on the 06th of September 2012 due to afternoon and evening thunderstorms. A total of 23 delays were recorded resulting in 29 hours and 20 minutes of delay time, with an average delay time of 70 minutes.

The following TAF was issued at 2200 Z on the 05th of September 2012:

TAF FAOR 052200Z 0600/0706 35012KT 9999 SCT010 BKN030

PROB30 TEMPO 0600/0607 4000 BR –DZRA BKN008

PROB40 TEMPO 0608/0610 5000 –SHRA BKN015

TEMPO0611/0619 4000 TSRA BKN012 FEW025CB OVC060 BECMG 0619/0621 BKN010

TEMPO 0622/0706 4000 BR BKN005 TX16/0612ZTN08/0604Z=

Table 21 shows the weather impact index applied to the TAF. The entire day was at risk of delays due to the poor weather expected throughout the day. The risk started at 55% during the morning, reducing to 27% for the early afternoon, picking up again to 61% for the afternoon, increasing even further to 85% for the early evening and then dropping down to around 20% for the remainder of the night. The vast majority of the delays occurred between 1500 Z and 1900 Z. The index during this period was at its highest for the day ranging from 61% to an 85% risk. Only three delays occurred after 1900 Z, and hence the index handled the decrease in delay risk well. This case study reflects a situation where a degree of delay risk is present throughout the day, but the worst delays occurred when the delay risk was at its highest.

Table 21: The weather impact index valid for 06/09/2012

Hour	Forecast	Index	Coefficient	Final Index Score	Delay
00 Z	Rain and Mist	46	1.2	55	No
01 Z	Rain and Mist	46	1.2	55	No
02 Z	Rain and Mist	46	1.2	55	No
03 Z	Rain and Mist	46	1.2	55	No
04 Z	Rain and Mist	46	1.2	55	No
05 Z	Rain and Mist	46	1.2	55	No
06 Z	Rain and Mist	46	1	46	Yes
07 Z	Rain and Mist	46	1	46	Yes
08 Z	Rain	27	1	27	No
09 Z	Rain	27	1	27	No
10 Z	Rain	27	1	27	No
11 Z	Thunderstorms	61	1	61	No
12 Z	Thunderstorms	61	1	61	No
13 Z	Thunderstorms	61	1	61	No
14 Z	Thunderstorms	61	1	61	No
15 Z	Thunderstorms	61	1	61	Yes
16 Z	Thunderstorms	61	1	61	Yes
17 Z	Thunderstorms	61	1.4	85	Yes
18 Z	Thunderstorms	61	1.4	85	Yes
19 Z	Thunderstorms	61	1.4	85	Yes
20 Z	Low Cloud	13	1.4	18	Yes
21 Z	Low Cloud	13	1.4	18	Yes
22 Z	Mist	22	1.4	30	No
23 Z	Mist	22	1.2	26	No
24 Z	Mist	22	1.2	26	No

5.1.2.5.3 Case Study 3: 01/03/2013

On the 01st of March 2013, 6.5 hours of delay time occurred with an average delay time of around 16 minutes. Consecutive delays occurred over 2 hours (from 1900 Z to 2045 Z) due to thunderstorms over the aerodrome. As is highlighted in Table 22, this is when the delay risk was at its highest (85%). Applying the index during the morning of the 01st, would have given ATM a clear indication when to expect the highest risk of disruption.

The following TAF was issued at 0400 Z on the 01st of March 2013:

TAF FAOR 010400Z 0106/0212 08006KT CAVOK

TEMPO 0106/0107 4000 BR SHRA BKN005 FEW030CB BKN080

BECMG 0107/0109 33010KT SCT035 TEMPO 0112/0122 5000 TSRA FEW030CB

BECMG 0118/0120 08010KT BKN008 TEMPO0200/0206 4000 BR BKN003

BECMG 0204/0206 03010KT BECMG 0207/0209 34010KT SCT035

TX25/0112ZTN14/0203Z=

Table 22: The weather impact index valid for 01/03/2013

Hour	Forecast	Index	Coefficient	Final Index Score	Delay
00 Z	Fine	0	1.2	0	No
01 Z	Fine	0	1.2	0	No
02 Z	Fine	0	1.2	0	No
03 Z	Fine	0	1.2	0	No
04 Z	Fine	0	1.2	0	No
05 Z	Fine	0	1.2	0	No
06 Z	Thunderstorms	61	1	61	Yes
07 Z	Thunderstorms	61	1	61	No
08 Z	Fine	0	1	0	No
09 Z	Fine	0	1	0	No
10 Z	Fine	0	1	0	No
11 Z	Fine	0	1	0	No
12 Z	Thunderstorms	61	1	61	No
13 Z	Thunderstorms	61	1	61	No
14 Z	Thunderstorms	61	1	61	No
15 Z	Thunderstorms	61	1	61	Yes
16 Z	Thunderstorms	61	1	61	Yes
17 Z	Thunderstorms	61	1.4	85	Yes
18 Z	Thunderstorms	61	1.4	85	Yes
19 Z	Thunderstorms	61	1.4	85	Yes
20 Z	Thunderstorms	61	1.4	85	Yes
21 Z	Thunderstorms	61	1.4	85	Yes
22 Z	Thunderstorms	61	1.4	85	No
23 Z	Low Cloud	13	1.2	16	No
24 Z	Mist	22	1.2	26	No

5.1.2.5.4 Case Study 4: 29/10/2010

On the 29th of October 2010 fog resulted in 5 delays with 56 delay minutes. From applying the index, a risk of 26% to 30% was apparent for the morning. Table 23 shows that the delays occurred during this period of risk.

