

The Influence of Climate Change and Variability on Aircraft Take-off and Landing Performance; a Case Study of the Abeid Amani Karume International Airport-Zanzibar

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Abstract

Climate change (CC) and variability have been world widely reported to pose number of risks in aviation industry including accidents, astray, and other operational difficulties. The impact of weather on landing and take-off performances has been several times experienced at Abeid Amani Karume International Airport (AAKIA); however, the influence of climate change and variability to the aircraft performance needs to be assessed. Thus, this study investigated the influence of climate change and variability on aircrafts take-off and landing performances. Specifically, the study investigated; i) the influence of climate change on Take-off Distance Required (TODR) and Maximum Take-off Mass (MTOM) for different types of aircraft; ii) the influence of climate variability to the aircraft landing performance on light, medium and heavy aircraft and lastly, iii) the study investigated the seasonal and annual variability on aircraft landing performance due to climate variability. The datasets used in this study include the eight years (2014-2021), aircraft operational records (diversion and missed approach events) and Aviation Routine Weather Reports (METAR) records which were utilized as the indicators for landing performance, the long-term (1990-2020) annual maximum temperatures (Tmax) which was used to determine the TODR and MTOM. Statistical tools including mean, percentage changes, correlations, regression, and the chi-square test were used for analysis and hypotheses testing. The results revealed that light and medium aircraft categories were significantly most affected on diversion events as compared to the heavy categories; however, for the missed

approach events the impact was vice versa. Moreover, the seasonal and annual variability on diversion and missed approach events were significantly different (at $p \leq 0.001$). As for the take-off performance, results show that the TODR and MTOM were significantly increasing and decreasing (at $p \leq 0.001$), based on increasing air temperatures. Therefore, the study concludes that the changing climate has significantly affected aircraft by increasing the TODR and decreasing the MTOM, while the climate variability has significantly affected landing performance by influencing the diversion and missed approach events. Thus, the study recommends (i) further research works including the feasibility study on runway extension for the safety of future aircraft operations at the AAKIA and (ii) proper maintenance and improvement of the Instrumental Landing Systems (ILS) as an adaptation measures to the landing aircraft during bad weather events.

Keywords

Aircraft Take off/Landing Performance, Missed Approach, Diversion, Take off Distance Required, Maximum Take-off Mass, Diversion, Missed Approach

1. Introduction

Currently, Climate Change (CC) has become a very crucial issue, which raised number of concerns about its impacts on human life and the environment [1]. The CC is mainly caused by the increased anthropogenic activities resulting in doubling or tripling of the Green House Gas (GHG) emission in the atmosphere, which in turn causes the adjustment of the climate radiative budget [2]. Fossil fuels used in industries, transportation sectors (aircrafts emissions), and agricultural activities are believed to be among the main contributors of the GHG emission into the atmosphere [3]. [4] and other IPCC reports noted that global warming threats have increased significantly as compared to the pre-industrial level. Also, projection models have shown that global warming impacts will alarmingly rise due to increased GHG emissions as narrated by Special Report on Emission Scenarios—IPCC SRES [5].

Aviation, like any other form of transport is dependent on the atmospheric weather conditions. Therefore, the need of analyzing the impact of the environment on the lift force, drag, and a thrust of the aircraft is vital for the safe aircraft operations. The values of these parameters are proportional to the air density [6]. In practice, the effect of an altitude on the engine thrust is considered, while the influence of the temperature and humidity is often overlooked. Higher values of these two parameters tend to decrease the lift force and engine thrust, the condition which limits safe take-off of heavy loaded aircraft (including aerostats “lighter-than-air aircraft”). Also higher humidity increases the likelihood of inlets icing and can cause engine shutdown during flight [6].

For the influence of airport altitude on aircraft performances, studies have shown that both aircrafts lift force (P_z) and drag force (P_x) are functions of the

atmospheric air density (ρ_H) as shown in Equations (1) and (2)

$$P_z = \frac{1}{2} C_z V_H^2 S \rho_H \quad (1)$$

$$P_x = \frac{1}{2} C_x V_H^2 S \rho_H \quad (2)$$

where: C_z = Lift force coefficient, C_x = Drag force coefficient, V_H = Flight speed, S = Wing lifting surface. These factors influence the changes of the lift and the drag forces, while the changes in temperature and altitude of the airport are proportional to the changes in the density of the air column as shown in Equations (3) and (4) for the dry air conditions.

$$\rho_H = pR^{-1}T^{-1} \quad (3)$$

$$\rho_H = pg^{-1}A^{-1} \quad (4)$$

where: R = universal gas constant for dry air ($287 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$), p = air pressure, A = Airport altitude, g = acceleration due to gravity and T = surface air temperature.

Density is directly proportional to pressure and indirectly proportional to temperature/airport altitude. Since the lift force coefficient, is much greater than that of drag force, the decrease in air density decreases drag force, but much more lift force is reduced. During take-off, pilot can increase lift force by flap extension, but this increases the drag force as a result, the necessary value of the lift force can be achieved by increase of flight speed. This causes building of the longer runways, and in addition as already mentioned, under such conditions, the crew has less thrust from the engines [7].

The aircrafts manufactured certified operating weights are developed during the aircraft design and certification phase, and are laid down in the aircraft type certificate and manufacturer's specification documents such as the Aircraft Flight Manual (AFM) and Aircraft Weight & Balance Manual (AWBM) [8]. Manufacturer certified operating weights are categorized as: 1) Maximum Taxi Weight (MTW) *i.e.* the maximum weight for ground maneuver as limited and/or authorized by airplane strength and airworthiness requirements. This includes the weight of fuel for taxiing to the take-off position; 2) Maximum Take-off Weight/Mass (MTOW/MTOM) which is referred to as Brake Release Gross Weight. This is the maximum weight/mass for take-off as limited and/or authorized by airplane strength and airworthiness requirements. This is the maximum weight at the start of the take-off; 3) Maximum Landing Weights (MLW) means the maximum weight for landing as limited and/or authorized by airplane strength and airworthiness requirements; 4) Maximum Zero-fuel Weight (MZFW) means the maximum weight permitted before usable fuel and other specified usable fluids are loaded. The MZFW is limited and/or authorized by strength and airworthiness requirements [8].

As for the runway operations, this is defined based on the requirements and standards of the organization. For instance, International Civil Aviation Organ-

ization (ICAO) defined the runway as a rectangular area on land aerodrome prepared for the landing and take-off of aircraft. In addition, the Federal Aviation Administration (FAA) has defined the runway strip as a strip surrounding the runway that is prepared or suitable for reducing damage to aircraft in the event of unintentional excursion from the runway surface. Whereby, the Runway End Safety Area (RESA) is defined as the area beyond the end of the runway that is prepared or suitable for reducing damage to aircraft in the event of undershoot or overshoot [9].

