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İklim değişikliğinin sıcaklık yükselişine etkileri ve motor performansının değerlendirilmesi

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Anahtar Kelimeler:
- İklim değişimi
- Atmosfer ısınması
- Uçak performansı
- Motor performansı

ÖZET

İklim değişikliği günümüzde yüksek sıcaklıklara neden olan bir gerçektir. Bu çalışmanın amacı, küresel iklim değişikliğini dikkate alarak, bunun uçak motoru performansı üzerindeki etkisini Azerbaycan havalimanları ve havacılık sistemi özelinde analiz etmektir. İklim değişikliğinin neden olduğu hava koşulları, uçak motorunun ve uçuş performansının düşmesine neden olmaktadır. Azerbaycan Bakü Uluslararası Havalimanı'nda (GYD) GEnx-1B motorlu bir Boeing 787-8'in motor parametreleri üzerindeki iklim değişikliğinin etkisini araştırmak için gerçek zamanlı veriler toplanmış ve analiz edilmiştir. Bu çalışmada, motor performans hesaplaması için uçuşların kalkış ve seyir aşamalarında Enhanced Airborne Flight Recorder'a (EAFR) kaydedilen veriler kullanılmıştır. Egzoz gazı sıcaklığı, yakıt akışı ve kalkış ağırlıkları üzerinde performans analizi yapılmıştır. Uçağın kaydettiği verilerde, 38000ft seyir irtifasında iklim değişikliğinin sonuçları görülebilmektedir. Değişiklik, standart atmosfer değerleriyle karşılaştırılarak tartışılmıştır. Ayrıca, sıcaklık değişiminin etkisi değerlendirilmiş ve küresel ısınma nedeniyle yaz döneminde uçağın seyir aşamasında EGT değerlerinde hali hazırda ortalama 200°C'lik bir artış olduğu gösterilmiştir. Bu artış ek emisyonlara ve daha fazla atmosferik kirliliğe, işletme tarafında ise yakıt maliyetlerinin artmasına ve türbin bölümünün erken yaşlanmasına neden olmaktadır.

Climate change effects on temperature elevation and evaluation of engine performance

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ABSTRACT

Keywords:
- Climate change
- Atmospheric warming
- Aircraft performance
- Engine Performance

Climate change is now a reality which causes increased temperatures. Taking into account global climate change, the purpose of this study is to analyze its effect on aircraft engine performance with a specific focus on the Azerbaijan airports and aviation system. Climate change will affect weather conditions which will cause performance degradation of aircraft engine and flight performance. Real time data was collected and analyzed to investigate the impact of climate change on engine parameters of a Boeing 787-8 with GEnx-1B engines in Baku International Airport (GYD), Azerbaijan. For this study, data recorded in the Enhanced Airborne Flight Recorder (EAFR) was used for the take-off and cruise phases of flights for engine performance calculation. The performance analyze was performed on the exhaust gas temperature, fuel flow and take-off weights. It is found out that the results of climate change can be seen on the data recorded by the aircraft at the cruising altitude of 38000ft. The change is discussed in comparison with standard atmosphere values. Also, the effect of temperature change is discussed and have been shown that there is already an average 200°C increase in the EGT values during the cruise phase of the aircraft during the summer period because of the global warming. This increase is in return causes further atmospheric pollution by additional emissions and on the operation side, this change results in increase of fuel costs, and early aging of the turbine section.

1. Introduction

According to the Union of Concerned Scientists (2004), climate change occurs over a period of years to decades whereas human-caused changes in climate occur over a timespan of decades to centuries. Certainly, the climate change caused by human factors is ongoing and is expected to continue in the near future as a result of the emissions of carbon dioxide and other gases.

The changes in climate have occurred rapidly in the current era, and therefore, the earth's surface temperature has increased over the last century. Since the start of the twentieth century, the global average earth surface temperature has increased by approximately 1°C, with the most intensive changes occurring after 1980 (Walsh et al. 2014; Coffel et al. 2017). As global temperatures rise, extreme weather conditions is expected to affect human health, will increase the demand of water, energy and agriculture products as well as nature and biodiversity/ecosystems. Rising sea levels also is expected to have an impact on coastal communities causing more frequent flooding and more severe damage from coastal storms. At the same time, the weather conditions in most cases will not correspond to the accepted standard values.