The following TAF was issued at 2200 Z on the 28th of October 2010:

TAF FAOR 282200Z 2900/3006 18010KT CAVOK PROB40 TEMPO 2900/2903 4000 BR BKN006

BECMG 2901/2903 12010KT TEMPO 2903/2905 0800 FG OVC001

BECMG 2908/2910 30008KT BECMG 2912/2914 24010KT SCT045

BECMG 2916/2918 01007KT CAVOK TX27/2912ZTN09/2904Z=

Table 23: The weather impact index valid for 29/10/2010

Hour	Forecast	Index	Coefficient	Final Index Score	Delay
00 Z	Mist	22	1.2	26	No
01 Z	Mist	22	1.2	26	No
02 Z	Mist	22	1.2	26	No
03 Z	Fog	25	1.2	30	No
04 Z	Fog	25	1.2	30	Yes
05 Z	Fog	25	1.2	30	Yes
06 Z	Fog	25	1	25	Yes
07 Z	Fine	0	1	0	No
08 Z	Fine	0	1	0	No
09 Z	Fine	0	1	0	No
10 Z	Fine	0	1	0	No
11 Z	Fine	0	1	0	No
12 Z	Fine	0	1	0	No
13 Z	Fine	0	1	0	No
14 Z	Fine	0	1	0	No
15 Z	Fine	0	1	0	No
16 Z	Fine	0	1	0	No
17 Z	Fine	0	1.4	0	No
18 Z	Fine	0	1.4	0	No
19 Z	Fine	0	1.4	0	No
20 Z	Fine	0	1.4	0	No
21 Z	Fine	0	1.4	0	No
22 Z	Fine	0	1.4	0	No
23 Z	Fine	0	1.2	0	No
24 Z	Fine	0	1.2	0	No

5.1.3 Collaborative Decision Making

The Airport Management Centre (AMC) at ORTIA is a collaborative working environment centre where the airport's major stakeholders come together in the decision making process (ICAO, 2012). This centre is, therefore, crucial for data sharing and decision making in a timely manner. However, the aviation meteorological office currently does not have a physical place at the AMC. It is recommended that a forecaster is physically present at the AMC in order to brief the numerous role-players regarding the expected weather conditions and advise role players regarding warnings that may affect airport operations. In order for the collaborative decision making process to be successful, the timeliness of the process is crucial. Therefore it is vital that the aviation weather centre at ORTIA is physically a part of the AMC in order to expedite the process even further.

5.2 Conclusion

5.2.1 Limitations and Future Research

The research is limited in two aspects. First, the data was collected over a four-year period, a limited sample size. A longer study period would yield less bias and be more representative. Second, the data obtained was only for departure delays. Arrival delays are potentially more significant than departure delays due to the fuel burn associated with holding patterns and diversions. Thus, there is much room for future research with regard to arrival delays due to the weather overhead ORTIA. Also, the research can be expanded to other airports across South Africa, such as Cape Town International Airport and King Shaka International Airport, where adverse weather also occurs.

5.2.2 Conclusion

Climate change is expected to lead to changes in localised weather, and possibly to more severe weather patterns (Pejovic *et al.,* 2009). This is likely to include more intense rainfall, more frequent thunderstorms, and changes in wind patterns, all of which can reduce safety margins and decrease runway capacity in the aviation industry. The projected increase in air travel will exacerbate this impact. South Africa is predicted to be particularly severely affected by climate change. Assuming a moderate to high growth in greenhouse gas concentrations, projections show that by 2050, the interior of South Africa is likely to warm by around 3°C (Archer, 2010). By 2100, the temperature increase is likely to approach 5°C in the northern interior (Archer, 2010). Projected rainfall changes show that rainfall intensity is also likely to increase. Therefore, the impact of weather on aviation will most likely increase with time, unless new solutions are tailored.

Delays in aviation are not completely avoidable. Due to the very (dynamic) nature of weather, there will always be weather-related delays as long as weather negatively influences the performance of aircraft and/or operations at airports. The fact that there are delays indicates that safety is a priority within the industry. Indeed, if delays did not exist, major concerns should be raised. Therefore, the purpose of research with reference to aviation delays should not be to eliminate delays altogether, but rather to reduce the number and duration of delays, as a result of effective delay management and improved weather forecasting.

The type of weather identified within the research that causes the most significant aviation departure delays at O.R. Tambo International Airport (ORTIA) are thunderstorms, followed by fog. Fog is poorly forecasted at ORTIA, and, therefore, needs due attention. The third highest delay contributor is rainfall (rainfall without the influence of other weather elements), a significant result, as light rainfall is usually deemed insignificant. Surface icing, a previously neglected weather phenomenon in terms of forecasting at ORTIA, has proved to be a significant element due to the length of delay it can cause.