In aviation industry, changes in weather and climate poses significant risks on aircrafts operation especially during landing and cruising. Severe weather conditions including strong wind (gale force), visibility/ceiling, high density altitude, turbulence, carburettor icing, updrafts/downdrafts, precipitation, icing, thunderstorms, wind shear, thermal lift, temperature, and lightning have great impacts to aviation (normally causes accidents) [10]. Number of studies including [11] have been conducted to understand the impact of extreme temperatures on take-off performance and future operational projection has been conducted on different airports. [11] has noted that air temperatures have significant role on altering the air density that affects aircraft take-off performance (*i.e.* at higher temperatures, less air density resulting the aircraft to run for long distance before the lift-off). Moreover, [12] noted that for overcoming the impact of the extreme temperatures for safe operations during take-off, the airlines have to reduce payloads (*i.e.* passenger or cargo) especially when the existing runway does not support the required take-off distance. In addition, [13] noted that the TODR and MTOM were affected with the increase of temperatures for the corresponding year of observations. Moreover, [14] found that the performance of aircraft on departure was affected significantly by causing a delay for the scheduled airline that was slotted to depart at the specified time at Oliver Tambo International Airport in Johannesburg-South Africa due to bad weather. Also, [14] noted that thunderstorm, fog, rainfall and icing are among the weather elements, which may cause problems on aircrafts during take-off.

The Abeid Amani Karume Interantional Airport (AAKIA) is the only international airport in Zanzibar (Unguja and Pemba Islands) that accommodates international flights, and it is a great contributor to the Zanzibar economy through tourism industries, which currently contributes to 27% to the Zanzibar Gross Domestic Product (GDP) [15]. Moreover, [16] noted that tourism industry helps in improving individual's living standards and the nations through foreign exchange earnings, which may raise the country's GDP. Indeed, the assessment made by UNICEF and Revolutionary Government of Zanzibar [17] noted an increase of 90% in international tourist arrivals from 42,141 in 1990 to 433,474 in 2017, thus approaching the national tourist target of 500,000 by 2020. In daily operations number of airlines and aircraft operators (captains and their teams) at the AAKIA has been forced to release their payloads (cargo and passengers) from time to time whenever severe weather restrict safe take-off

as was narrated by Zanzibar Aviation Services & Travel Trade (ZAT) (ground handlers) administration. Though these events have negative implications to the economics of both airlines and passengers, but currently either no or limited study has been conducted to examine the extent to which the climate change induced severe weather events affects the aircrafts/airlines and individuals in Zanzibar.

Initial investigation on the impact of temperatures on aircraft's take-off performance at AAKIA was conducted on 31st December, 2020 using an aircraft DH8D (Q400 bombardier) 5HTCB owned by the Air Tanzania. The preliminary investigation results using the aircraft built in Electronic Flight Bag (EFB) indicated that a distance 1708 m was required before the aircraft to achieve a lift-off at 30°C as compared to a distance of 1850 m at 40°C, which is equivalent to an increase of 142 m under constant conditions (*i.e.* zero winds, QNH 1013 and maximum loading).

Number of studies including [18] [19] [20] have noted the influence of weather and climate system to Zanzibar. However, no or limited documented information, examined or studied the influence of climate change and variability on aircraft take-off and landing performance at AAKIA. The phenomenon could limit the future growth of tourism industry in Zanzibar [15]. Thus, this study aimed to investigate the influence of climate change and variability on aircraft take-off and landing performance at AAKIA to raise awareness to the government, airlines, and other stakeholders on the impact of climate change and take necessary adaptation measures for smooth running of the airport and aircraft operations. Specifically, the study aimed to examine the influence of climate variability using severe weather elements including low clouds, CB, TS among others, on diversion and missed approach events with respect to aircraft categories, annual and seasonal variability. Besides, the study investigated the relationship (trend) of the inter-annual variability of TODR for the different type of aircraft under mean maximum temperature and zero wind conditions per year; and lastly, the inter annual variability of MTOM for the jet-engine and turboprop aircraft was determined. This study has significant applications to aircraft operators (airlines, pilots, crew among others), as a base line information to aviation managers and policy makers on focusing to the special attention on adaptation measures for TODR and MTOM which might necessitate the extension of the existing runway toward the South with the required Runway End Safety Area (RESA). However, the ongoing European project on undercarriage-less aircraft operations has suggested the improvement of takeoff performance if the airport operators will adopt to Magnetic levitation runway Concept-Gabriel concept [21], but the AAKIA adaptation capacity might be economically limited. Furthermore, the study results might be compared with the future study on landing performance with the ILS in operation, as adaptation measure to assess its efficiency on reducing the diversion and missed approach events at the AAKIA.

2. Methods

2.1. Description of Study Area

The Abeid Amani Karume International Airport (AAKIA) is located in Zanzibar urban west region, at “West B” district in Kisauni area in Unguja Island. According to Tanzania Civil Aviation Authority (TCCA), Aerodrome Reference Point (ARP-geographical coordinates) the airport is located at 061329.61S and 0391330.63E [22]. It comprises of tarmac runway (which is aligned in North-South direction) and networks of taxiways with three terminal buildings. The airport has two runways namely Runway 18 (R18) and Runway 36 (R36) based on the landing or take off direction. The length of the runway is 3.022 km [22], **Figure 1**.

2.2. Datasets Used

The study utilized climate data for two periods namely, 1) short term *i.e.* eight-year



(a)



(b)

Figure 1. (a) Airside view of Abeid Amani Karume International Airport (AAKIA); (b) the Airside view of AKIA Runway for Landing and Take-off of Aircraft with Network of Taxiways. Source: Aerial photograph captured by microlight aircraft of the Zanzibar Recreational Products Co. Ltd (ZRP).

(2014-2021) observed data. This data was aimed on addressing the influence of the variability of severe weather events (e.g. heavy rains, cloud cover, strong winds, Cumulonimbus clouds (CBs) and Thunder Storms (TSs) among others) to the variability of the aircraft landing performance. The occurrence of the missed approach and diversion events in monthly, seasonal and annual time scales were used as the indicators on reduction of the landing performance. These data were extracted through the Meteorological Terminal Aviation Reports (METAR) acquired from TMA-Zanzibar office and the monthly Air Traffic Management operational reports, and daily events registers or Air Traffic Control logbooks from Tanzania Civil Aviation Authority (TCAA) -Zanzibar office. 2) The 30-year long term (1990-2020) historical observed data on maximum (Tmax) and minimum (Tmin) temperatures records acquired from TMA-Zanzibar office. This data was used for analysing the take-off performance, where the annual mean Tmax were used as inputs to the Electronic Flight Bag (EFB) system for the TODR and MTOM calculations.

2.3. Analytical Method

The previous severe weather events including TSs, dense cloud cover, poor visibility among others, that were extracted from METAR records were compared with the monthly TCAA ATM reports and the ATC control logbooks to see if these events were associated on declining landing performance (*i.e.* resulted to the diversion and missed approach events). Indeed, all diversion and missed approach events registered in the ATC logbooks and ATM operational reports were recorded and checked if they are associated with the registered severe weather events in the TMA METAR reports. Those, which were associated with weather events, were retained and those, which were not, were filtered out. Moreover, the time of the reported missed approach and diversion event was crosschecked with the time where the severe weather events occurred. If the two coincides, the event was taken as associated with weather, if not the event was considered as not associated with weather. Using these two datasets (*i.e.* TMA-METAR and TCAA ATM reports) all the diversions and missed approaches with their corresponding severe weather events were tabulated and grouped in monthly, seasonal, and annual time scales. As for the accuracy and reliability of the TCAA ATM reports data (information), any diversion or missed approach event found in the report was then confirmed by using the Air Traffic Control logbook and tabulated in a Microsoft excel spreadsheet with corresponding date, month, year and the time of occurrence. Apart from the diversion and missed approach reports, other aircraft information including the Airline involved, the type of aircraft and registration mark, point of departure, passengers on board and the runway-in-use were also incorporated in the tabulated excel sheet. The simple statistics of mean, sum percentage changes were taken and followed by plotting of the sorted severe weather events associated with the diversions and missed approaches in monthly, seasonal and annual scales.