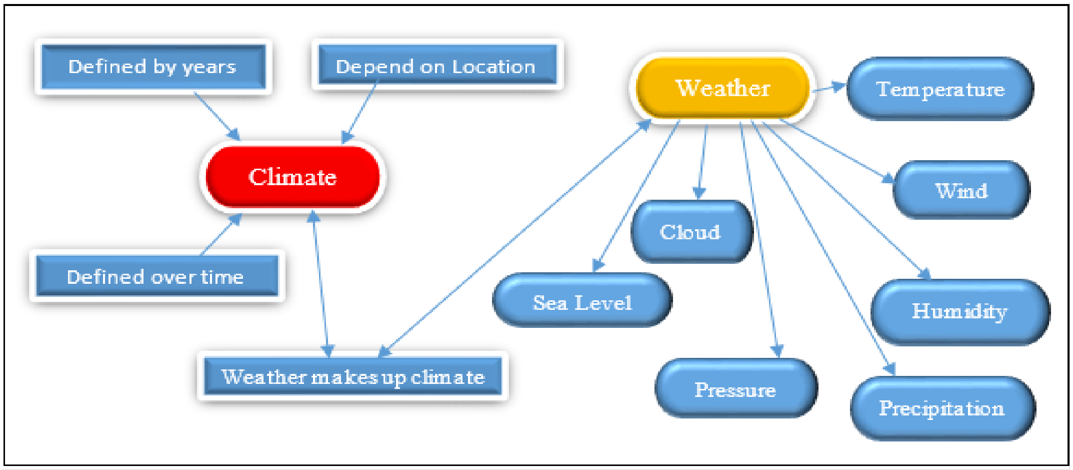

Figure 1. Climate and Weather classification

Weather conditions and given daily forecasts of the atmosphere at a given time and location with respect to variables such as ambient temperature (hot or cold), humidity (wetness or dryness), wind speed and direction (calm or storm), cloud formation/visibility (clearness or cloudiness), precipitation (rain and snow), sea level (rise), and air pressure (high or low) are important factors that can affect aircraft performance, airport operations and flight safety (FAA, 2021). It is obvious that the expected impacts of climate change will result in changes in weather variables, which are already above the pre-industrial levels, consequently affecting aircraft performance with uncertain implications. Weather affects aircraft operations and aviation as a whole because of meteorological features of the atmosphere (Zhou et al. 2018), which is responsible for about 80% of flight delays and cancellations causing millions of dollars of lost revenue each year for the airlines (Williams, 2017).

Figure 2 clearly displays that current temperature change does not conform to the trends observed for the last 4000 years. We can deduce that climate change is a current reality other than an expectation for the future.

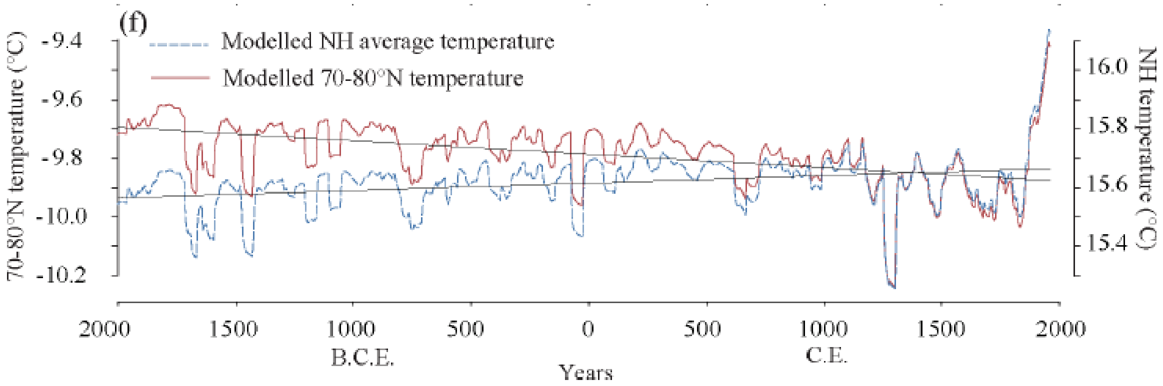

Figure 2 Temperature variability over the past 4000 yrs. at 70-80 N hemisphere. (Kobashi et.al. 2013)