The accuracy of a weather forecast does not impact on the number of departure delays. It can, therefore, be concluded, that departure delays due to weather are largely unavoidable. However, it is still important to be prepared for departure delays, in order for airport operations to run efficiently, and therefore planning is crucial. Through preparedness, planning and the use of TAFS, the length and impact of departure delays could be reduced, but not completely avoided. It is arrival delays that could be largely avoided due to improved TAF accuracy, resulting in significant financial savings, as highlighted in previous research (e.g. Leigh *et al*., (1997), Klein *et al*., (2009)). Thus, improved TAF accuracy (through further research and development, and forecast monitoring and verification) at ORTIA would be greatly beneficial, as the current accuracy is poor.

Improved weather forecasts, enhanced assessments of the weather forecasts and collaborative and timely decision making are the three identified pillars to reducing the impact of weather on aviation delays (both departure and arrival), as set out by Eurocontrol (2014). A strong recommendation for the development and use of a weather impact index system is given here. It is further suggested that it be used on a daily basis. Ideally, once such a system is developed and operational, a simple comparison of the delays before and the delays after would show the benefits of such a system. However, in reality, this would be difficult. No two delays are the same and delays are very sensitive to changes in the demand (Evans & Robinson, 2005). Delays arise from a very complicated combination of actual weather characteristics, errors in weather forecasts, the decision-making process and the ability to execute mitigation plans in a timely manner (Evans & Robinson, 2005). Instead, interviews and/or direct observations of Air Traffic Management (ATM) and airline decisions can be used. This method assumes that the system or tool in place is only useful or effective to the extent that it changes user decisions. Therefore, an analysis (through interviews and observations) of these decisions can be made to determine the effectiveness of the system.

It can be reasonably assumed that arrival delays (due to weather at ORTIA) would be caused by the same set of weather, with the same or similar characteristics i.e. time of day, frequency etc., to that of departure delays. It is the duration or length of an arrival delay, and the financial cost of an arrival delay, that would be significantly different to that of a departure delay. Thus, the weather impact index system would have to be adjusted to take into account the difference in duration characteristics in order to be applied to arrival delays. Other key elements to reducing the impact of weather on aviation are improved weather forecasts (specifically fog in the case of ORTIA), the introduction of weather advisories and better collaborative decision making.

There is much room for further research of delays at ORTIA, and regionally across South Africa. Research into arrival delays would be the next progressive step. Also, once the recommendations, specifically the weather impact index system, have been established, research is needed to evaluate the success of such a program at ORTIA.

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Appendix 1: IATA Delay Codes (Eurocontrol, 2014)

Others			
6	OA	NO GATE/STAND AVAILABLE	Due to own airline activity
9	SG	SCHEDULED GROUND TIME	Planned turnaround time less than declared minimum
Passenger and baggage			
11	PD	LATE CHECK-IN	Check-in reopened for late passengers
12	PL	LATE CHECK-IN	Check-in not completed by flight closure time
13	PE	CHECK-IN ERROR	Error with passenger or baggage details
14	PO	OVERSALES	Booking errors – not resolved at check-in
15	PH	BOARDING	Discrepancies and paging, missing checked in passengers
16	PS	COMMERCIAL PUBLICITY/PASSENGER CONVENIENCE	Local decision to delay for VIP or press; delay due to offload of passengers following family bereavement
17	PC	CATERING ORDER	Late or incorrect order given to supplier
18	PD	BAGGAGE PROCESSING	Late or incorrectly sorted baggage
Cargo and Mail			
21	CD	DOCUMENTATION	Late or incorrect documentation for booked cargo
22	CP	LATE POSITIONING	Late delivery of booked cargo to airport/aircraft
23	CC	LATE ACCEPTANCE	Acceptance of cargo after deadline
24	CI	INADEQUATE PACKING	Repackaging and / or re-labelling of booked cargo
25	CO	OVERSALES	Booked load in excess of saleable load capacity (weight or volume), resulting in reloading or off-load
Mail only			
27	CE	DOCUMENTATION, PACKING	Incomplete and / or inaccurate documentation
28	CL	LATE POSITIONING	Late delivery of mail to airport / aircraft
29	CA	LATE ACCEPTANCE	Acceptance of mail after deadline
Aircraft and Ramp Handling			
31	GD	LATE/INACCURATE AIRCRAFT DOCUMENTATION	Late or inaccurate mass and balance documentation, general declaration, passenger manifest
32	GL	LOADING/UNLOADING	Bulky items, special load, lack loading staff
33	GE	LOADING EQUIPMENT	Lack of and / or breakdown, lack of operating staff