As for the take-off performance, the annual mean T_{max} was calculated and tabulated for the whole period (30 years) and its range was from 16°C to 37°C. These tabulated annual mean T_{max} values were then submitted to the pilots and used as an input to EFB system for different type of aircrafts under investigation. The calculated T_{max} data was fed to the EFBs of five aircrafts namely, Bombardier (DH8D/Q400), Boeing 763 (B763), Boeing 737 (B737), Boeing 738 MAX8, and the Airbus 220 (A220/BCS3). This process was aimed on getting the take-off data for each aircraft in the form of TODR/MTOM (EFB outputs), and was then tabulated with observed T_{max} for further analysis. Other main assumptions (which were additional inputs to the EFB system) under calculations of TODR/MTOM were standard QNH (*i.e.* 1013.25 Hpa) and zero wind.

Moreover, correlations between aircraft categories, annual and seasonal variabilities, with reference to missed approach and diversions due to weather conditions were conducted. In addition, correlation between the annual variability of take-off performance indicators (TODR/MTOM) under the influence of T_{max} , were performed. The, scatter plots, time series, as well as pie charts were used in presenting the results.

Significance tests (at $p \leq 0.05$) were used in either rejecting or accepting the five stated null hypotheses, which include: (i) diversions and missed approaches due to severe weather events have no significant difference between aircraft categories at the AAKIA. (ii and iii) Diversion and missed approach events due to severe weather events have no significant difference with annual and seasonal variabilities (iv and v) There is no significant relationship between the variability of the TODR and MTOM with time.

For the analysis of the variables, the study used the Statistical Package for Social Sciences (SPSS) and Microsoft spread sheet to determine the trend of the variables (weather and aircraft performance) and making the general conclusion. Chi-squared test was employed to find significance of the relationship between the impact of weather and climate variability on aircraft landing at the AAKIA as advised by [23] for categorical data set.

2.4. Results and Discussion

2.4.1. The Annual Variability of Aircraft Landing Performance Due to Weather Conditions

The results of the analysis of the landing performance indicators presented in **Table 1** revealed that for the 8 years period, 115 diversions and missed approaches

Table 1. The inter annual variability of diversion and missed approach events observed at AAKIA.

YEAR	2014	2015	2016	2017	2018	2019	2020	2021	TOTAL
DIVERSION	8	13	7	4	3	3	0	0	38
MISSED APP.	2	7	3	23	11	21	5	5	77
TOTAL	10	20	10	27	14	24	5	5	115

events observed to interrupt the landing of different types/categories of aircraft at AAKIA. In addition, the results showed that the main cause of the observed diversions and missed approaches was the presence of the severe weather events, and hence hindered the smooth operations of these aircrafts. Further results in **Table 1** reveals that 38 (33%) of the total events were associated with diversions, while 77 (67%) were associated with the missed approaches.

The results of the annual variability of the percentage contribution of the diversion and missed approaches are presented in **Figure 2**. The results in **Figure 2(a)** revealed that 2017 and 2019 had higher percentage of missed approach events *i.e.* 23 (30%) and 21 (27%) respectively, while 2014 had only three (3%) events of missed approach. This could be explained by the fact that the years 2017 and 2019, were characterized by weak El Nino influenced the coastal line to be dominated by significant amount of low clouds [24] [20], thereby mostly leads in causing the missed approaches. As for diversions, **Figure 2(b)** revealed that 2015 and 2014 had the highest diversion records of 34% and 21% of the total diversion events, whilst 2020 and 2021 had no records for the diversion event.

2.4.2. The Monthly Variability of Aircraft Landing Performance Due to Weather Conditions

The monthly variability of the missed approach and diversion events at AAKIA is presented in **Figure 3**. The results revealed that for the period of 8 years (2014-2021), 38 diversions and 77 missed approach events were observed from January to December, with the highest frequency of diversions observed in May and December, and that of missed approaches during December through May of the second year (**Figure 3**). This could be explained by the fact that Zanzibar lies on the bimodal rainfall regime and during the MAM period, the area is characterized by abundant and well-distributed long rains “Masika” [24]. Hence, the presence of heavy rains episodes and wide coverage of low clouds hinder the landing performance, resulting in higher frequencies of missed approaches and diversions. Similar cases hold for the OND period except that during this period the weather is characterized by towering clouds and even CBs but with poor temporal and spatial rainfall distribution [19] [24], hence resulting in significant number of missed approaches and diversions.

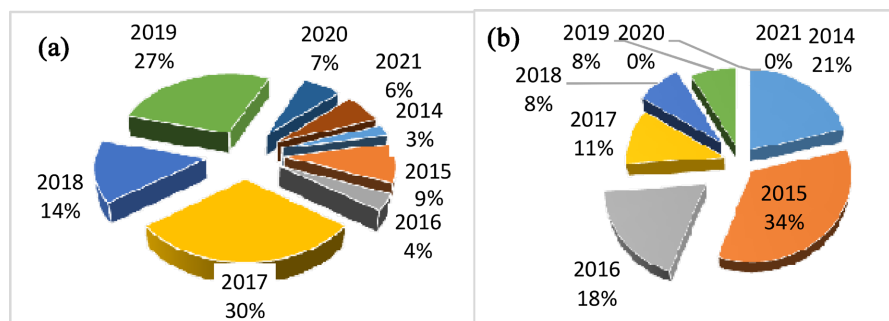


Figure 2. The inter-annual variability of percentage contribution to the total (a) missed approaches—left panel and (b) diversions—right panel.

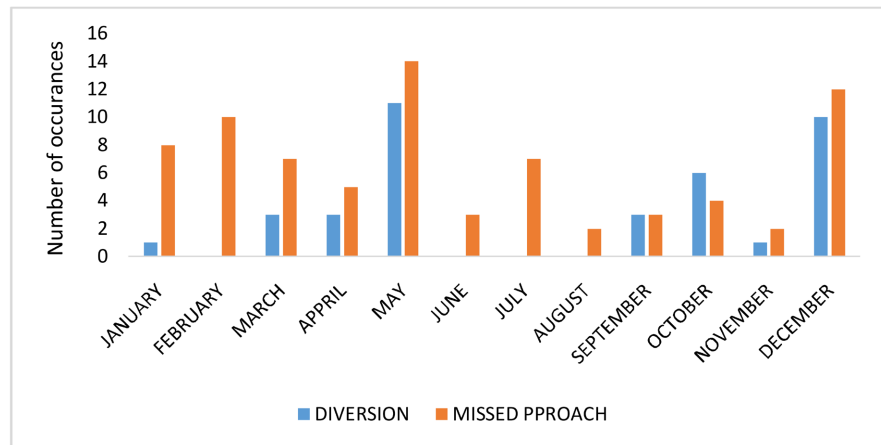


Figure 3. Monthly variability of diversion and missed approach events at AAKIA.