Figure 3 also shows that since 1950, atmospheric CO2 has increased to an unprecedented level. The rise seemed to accelerate after the Industrial Revolution when fossil fuels become the main source of energy. The data given in this figure is based on calculations of the comparison of air samples contained in ice cores (ProOxygen 2021)

Figure 3 Atmospheric CO2 levels for the last 800000 years (ProOxygen 2021)

1.1. Classification of Weather Elements and Implications for Aviation

Understanding how global warming can cause changes in aircraft performance such as MTOW is crucial for the planning of future flight operations to ensure the safety of crew and passengers (Coffel and Horton, 2015; Zhou et al. 2018). Aircraft take-off performance is influenced by airport elevation and ambient temperature. A rise in ambient temperature leads to less surface air density, which influences the maximum allowable takeoff weight of the aircraft, accordingly decreasing lift generation produced at a given speed. Climate change seems to be leading to higher temperatures, which may lead to take-off weight limitations on current aircraft types (Coffel et al., 2017).

Other issues related to adverse weather can be characterized as excessive wind, turbulence, lightning strike, barometric and temperature anomalies and change in precipitation. These factors are discussed in the following paragraphs.

Excessive wind shifting on the ground and at cruise altitudes that changes the circulation of the atmospheric air can cause delays or flight cancellations as well as deviation from the flight routes and the resulting flight time (Irvine et al. 2016).

Lightning strikes are an element of extreme weather that play an important role in the chemical structure of the atmosphere, and an increase in lightning flash rates due to global warming is expected in the future (Romps at al. 2014). Depending on the geographic location, lightning strikes are occurring at temperatures near to 0° C during areas of turbulence, which are triggered by the aircraft itself passing through the clouds during the climb and descent phases of flight at altitudes of between 1,524 and 4,572 meters (Zoriy, 2020). Irvine et al. (2016) stated that changes in the wind velocity and direction in the upper level of atmosphere caused by climate change could affect the aviation industry and could have the potential to increase the intensity and strength of clear air turbulence (Williams and Joshi, 2013). Turbulence has the potential to injure passengers and crew members, as well as cause structural damage to aircraft. Therefore, the negative economic effect of turbulence arises due to damage to airframes and engines, their inspection and repair, flight delays, and accident investigations (Williams, 2017).

Precipitation is an important meteorological factor that can impact flight safety, which adversely affects aircraft aerodynamics. Since the beginning of the 21st century, extreme changes in the climate particularly heavy rainfall, have caused huge losses around the world (Cao et al., 2014). In 2011, heavy rainfall caused the worst flood in the history of Pakistan, which increased the focus of meteorology and aviation researchers on this global problem (Webster et al., 2011).

Barometric altitude is an indicator of atmospheric pressure which is equivalent to the ISA (1013hPa/29.92inHg/760mm/Hg)/14.7psi) pressure and has used by the international aviation community for the purpose of comparing and calibrating flight instruments such as barometric altimeters, ATC Transponders, air data computers among others. High temperature and low air pressure (i.e., high pressure altitude) can result in reduced air density, which causes decreased aircraft take off performance, particularly leading to lift force creation of aircraft (Coffel and Horton 2015). At less air density, it is necessary to reach a higher speed in order to obtain nominal lift and take off (Anderson, 2016; Zhou et al., 2018).