34	GS	SERVICING EQUIPMENT	Lack of and / or breakdown, lack of operating staff
35	GC	AIRCRAFT CLEANING	Late completion of aircraft cleaning
36	GF	FUELLING/DEFUELLING	Late delivery of fuel; excludes late request
37	GB	CATERING	Late and / or incomplete delivery, late loading
38	GU	ULD	Lack of and / or unserviceable ULD's or pallets
39	GT	TECHNICAL EQUIPMENT	Lack and / or breakdown, lack of operating staff; includes GPU, air start, pushback tug, de-icing
Technical and Aircraft Equipment			
41	TD	TECHNICAL DEFECTS	Aircraft defects including items covered by MEL
42	TM	SCHEDULED MAINTENANCE	Late release from maintenance
43	TN	NON-SCHEDULED MAINTENANCEE	Special checks and / or additional works beyond normal maintenance schedule
44	TS	SPARES AND MAINTENANCE	Lack of spares, lack of and / or breakdown of specialist equipment required for defect rectification
45	TA	AOG SPARES	Awaiting AOG spare(s) to be carried to another station
46	TC	AIRCRAFT CHANGE	For technical reasons, e.g. a prolonged technical delay
47	TL	STANDBY AIRCRAFT	Standby aircraft unavailable for technical reasons
Damage to Aircraft			
51	DF	DAMAGE DURING FLIGHT OPERTIONS	Bird or lightning strike, turbulence, heaving or overweight landing, collisions during taxiing
52	DG	DAMAGE DURING GROUND OPERATIONS	Collisions (other than taxiing),loading / offloading damage, towing, contamination, extreme weather conditions
EDP/Automated Equipment Failure			
55	ED	DEPARTURE CONTROL	Failure of automated systems, including check-in; load control systems producing mass and balance
56	EC	CARGO PREPARATION DOCUMENTATION	Failure of documentation and / or load control systems covering cargo
57	EF	FLIGHT PLANS	Failure of automated flight plan systems
Flight Operations and Crewing			
61	FP	FLIGHT PLAN	Late completion of or change to flight plan
62	FF	OPERATIONAL REQUIREMENT	Late alteration to fuel or payload

63	FT	LATE CREW BOARDING OR DEPARTURE PROCEDURES	Late flight deck, or entire crew, other than standby, late completion of flight deck crew checks
64	FS	FLIGHT DECK CREW SHORTAGE	Sickness, awaiting standby, flight time limitations, valid visa, health documents, etc.
65	FR	FLIGHT DECK CREW SPECIAL REQUEST	Requests not within operational requirements
66	FL	LATE CABIN CREW BOARDING OR DEPARTURE PROCEDURES	Late cabin crew other than standby, late completion of cabin crew checks
67	FC	CABIN CREW SHORTAGE	Sickness, awaiting standby, flight time limitations, valid visa, health documents
68	FA	CABIN CREW ERROR OR SPECIAL REQUEST	Requests not within operational requirements
69	FB	CAPTAIN REQUEST FOR SECURITY CHECK	Extraordinary requests outside mandatory requirements
Weather			
71	WO	DEPARTURE STATION	Below operating limits
72	WT	DESTINATION STATION	Below operating limits
73	WR	EN-ROUTE OR ALTERNATE	Below operating limits
75	WI	DE-ICING OF AIRCRAFT	Removal of ice and / or snow, excludes equipment – lack of or breakdown
76	WS	REMOVAL OF SNOW, ICE, WATER, AND SAND FROM AIRPORT	Runway, taxiway conditions
77	WG	GROUND HANDLING IMPAIRED BY ADVERSE WEATHER CONDITIONS	High winds, heavy rain, blizzards, monsoons etc.
Air Traffic Flow Management Restrictions			
81	AT	AFTM DUE TO ATC EN-ROUTE DEMAND / CAPACITY	Standard demand / capacity problems
82	AX	AFTM DUE TO ATC STAFF / EQUIPMENT EN-ROUTE	Reduced capacity caused by industrial action or staff shortage, equipment failure, military exercise or extraordinary demand due to capacity reduction in neighbouring area
83	AE	AFTM DUE TO RESTRICTION AT DESTINATION AIRPORT	Airport and / or runway closed due to obstruction, industrial action, staff shortage, political unrest, noise abatement, night curfew, special flights
84	AW	AFTM DUE TO WEATHER AT DESTINATION	
Airport and Government Authorities			
85	AS	MANDATORY SECURITY	Passengers, baggage, crew, etc.
86	AG	IMMIGRATION, CUSTOMS, HEALTH	Passengers, crew
87	AF	AIRPORT FACILITIES	Parking stands, ramp congestion, lighting,

			buildings, gate limitations etc.
88	AD	RESTRICTIONS AT DESTINATION AIRPORT	Airport and / or runway closed due to obstruction, industrial action, staff shortage, political unrest, noise abatement, night curfew, special flights
89	AM	RESTRICTIONS AT AIRPORT OF DEPARTURE	Including air traffic services, start-up and pushback, airport and / or runway closed due to obstruction or weather (restriction due to weather in case of AFTM only) industrial action, staff shortage, political unrest, noise abatement, night curfew, special flights
Reactionary			
91	RL	LOAD CONNECTION	Awaiting load from another flight
92	RT	THROUGH CHECK-IN ERROR	Passenger or baggage check-in error at origination station
93	RA	AIRCRAFT ROTATION	Late arrival of aircraft from another flight or previous sector
94	RS	CABIN CREW ROTATION	Awaiting cabin crew from another flight
95	RC	CREW ROTATION	Awaiting flight deck, or entire crew, from another flight
96	RO	OPERTIONS CONTROL	Re-routing, diversion, consolidation, aircraft change for reasons other than technical
Miscellaneous			
97	MI	INDUSTRIAL ACTION WITHIN OWN AIRLINE	
98	MO	INDUSTRIAL ACTION OUTSIDE OWN AIRLINE	Industrial action (except Air Traffic Control Services)
99	MX	MISCELLANEOUS	No suitable code, explain reason(s) in plain text

Appendix 2: General weather conditions over Gauteng during the period 2010 - 2013

2010

Within the first three weeks of January, the Johannesburg region received persistent rain which led to damage in several homes, flooding and road destruction and many road accidents. Heavy rains fell in the catchment area of the Vaal Dam, which resulted in the dam overflowing for the first time in 13 years. These conditions were a result from a series of successive surface troughs bringing isolated thunderstorms and rain to the area.