More results, which signify severe weather events responsible to diversion and missed approaches, are presented in [Figure 3](#) which shows that the period during July through November, is characterized by low frequency of missed approaches and diversions. This could be explained by the fact that during this period the weather at AAKIA is characterized by windy conditions and very weak low thin clouds, the situation that might not led to the occurrence of diversions and missed approaches. Besides, results in [Figure 3](#) shows that on average, missed approach events had occurred for each month. This could be explained by the fact that the occurrence of missed approaches events is not only caused by rainfall, visibility or cloud cover, but also wind shear, clear air turbulence among others, may severely results in missed approach events.

2.4.3. Variability of Missed Approaches and Diversions Based on Airlines

The distribution of the frequency of diversion and missed approached for specific airlines presented in [Figure 4](#) shows that Local Operators (General Aviation) including aircrafts operated by Zanair, Tanzanair, Asalaam Air and Coastal Aviation are leading on reporting the diversion events (18) due to severe weather events. As for individual airlines, results showed that Oman Air, Fly Dubai and Precision Air had 15, 13 and 10 diversions events respectively, while Kenya Airways and Air Tanzania, as well as Condo Airline had /6, and 5 diversion events, respectively. Other airlines including Ethiopian Airline, Qatar Airways, Fly 540, VIP flights among others, had less than 4 diversions events. These results indicate that 50% of the reported diversion events contributed by General aviation operators, followed by Precision air (18%) and Oman air (13%). As for the percentage contribution of the missed approaches, results show that the Oman Air, Fly Dubai and Precision Air are leading by having 15, 13 and 10 missed approach events equivalent to 19%, 17% and 13%, respectively. However, result shows that VIP flights had not reported the missed approach events for the whole period of study.

As for the influence of weather on landing performance of aircraft weights (*i.e.* heavy, medium and light aircraft categories), [Figure 5\(a\)](#) reveals that light

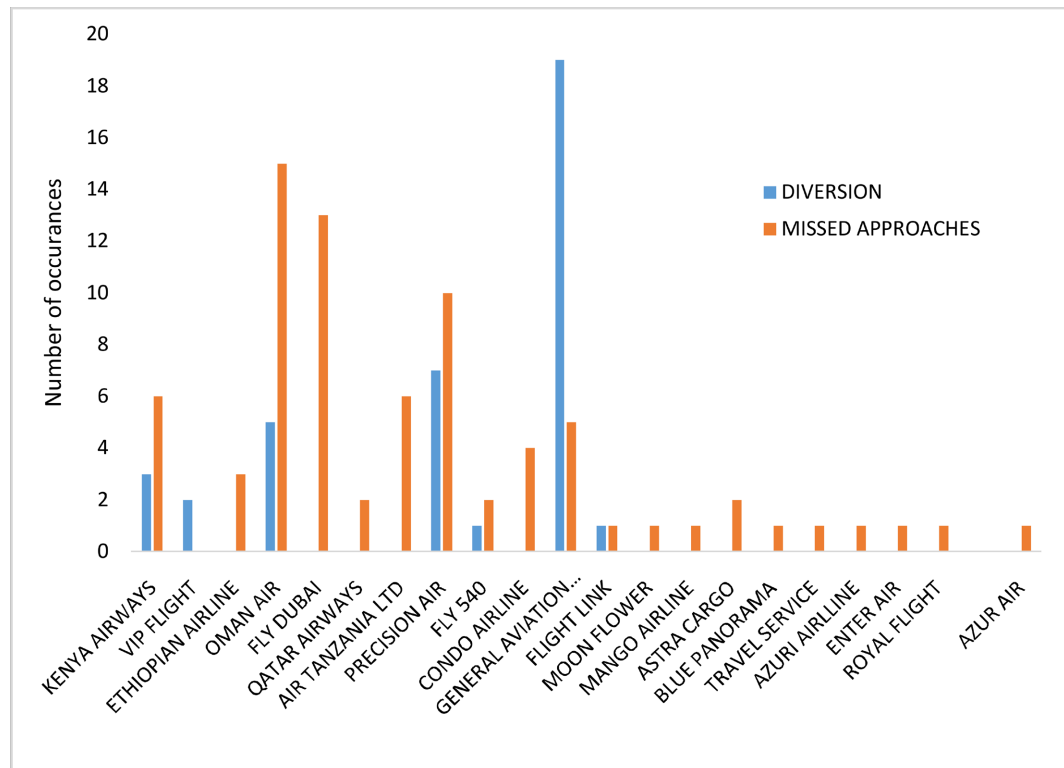


Figure 4. Diversion and missed approach events for specific airlines at AAKIA.

aircrafts are mostly affected by the weather. For instance, 2015 light aircraft category had 8 events (*i.e.* the highest reported number of diversions), medium aircrafts had 6 and 4 diversion events in 2014 and 2015, respectively. Further results in **Figure 5(a)** show that heavy aircrafts had only 3 diversions in 2016 and 1 in 2015 and 2017, respectively. An interesting study finding is that, Super Heavy aircrafts experienced no diversion for the entire study period.

As for missed approaches **Figure 5(b)** indicate that heavy aircrafts had several number of attempts to land (first, second, third etc.) on the respective RWY. Indeed, **Figure 5(b)** show that 2017 was leading on reported frequency of missed approaches. Apart from heavy air crafts **Figure 5(b)** show that also medium aircrafts were affected and resulted into eight 8 events in 2017 and 2019, and only one event per year in 2016 and 2021. Unlike the heavy and medium aircrafts categories, the light aircrafts had experienced fewer missed approach events, for instance, only 4 cases had been reported in 2019 and 1 missed approach per year in 2020 and 2021, respectively.

2.4.4. Inter Annual Variability of Weather Events Posing Threats to Aircraft Landing Performance

As for the variability of weather events that pose threats to landing performance **Figure 6** shows that diversion events are associated with the presence of the rain, heavy towering clouds including CBs, TSs, very low cloud base and events of poor ground visibility. Moreover, results revealed that strong wind conditions did not pose any diversion threats to aircrafts attempted to land. For instance,

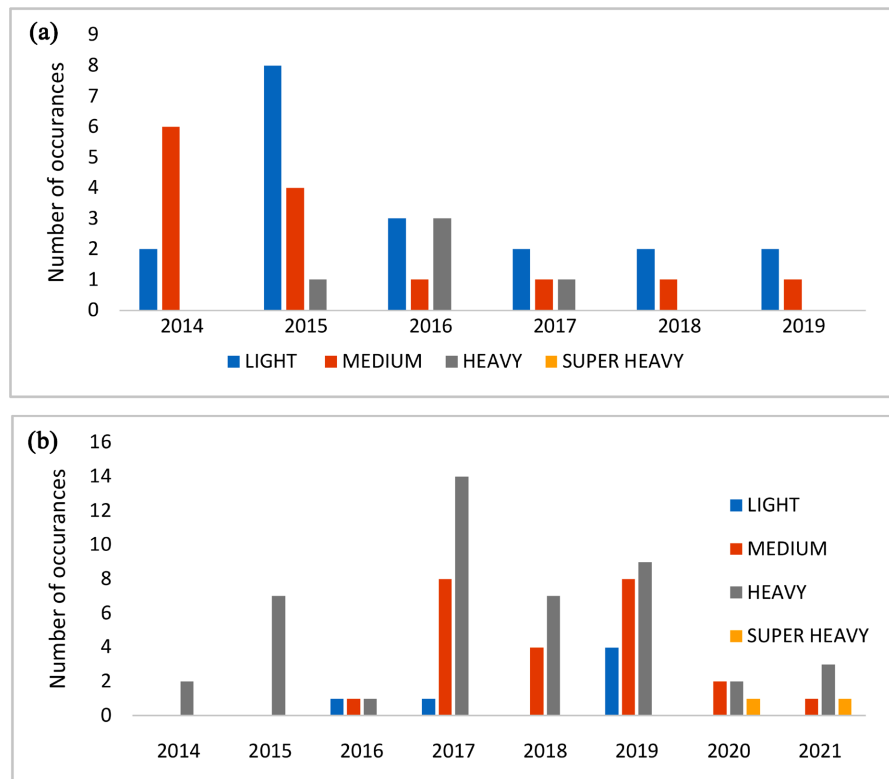


Figure 5. Inter annual variability of (a) diversions and (b) missed approaches for different categories of aircraft.

during 2017 low cloud base, CBs, TSs, and the heavy rain contributed to 4 diversions for each severe weather event, while the poor visibility conditions contributed to 2 events. As for 2018 and 2019, **Figure 6** indicated that severe weather events had the same impact on diversion whereby the poor ground visibility, CBs, TSs, and heavy rain contributed to 4 diversion events, while low cloud base contributed to 3 diversion events per year. As for weather events posed threat on missed approach, **Figure 6(b)** show that missed approach events are associated with the presence of all severe weather events. For example, during 2017 and 2019, the low cloud contributed to 20 and 21 missed approaches events, while CBs and TSs caused 15 and 10 missed approach events. The presented higher records of diversion and missed approaches in 2017 and 2019 could be explained by the fact that 2019 was the wettest year with higher rainfall records especially during October to December (OND) and coincided to MAM 2021 seasonal rains as agreed by [19] [25].

2.4.5. Monthly and Seasonal Variability of the Weather Elements Posing Threats on Landing Performance

The results of monthly and seasonal variability of weather events leading to reduced landing performance at the AAKIA presented in **Figure 7(a)** and **Figure 7(b)** show that diversion events are very common during May, October and December. This could be attributed by the fact that Zanzibar experiences two rainfall regimes of MAM and OND. Thus the months of May, October and December

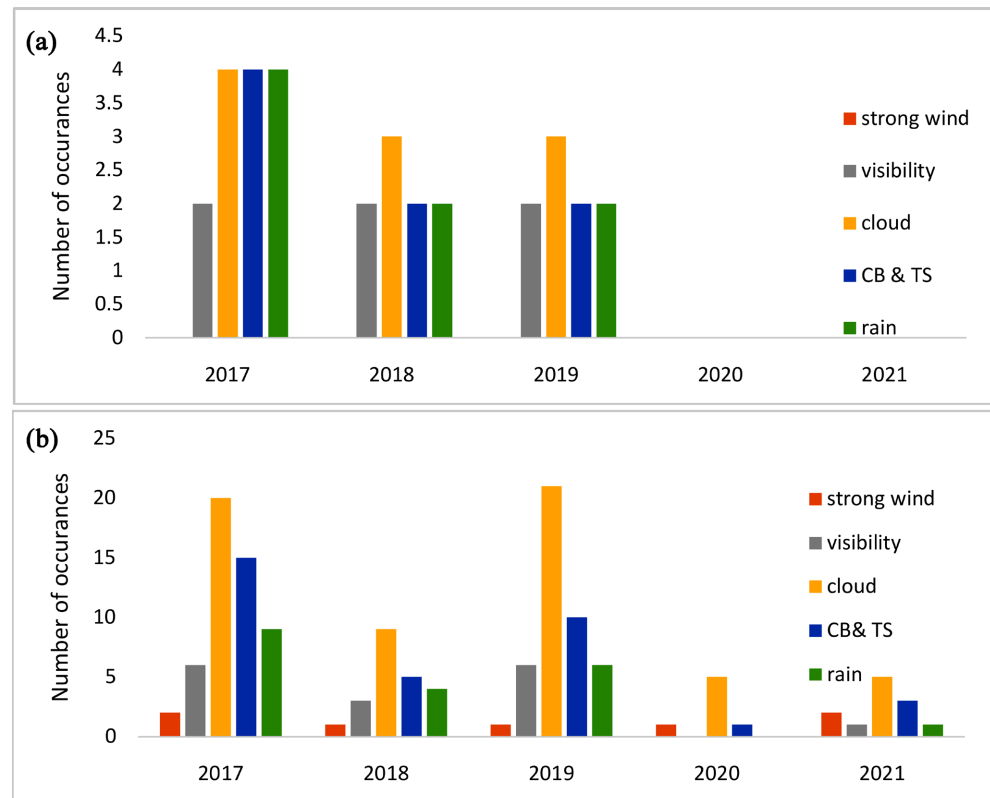


Figure 6. Inter annual variability of severe weather events leading to (a—left panel) diversion and (b—right panel) missed approach events.

falls on the two regimes, indicating that these periods are associated with convective clouds including towering clouds such as CBs as well as tropical cyclones events, these events may result in heavy downpours and strong winds. For instance, during May results indicate that severe weather events contributed to 4 diversions, while during October, the low cloud base contributed to 5 events, CBs, TSs and rain contributed to 4 events; while 2 events were associated with poor ground visibility. Similar case holds for December, where diversion events are mostly contributed by cumulus clouds, which develops to CBs and TSs low clouds contributed to a frequency of 7 events. As for the variability of the weather events resulting into missed approaches, **Figure 7(b)** shows that low cloud base is the most contributor to missed approach. Further results reveals that missed approach events are less common for the months of July, August, and September while the low cloud and strong winds seems to be the most influential contributing factor to the missed approach events during the mentioned period. This could be explained due to the fact that during July to September Zanzibar is having dry conditions associated with cold air and characterized by shallow or thin low clouds and episodes of poor visibilities.

As for the seasonal variability of the missed approaches and diversion events **Figure 7(c)**, shows that DJF and MAM had higher frequency of both missed approaches and diversions, compared to JJA and SON. This could be explained by the fact that MAM and DJF is characterized by the existence of heavy clouds and