These troughs continued through the month of February. On the 3rd of February, 2 people died in a light aircraft crash. The accident occurred near the Wonderboom Airport in Gauteng and the identified cause of the crash was poor weather conditions, specifically mist and low cloud. Thunderstorms caused flooding and mudslides leading to extensive damage in parts of Gauteng on the 17th.

The month of March was not a particularly significant month, apart from the last week of March, where an upper-air trough brought rains to Johannesburg, which further developed into heavy rains as the trough progressed into an upper-air cut-off-low.

At the beginning of April, an upper-air trough moved over the central interior of the country, producing scattered thunderstorms and rain over Gauteng. Heavy falls were measured in parts of Gauteng on the 5th, and rain continued to fall in Johannesburg over the Easter holidays resulting in damage to several roads as the drainage system could not handle the high amounts of water. Dense fog in Gauteng on the morning of the 28th of April caused chaos within the traffic and resulted in six major road accidents. Towards the end of the month, a cold front moved over the eastern parts of the country, with the Atlantic High Pressure System (AHPS) ridging in behind it, bringing in further thunderstorms and rain over Gauteng.

On the 3rd of May, heavy rain fell in Gauteng resulting in numerous car accidents. These rains were a result of a broad surface trough and an upper-air trough over the central interior of the country. Further upper-air troughs brought thunderstorms to the area during mid-May. Towards the end of the month, a cold front was situated north-east of the country with the AHPS strongly ridging in behind it, resulting in isolated thunderstorms and light rain in Gauteng.

In June, Gauteng experienced particularly cold conditions on the 16th and 17th with several roads covered in ice, resulting in several road accidents. Power failures occurred in some places across Johannesburg due to overloading circuits. Surface and upper-air high pressure systems influenced Gauteng for most of the month, resulting in sunny and cool/cold conditions. These conditions also persisted through the month of July.

During mid-August, a cold front was situated over the south-eastern parts of the country with a high ridging in behind it, resulting in partly cloudy to cloudy conditions over the majority of the country. Cold and dense fog conditions were experienced on the 22nd resulted in a light-aircraft crash just after take-off from the Springs airfield in Gauteng.

No significant weather or weather producing systems occurred in September.

In October, the high east of the country ridged in over the north-eastern parts, resulting in isolated light thundershowers. On the 7th, one person was killed and another seriously injured when hit by lightning during a thunderstorm. A series of surface and upper-air troughs (and 2 cut-off low systems) moved over Gauteng during the month, resulting in showers and thundershowers. A woman died in Pretoria on the 24th, after being struck by lightning, and on the 26th, extensive damage from strong winds occurred in parts of Gauteng.

During the first week of November, surface and upper-air troughs over the central parts of the country again led to showers and thunderstorms over Gauteng. Around the 9th, a cut-off low situated over the western interior resulted in scattered thundershowers over the country. On the 18th, a surface trough extending from Namibia to the western parts of the country, together with the high to the southeast of the country ridged over the north-eastern parts, resulting in showers and thundershowers occurring over nearly the entire country. On the 28th, multiple roofs were blown off and trees uprooted and other extensive damage due to severe storms in Gauteng province.

Within the first two weeks of December, surface and upper-air troughs moved over Gauteng. An upper air cut-off low developed over the west coast on the 14th, bringing thunderstorms and showers over the whole country. Intense lightning storms in Gauteng during the second week of December resulted in a dramatic increase in insurance claims for several electrical household appliances. Thunderstorms and rain continued over the next few days, bringing heavy rain to Gauteng. On the 16th, parts of Gauteng experienced flooding, resulting in extensive damage to infrastructure, and more than 200 families were displaced. On the 29th, hundreds of houses were flooded after flash floods occurred in the Soweto area.

2011

During the month of January, widespread floods causing extensive damage were observed countrywide. On the 5th of January, air traffic at ORTIA was affected by heavy rains, and many airplanes were unable to land, resulting in diversions to other aerodromes. These heavy rains also affected many residents of the area due to the associated flooding. Heavy rain fell over the majority of the interior during the week of the 18th, which resulted in the Vaal Dam reaching full capacity. Much of the rain was caused by tropical air circulating across most of the country. During the second week of the month, a surface trough extended from Namibia to the western interior. Together with the high to the south east of the country, rain and isolated thunderstorms occurred over nearly the entire country. This synoptic set-up persisted throughout the month, with a particularly deep surface trough affecting the eastern parts of the country towards the end of the month, resulting in heavy falls over Gauteng.

Towards the end of the first week of February, a broad surface trough was situated over the central interior, with a high east of the country, and an upper-air trough west of the country. This produced isolated thundershowers and light rain over the eastern parts of the country. Towards mid-month, again a surface trough dominated the country, with an upper-air trough over the western parts bringing in further rain and showers.

During mid-March, heavy rain across Gauteng resulting in numerous car accidents, road closures, flooded bridges and burst dams. These conditions were a product of a surface trough over the central interior, together with an upper-air trough south west of the country. A series of surface troughs continued throughout the month bringing further showers and thundershowers.