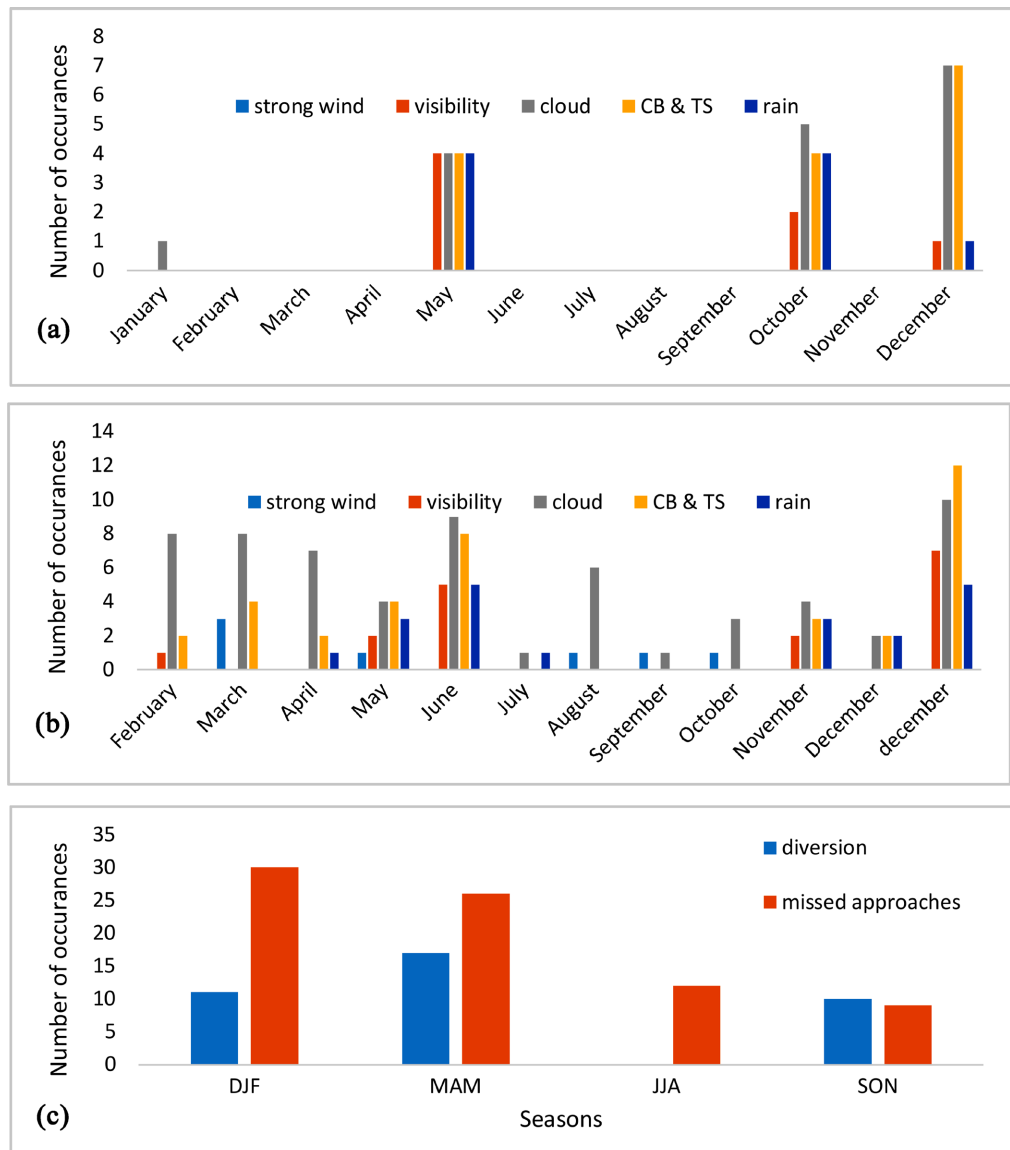


Figure 7. Monthly variability of (a) diversions and (b) missed approaches contributed by severe weather events; and (c) seasonal variability of diversion and missed approach events.

poor visibilities leading to reduced landing performance (*i.e.* increased number of diversions and missed approaches than during JJA and SON).

As for the variability of diversions and missed approach events with reference to runway-in-use, **Figure 8(a)**, revealed that 10 diversions and 42 missed approaches occurred on R18 while 7 diversions and 26 missed approach occurred on R36. This indicated that both runway had encountered nearly the same number of diversion events, with higher number of missed approaches in R18 compared to R36. The monthly variability of the missed approach and diversion events for R18, **Figure 8(b)** revealed that May and December had high frequency of up to 4 events per month, while October had up to 2 diversion events. As for missed approach events, results show that May had up to 9 events, July and December had 7 events per month, while November had no missed approach

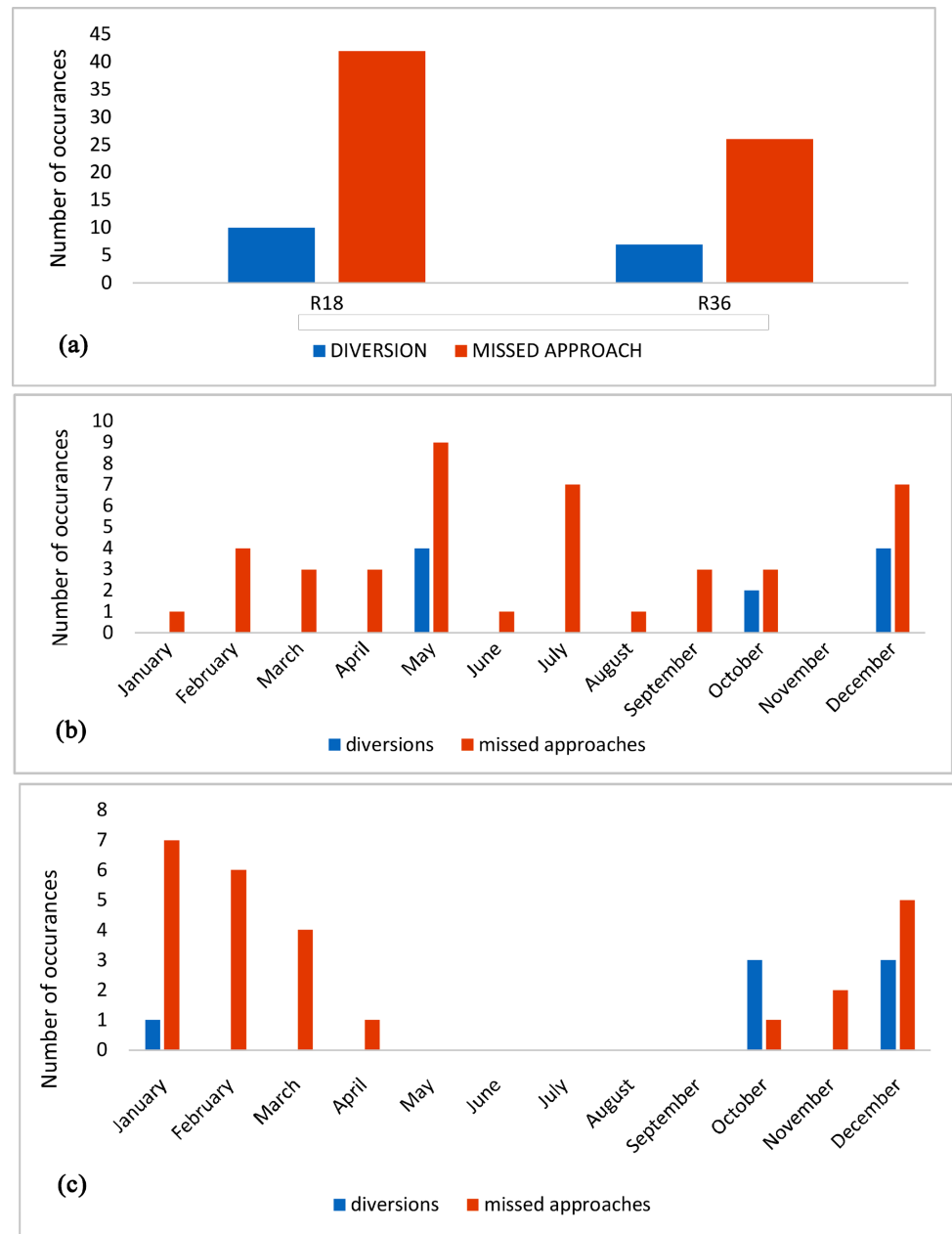


Figure 8. (a) Missed approach and diversion events based on runway-in-use; (b) the monthly variability of missed approach and diversion events for R18; (c) the monthly variability of missed approach and diversion events for R36.

event on Runway 18. More results in **Figure 8(b)** shows that missed approach events were reported from May to September, while higher records of missed approach events were experienced during the months of December, January and February. As for diversion events on R36, **Figure 8(c)** shows that, the higher frequency was in October and December.

2.4.6. The Impact of Maximum Temperature (Tmax) on Aircraft Take-off Performance (MTOM and TODR)

The results of the analysis show that both Tmax and Tmin had an increasing

trend. Tmax increased at $0.03^\circ\text{C}/\text{year}$, with the highest temperature record of 31.8°C observed in 2016 and the lowest record of 30.3°C observed in 2002 (Figure 9(a)), while Tmin had increased at a rate $0.06^\circ\text{C}/\text{year}$ (i.e. twice that of Tmax) with the highest temperature record of 24.4°C in 2019 and lowest record of 21.9°C in 1993 Figure 9(b), respectively. The results of the inter annual variability of the take-off performance indicators i.e. Take-off Distance Required (TODR) and Maximum Take-off Mass (MTOM) for the two turboprop (DH8D) and Jet-engine (i.e. B763, B737, B738MAX8 and A220/BSC3) aircrafts presented in Figure 9(c) revealed that TODR trends were increasing with time at different rates based on the type of aircraft. Also, Figure 9(c) shows that the TODR is increasing with time similar to Tmax and Tmin, and effective from 2005 the TODR for all aircrafts were having positive standard anomalies indicating a shift from negative to positive standard anomalies based on the increased maximum temperatures. In contrast to TODR, the inter-annual variability of the MTOM, Figure 9(d) revealed a negative trend, indicating that MTOM is decreasing with time i.e. the more we go in a climate change environment the maximum loading of the aircraft is expected to be decreased due to increased Tmax and Tmin trends.

Further results in Figure 9(d) show that the highest decrease in MTOM found in last ten years of the 21st century where air temperatures are projected to increase [26]. Thus, the presented results of increasing TODR and decreasing MTOM with time indicates that the airlines are being faced to conditions of flying with less cargo and passengers (i.e. reduced payloads) to meet the take-off

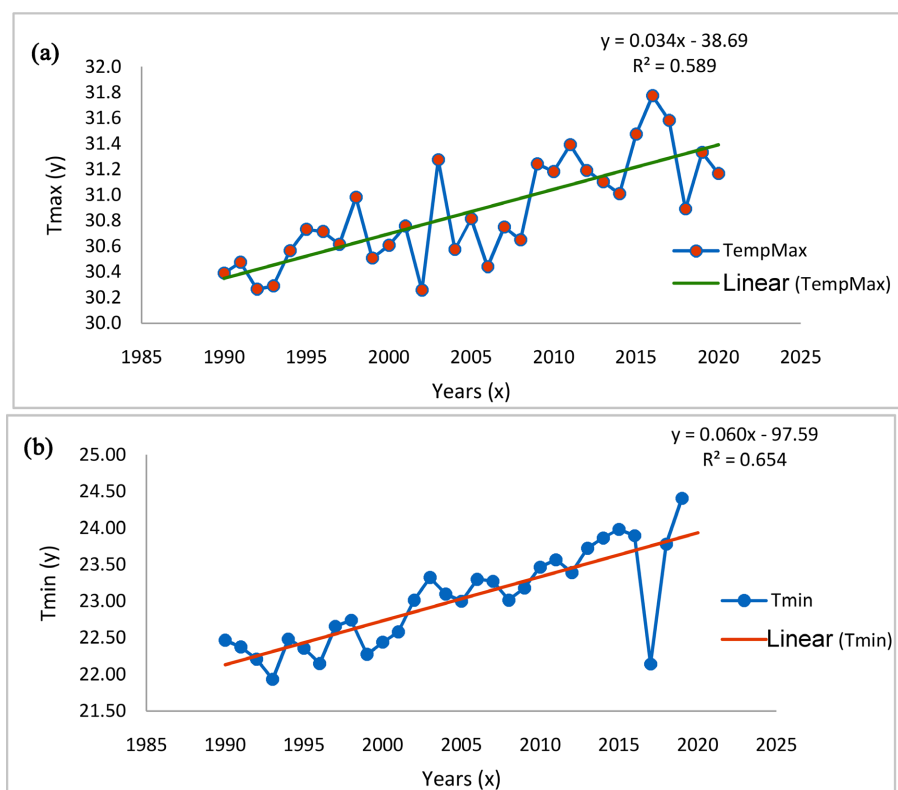




Figure 9. The Inter annual variability of (a) Tmax and (b) Tmin trend (c) TODR and (d) MTOM at Tmax.

requirements under climate change environments with higher increasing rates of Tmax and Tmin as projected in different time scales.

2.4.7. Correlation between the TODR/MTOM, Tmax and Tmin

The results of the Pearson correlations between the TODR/MTOM, Tmax and Tmin presented in **Table 2** indicate that annual mean daily maximum temperature (Tmax) and the year of observation (Year) were found to be significantly and strongly positive correlated, $r(31) = 0.768$, $p < 0.01$. Furthermore, the TODR for the three aircrafts namely B763, B737MAX8, and DH8D were found to be strongly and positively correlated with year of observation $r(31) = 0.664$, 0.704 , and 0.783 , $p < 0.01$, respectively. However, for the A220/BSC3 the correlations were weak and not significant.

As for the correlation between MTOM for the two aircraft namely A220/BSC3 and B737, Tmax, and the year of observation, the results are presented in **Table 3**. The table revealed that MTOM for A220/BSC3 was significantly moderate

Table 2. Pearson correlations analysis for the TODR, Tmax and the year.

	1.	2.	3.	4.	5.
1. Year	–				
2. TMAX	0.77**	–			
3. TODR_B763	0.66**	0.82**	–		
4. TODR_A220/BSC	0.31	0.54**	0.35	–	
5. TODR_B737 MAX8	0.70**	0.88**	0.55**	0.40*	–
6. TODR_DH8D_B	0.78**	0.99**	0.84**	0.57**	0.88**

Note: * $p < 0.05$. ** $p < 0.01$ level (2-tailed) $N = 31$.

Table 3. Pearson correlation of analysis for the MTOM.

variables	1.	2.	3.	4.
1. Year	–			
2. Tmax	0.77**	–		
3. MTOM_A220/BSC3	–0.50**	–0.62**	–	
4. MTOM_B738	–0.70**	–0.92**	0.65**	–

Note: ** $p < 0.01$. Level (2-tailed) $N = 31$; Tmax = Average annually observed maximum daily temperature; MTOM_A220 = Average annually MTOM for the A220/BSC3; MTOM_B737 = Average annually MTOM for the B737.

negative correlated ($r(31) = -0.501$ at $p < 0.01$) with the year of observation, while the MTOM for the B737 was significantly strong negative correlated with the year of observation $r(31) = -0.704$, $p < 0.01$.