During the first week of April, the Indian High Pressure System (IHPS) ridged over the eastern parts of the country. Together with a surface trough over the central interior, thundershowers and showers occurred. A deep upper-air trough was situated over the western parts of the country, with a surface trough over the central interior, around the 16th, producing rain over the whole country. Towards the end of the month, a cold front moved eastwards bringing showers, thundershowers and light rain over the eastern parts of the country. Further fronts moved across for the remainder of the month and dense fog effected Gauteng on the 25^{th}.

The general synoptic situation during May was that of a surface trough over the western interior and the surface high ridging from the east, with a series of cold fronts moving over the southern parts of the country. Cold conditions spread across the country during the last week of the month, with a cold front hitting Gauteng on the 26^{th}. After this, a high-pressure system dominated the weather over the country at the end of the month, resulting in mainly sunny skies.

On the 8^{th} of June, heavy rains coupled with strong winds around Gauteng resulted in flooded roads, accidents, traffic light outages and breakdowns. On the same day, a wind storm in Gauteng resulted in 8 trees around a school being torn apart and the school's tin roof was damaged. These conditions were a result of an upper-air cut-off low over the central interior of the country. This system was replaced by a cold front along the south coast with a high ridging in behind.

On the 5^{th} of July, a surface trough was situated over the northern parts of the country, with an associated upper-air trough, and the IHPS ridging over the south eastern parts of the country. This brought very cold conditions and light rain and showers to Gauteng. Over the following few days, this synoptic situation was replaced by a high pressure resulting in fine weather.

A high pressure system dominated the country with the first week of August, resulting in sunny and warm conditions. Hail and rain was observed over the southern parts of Gauteng on the 15^{th} of August, resulting in very cold conditions in places. These conditions were a result of the high pressure moving further south east of the country, bringing in moisture from the Indian Ocean. For the remainder of the month, numerous cold fronts and troughs moved across the southern parts of the country, however did not influence the weather of Gauteng.

Within the first week of September, high pressure conditions persisted, resulting in pleasant weather over Gauteng. During the second week of the month, a surface trough to the west produced light rain and isolated showers. This trough was replaced by a high pressure system causing mainly sunny conditions once again. Towards the end of the month, a surface trough over the western parts of the country, together with the high south east of the country, brought isolated thundershowers and light rain to Gauteng.

Within the first weekend of October, heavy rains fell in Gauteng, resulting in lengthy power failures and many road accidents. Severe storms swept through Gauteng on the 02nd of the month, together with a tornado which hit the Duduza settlement (south of Gauteng). This caused much destruction and hundreds were left homeless. A surface trough over the central parts of the country with a high south east of the country produced the unsettled weather. Around the third week of the month, an upper-air trough associated with an upper-air cut-off low was situated over the central interior, resulting in thundershowers and showers over nearly the entire country, including Gauteng. This system was replaced by an upper-air high towards the end of the month, bringing in hot and fine conditions over Gauteng.

Very hot conditions were reported in parts of Gauteng on the 12th and 13th of November, resulting in an increase in the number of patients to various hospitals with heat related conditions. On the 22nd and 23rd, numerous road accidents were reported and several roads closed due to heavy rains which produced localised flooding. A succession of surface troughs moved across the country, bringing summer rain to Gauteng on and off during the whole month.

Over the first week of December, a series of upper-air troughs brought showers and thundershowers to Gauteng. Heavy falls were measured on the 13th, produced by an upper-air cut-off low. Heavy falls were again reported on the 23rd due to a stationary surface trough over the central interior. Towards the end of the month, a surface trough extended from Namibia to a low south east of the country, with a deep upper-air trough to the west. This resulted in widespread thundershowers and showers.

2012

During the beginning of January, a surface trough over the central interior, with an upper-air trough over the western parts of the country, resulted in showers over the whole eastern part of the country. During the middle of the month, a tropical storm (Dando) was situated over the Mozambique Channel. This system produced isolated thundershowers and showers as well as light rain over the eastern parts. Towards the end of the month, a surface trough over the central interior associated with an upper-air trough, resulted in thundershowers and showers over Gauteng. The wet weather resulted in 2 major road accidents on the 24th where at least 60 people were injured.

Towards the end of the first week of February, a surface trough over the central interior, with a high east of the country, produced isolated thunderstorms and light rain in places over the whole country. On the 8th, rainy weather in Johannesburg resulted in at least 31 road accidents due to the slippery road conditions. A severe thunderstorm hit the northern parts of Gauteng on the 21st and 22nd, which resulted in power outages and flooding. Extreme winds lifted a couple of roofs from buildings and damaged windows. At Grand Central Airport, 2 light aircrafts were turned upside down during the extreme winds. A succession of surface troughs brought thundershowers and showers on and off throughout the month.

The beginning of March saw tropical storm Irina over the Mozambique Channel, however this system did not bring any significant weather to Gauteng. Lightning resulted in disruptions to train services across Gauteng on the 10th and 12th. This was a result of a surface trough over the western interior together with an upper-air trough to the west as well as the high ridging in the south-east of the country. Towards the end of the month, a surface trough extended from Namibia to a low over the south-east coast, resulting in isolated thundershowers across Gauteng.