2.5. Hypotheses Testing

2.5.1. Landing Performance

The results on the analysis of the stated hypotheses for either accepting or rejecting under the chi-squared test and the correlation and regression analysis for each stated objective revealed that (i) there is significant difference in diversions and missed approaches events between categories of aircraft. This is supported by the results of chi-square testing which showed that $X^2 = 34.09$ $p < 0.001$, $df = 3$, and Fisher's exact test $p < 0.001$ indicated that there was statistically significant difference between observed diversion and missed approach events due to severe weather events as compared with the different aircraft categories. The association between the two variables (events and aircraft categories) is strong with the Cramer's $V = 0.5$. Therefore, this leads to rejection of null hypothesis to favour the acceptance of the alternative hypothesis claiming that, there was a significant difference in the diversion and missed approach events between aircraft categories impacted by weather as influenced by climate variability.

Additionally, the results revealed that there was statistically significant difference between observed weather impact on diversion and missed approach events

as compared with the years of observations, chi-square testing $X^2 = 28.75$ $p < 0.001$, $df = 3$. The association between the two categorical variables is strong with the Cramer's $V = 0.5$. These results support the rejection of the null hypothesis and concluding that there is a significant difference in annual variability of aircraft diversion and missed approach events (landing performance indicators) influenced by the climate variability. Similar results hold for another hypothesis, thereby led this study to state that, there was a significant difference on diversion, and missed approach events as compared with the seasonal variation due to the impact of weather as influenced by the climate variability. It should be also noted that these results were not happened by chance, the climate variability influenced the difference as per the chi-square test. **Figure 10** demonstrate the

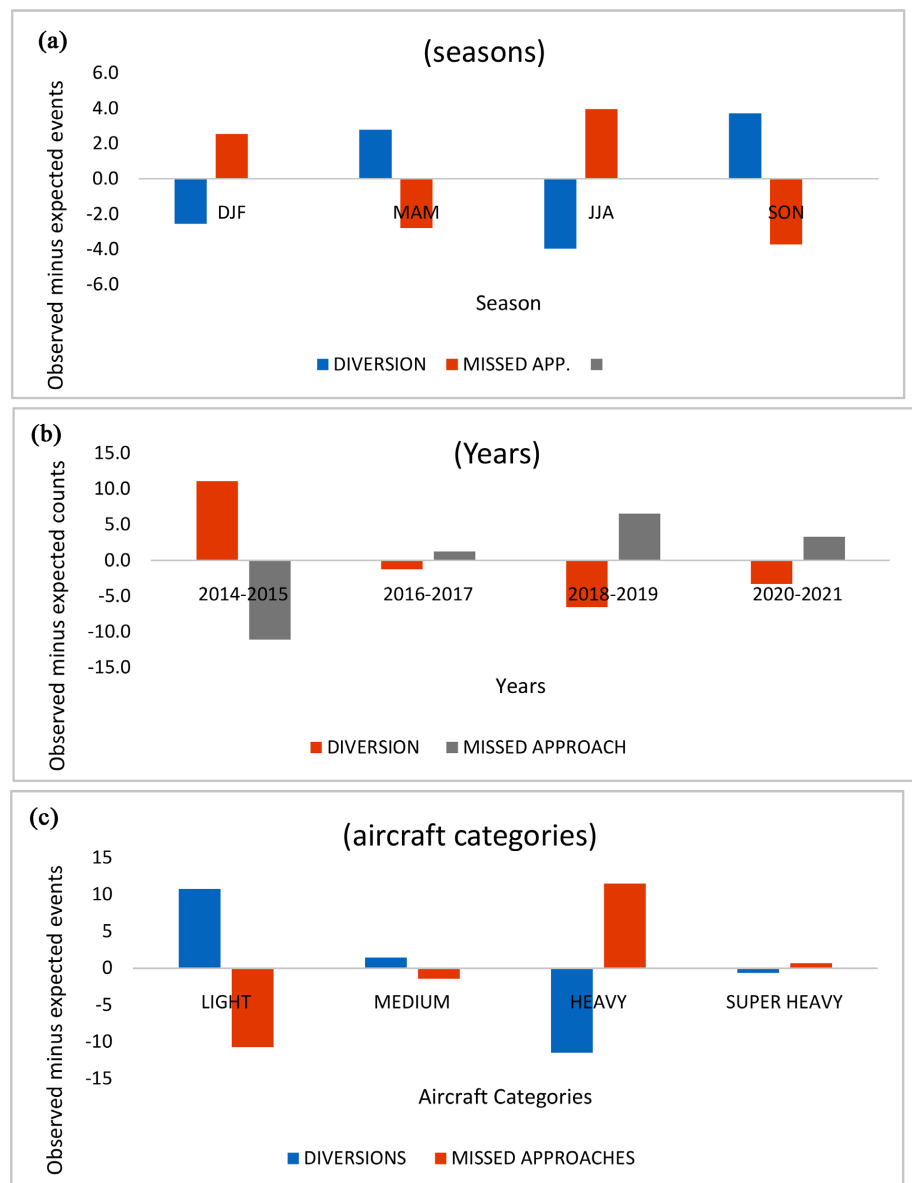


Figure 10. The diversion and missed approach events based on monthly, annually and aircraft categories for the hypotheses test based on chi-square statistical test.

differences.

2.5.2 Take-off Performance

On testing the take-off performance, the correlation and regression analysis form the basis of the hypothesis testing. The results revealed that the TODR for the three type of aircraft namely B763, B737MAX8, and DH8D were found to be significantly positive correlated with year of observation, $r(31) = 0.66, 0.70,$ and $0.78, p < 0.01$ respectively as per Pearson correlation. In addition, the Spearman correlation shows that TODR for the B763 was significantly positive correlated with the year of observation, $r(31) = 0.65, p < 0.01$. Furthermore, the TODR for the B738 MAX8 was significantly predicted by the model:

$$\text{TDOR_B737 MAX8} = 0.89 * \text{year of observation} + 1171.1$$

While for DH8D, (Bombardier) was significantly predicted by:

$$\text{TDOR_DH8D} = 0.37 * \text{year of observation} + 850$$

Therefore, the null hypothesis was rejected to favour the acceptance of the alternative hypothesis claiming that there is significant relationship between the year of observed Tmax and TODR under the influence of climate change.

As for testing the last hypothesis, the result shows that the MTOM for the A220/BSC3 was significant moderate negative correlated with the year of observation, $r(31) = -0.501, p < 0.01$; while the MTOM for the B738 was significantly very strong negative correlated with the year of observation, $r(31) = -0.704, p < 0.01$. Furthermore, the Spearman-rho correlation analysis showed that the MTOM for the A220/BSC3 was significantly negative moderate correlated with the year of observation, $r(31) = -0.504, p < 0.01$. Meanwhile the MTOM was significantly predicted by the model:

$$\text{MTOM_B738} = -15.49 * \text{year of observation} + 107,522.$$

Therefore, the null hypothesis is rejected to favor the acceptance of the alternative hypothesis claiming that there is significant relationship between the year of observed Tmax and the MTOM under the influence of climate change.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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