At the end of the first week of April, a cold front moved to the central parts of the country, with a high ridging in behind it. This brought isolated showers and light rain to Gauteng. This system was replaced by a high-pressure system which brought mostly sunny conditions. By the 19th, a surface trough was situated over the western interior, and the Indian high ridged in over the eastern parts, bringing isolated showers and light rain to Gauteng once again. Towards the end of the month, thundershowers and showers fell in places over Gauteng due to ridging high over the north-eastern parts of the country and a surface trough to the west.

A high-pressure dominated the weather in the first week of May, bringing settled conditions. On the 23rd, dense fog occurred in parts of Gauteng, resulting in a serious road accident where 5 were killed and 11 seriously injured. Many cold fronts and troughs moved across the southern parts of the country, but did not affect Gauteng.

On the 9th of June, a series of cold fronts moved over South Africa, bringing cold to very cold conditions over the entire country. On the 23rd, strong winds associated with a tornado, hit the Vaal Dam. One person lost their life and several were injured. The cause of these conditions was a surface low and an upper-air cut-off low over the south-west of the country.

In July, no significant weather occurred over Gauteng.

On the 7th of August, snow and very cold conditions occurred over nearly the entire country, including Gauteng. The combination of a cold front east of the country and associated upper-air cut-off low over the central parts, as well as a high pressure system ridging in behind them, brought the snow, rain and cold conditions. Several cold fronts swept across the southern parts of the country during the remainder of the month, but did not significantly affect Gauteng.

The beginning of September had a surface trough situated over the central interior with an upper-air cut-off low over the western interior. This brought heavy rain and thunderstorms which caused flooding in many parts of Gauteng on the 5th. Over the 5th and 6th, 66 cars were involved in reported accidents in Johannesburg. Severe storms, including hail occurred in Johannesburg on the 6th, which also resulted in many flight delays at ORTIA. The weather also brought large delays to train services in Gauteng. Rainfall continued over the next few days as a result of the synoptic situation. By mid-September, a cold front had made its' way to the central and eastern parts of the country, bringing further rainfall to Gauteng. By the end of the month, an upper-air cut-off low and a surface trough over the northern parts of the country, again brought showers and thundershowers to Gauteng.

On the 8th of October, a surface trough was situated over the western interior, with the IHPS ridging over the eastern parts, thundershowers and light rain occurred in parts of Gauteng. This scenario continued over the next few days. By mid-October, an upper-air trough west of the country, brought further thundershowers and showers to the region. A thunderstorm producing hail the size of golf balls as well as strong winds hit parts of Gauteng on the 20th, causing extensive damage to cars and buildings. These conditions were caused by a surface trough over the northern parts and an upper-air cut-off low over the western parts of the country.

Severe hailstorms hit the eastern parts of Gauteng on the 8th and 9th of November. Some of the hailstones were measured as golf ball size, and severe hail damage occurred. These storms were a product of a surface trough over the western and central interior, coupled with a high south-east of the country. A similar synoptic set-up brought further thundershowers and showers to Gauteng around mid-November. Heavy falls were measured in parts of Gauteng on the 25th, a result of a surface trough extending from Zimbabwe to a low along the east coast. Towards the end of the month, the dominant synoptic situation was a surface trough from Namibia to a low over the south-eastern interior, with a high east of the country. This brought further rainfall to Gauteng.

In the beginning of December, a cold front was situated south-west of the country with a surface trough over the western interior and a high east of the country, bringing showers and thundershowers to Gauteng. A succession of surface and upper-air troughs brought showers and thundershowers to Gauteng on and off for the whole month.

2013

During the beginning of January, a surface trough was situated over the central interior and the IHPS ridged in over the eastern parts, bringing showers and thundershowers to Gauteng. This scenario dominated through the first week of the month. By the 12th, a tropical low over Zimbabwe, brought further rainfall to the eastern parts of the country. Between the 15th to the 21st, a tropical low-pressure was present over Botswana, which moved to the southern parts of Mozambique, resulting in further rainfall over Gauteng.

During the beginning of February, a surface trough extended from Botswana to the central interior, bringing showers and thundershowers to the eastern parts of the country. Around the middle of February, a surface trough over the western interior, together with a high south-east of the country, brought further rainfall to Gauteng. Around the 20th, a cold front had moved to the east of the country with a high ridging in behind it. This brought showers and thundershowers to the province. Tropical cyclone Ha-Runa was situated in the southern parts of the Mozambique Channel on the 20th and 21st. Towards the end of the month, highs ridging in from the east and south-east brought further rainfall to the Gauteng.

Within the first week of March, a surface trough persisted over the western interior and the AHPS ridged in over the south-eastern parts, bringing showers and thundershowers to

Gauteng. On the 13th, several car accidents occurred due to wet, rainy conditions in the northern parts of Gauteng. A succession of surface troughs continued to move across the country during the middle and towards the end of the month, bringing thundershowers and showers to Gauteng at times. Around the 28th, a cold front together with an upper-air trough over the western interior caused more rain in places.

On the 4th of April, strong winds occurred in parts of Gauteng and blew a tree over which affected a train railway system, causing major disruptions. These winds were brought by a thunderstorm in the area from an upper-air trough. Heavy rains over the southern parts of Johannesburg on the 19th resulted in damage to properties and infrastructure. These conditions were brought about from a cold front situated over the northern parts of the country, with a high ridging in behind it, and an upper-air trough over the western interior.

On the 11th of May, a high to the east of the country brought very cold to cold conditions with thundershowers and light rain to Gauteng. The IHPS continued ridging intermittently during the month, bringing rainfall at times to Gauteng.

During June and July, a series of cold fronts moved across the country with high pressure systems ridging in behind them. These conditions did not bring any significant rainfall to Gauteng, only low clouds with misty/foggy conditions at times.

During the first few days of August, a surface trough was situated over the central interior with a ridging high over the eastern parts of the country. This produced scattered thundershowers and showers over Gauteng. This synoptic situation occurred again around the 11th, bringing further showers to Gauteng. Heavy falls were measured in places over the province on the 19th, as a cold front had moved across the northern parts of the country, bringing cold and wet conditions.

During the middle of September, a surface trough over the central interior and a high east of the country caused light rainfall over Gauteng. This synoptic situation dominated Gauteng again towards the end of the month, brining further rain to the province.

On the 7th of October, heavy rain caused numerous delays at ORTIA and also resulted in traffic congestion. These conditions were produced by a surface trough over the central interior, with a high ridging in over the north-eastern parts of the country. This synoptic situation continued on and off during the remainder of the month. Over the 10th and 11th, strong winds blew off the roofs of many buildings and homes in Gauteng leaving hundreds homeless. On the 17th, a severe storm with strong winds and heavy rain produced extensive damage to homes and buildings. Heavy rainfall that fell across Johannesburg on the 19th and 20th caused numerous and very serious road accidents and also left some areas without electricity.

On the 11th of November, a hailstorm swept across parts of Johannesburg that left hailstones the size of golf balls. This caused extensive damage to buildings and cars. A thunderstorm on the 13th resulted in hundreds being left homeless. A severe hailstorm hit parts of Gauteng on the 28th resulting in extensive damage. Again, the hailstones were reported to be golf ball size. The storm caused flight disruptions at ORTIA. These events were attributed to a surface trough over the central interior with a high east of the country.

During the first week of December, an upper-air cut-off low developed over the western parts of the country, causing thundershowers over the eastern parts of the country. Localised flooding occurred in parts of Gauteng on the 10th. This was the product of a surface trough over the central interior with an upper-air cut-off low to the west. For the remainder of the month, a series of surface troughs brought on and off thundershowers and rain to Gauteng. Flash floods after heavy rain affected several residents in parts of Gauteng on the 18th.

Appendix 3: Historical Weather Parameters at O.R. Tambo International Airport for the Period 2010-2013

Table 24: Number of recorded thunderstorm days for the period 2010 to 2013 at O.R. Tambo International Airport and climatic average.

Month	2010	2011	2012	2013	Average
January	20	10	19	10	12.4
February	11	10	12	13	8.1
March	15	12	9	6	8.0
April	5	5	5	6	4.4
May	3	3	0	1	1.5
June	0	1	0	0	0.4
July	0	0	0	0	0.7
August	0	1	0	1	1.2
September	0	1	9	0	2.6
October	11	8	14	11	8.8
November	13	10	11	15	12.1
December	17	13	10	12	12.6
Total	95	74	89	75	73

Table 25: Number of recorded fog days for the period 2010 to 2013 at O.R. Tambo International Airport and climatic average.

Month	**2010**	**2011**	**2012**	**2013**	**Average**
January	3	1	0	0	2.1
February	0	0	0	2	2.1
March	3	0	2	1	4.1
April	8	7	1	2	4.6
May	5	2	2	1	4.6
June	2	0	0	2	3.3
July	2	1	1	2	3.3
August	3	0	0	1	2.2
September	1	1	3	0	2.4
October	1	0	3	0	2.5
November	1	1	1	0	2.4
December	1	2	0	4	1.6
Total	30	15	13	15	35

Table 26: Average temperatures measured at 0800 SAST in Degrees Celsius for the period 2010 to 2013 with monthly climatic averages at 0800 SAST at O.R. Tambo International Airport.

Month	2010	2011	2012	2013	Average
January	18.1	17.5	18.7	19	17.9
February	18.8	17.1	18.8	18.4	17.1
March	17.7	18	16.7	16.4	16
April	14.7	13.6	13.4	14.1	13.3
May	12.2	11.5	13.1	12.3	10.3
June	7.7	7.7	7.8	9	6.7
July	7.6	5.8	8.3	9	6.8
August	10.1	9.9	11	8.8	9.5
September	14.7	14.9	12.3	15.1	13.3
October	17.4	16.9	16.2	15.7	15.4
November	18.1	17.7	17.8	18.3	16.7
December	18.4	18.5	18.1	17.6	17.7

Table 27: Monthly rainfall in millimetres for the period 2010 to 2013 with monthly climatic averages at O.R. Tambo International Airport.

Month	**2010**	**2011**	**2012**	**2013**	**Average**
January	269	170	126	106	125
February	132	64	92	34	90
March	101	135	51	34	91
April	98	69	16	117	54
May	35	7	0	15	13
June	0	22	3	0	9
July	0	0	0	0	4
August	0	5	0	7	6
September	0	2	95	2	27
October	29	82	71	87	72
November	110	80	70	129	117
December	209	209	143	176	105
Total	982	845	666	707	713