Aircraft create contrail/cirrus cloud formations at high altitude with low air density of the cold air, which have a very short existence of up to 24 hours. According to Professor Dr Grewe, in spite of the short life-span of these contrails and resultant cloud formation, atmospheric warming factors are so powerful that the daily heat capability is more than all the aviation carbon dioxide (CO2) that has accumulated in the atmosphere since the 1940s. Low-level clouds have a net cooling effect, as these high-flying contrail formed clouds do not reflect much sunlight, but ice crystals inside them keep heat thus contributing to warming of the environment (Bannon, 2018; Camero, 2019). Figure 1 is describe impact of the weather element to Aviation.

Table 1. Classification of Weather Elements for Aviation

Weather elements	Implications for Aviation
Temperature	Infrastructure, Aircraft Performance, Runway Length Requirement, Payload, Range, Demand Patterns, Reducing Lift
Wind	Turbulence, Disruption, Lightning Strike, Fuel burn/Emission Increase Flight Time, Flight Planning
Precipitation	Flight delays and cancellations, Flooding of airports and Surface De-Icing Requirements, Slot
Management	
Air Pressure	Take-off Performance, Reduce Lift Capability, Air Density
Cloud Formation	Impact to Visibility, Clear-Air Turbulence, Lightning Strike,
Sea Level	Airport Capacity, Network Disruption, Surface Transport Links
Humidity	Less thrust, Fuel burn, High corrosion risk

Referring to previous studies of climate factors, it is obvious that with the rising temperature, the air pressure decreases; therefore, this trend is accompanied by an increase in the humidity of the air. Jet engines are more susceptible to moisture and are designed to operate efficiently in cold and dry environments. In a humid atmosphere, as the density of the air decreases, engines experience insufficient oxygen molecule per unit volume, hence producing less thrust. Therefore, to increase the engine power in a humid environment, it is necessary to increase the fuel supply, which accordingly increases the values of EGT and the emissions of carbon dioxide to the atmosphere.

At a low level of relative humidity, structural elements are also exposed to less risk of corrosion, thus reducing the failures in conductivity in electrical circuits and the accumulation of condensates on electronic units, as well as preventing the growth of microorganisms on fuel tanks (Giaconia, 2013).

1.2. Global Climate Change Trend on the Earth's Surface and Case of Azerbaijan

By 2000, global warming had become one of the most important scientific challenges for humankind due to population growth as well as the increase in the release of greenhouse gases into the atmosphere (Mukhtarov et al., 2010). The average surface temperature in 2020 reached around 1.9°C above the average temperature from the last 2 centuries, which exceeded the previous record of 1.88°C that occurred in 2016. The warming temperature value for Azerbaijan territories is around 1.6°C. (Rohde, 2021) as given Figure 4.

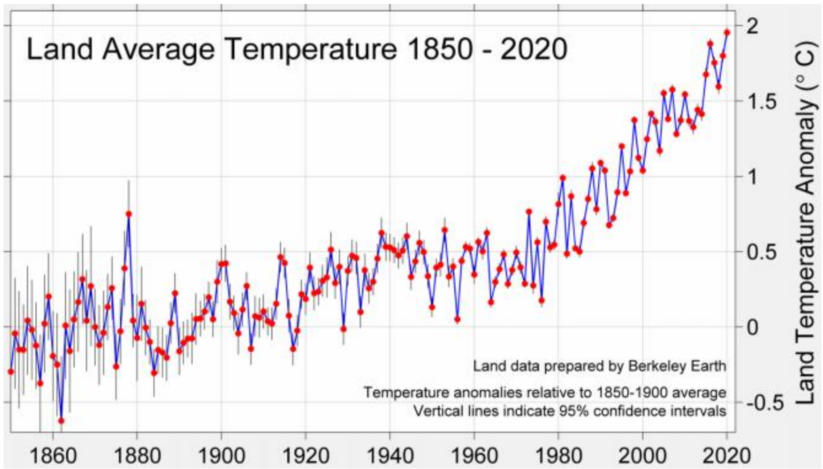

Figure 4. Land average Temperature 1850-2020. Source: Rohde (2021)

Azerbaijan has 9 climatic zones, where the annual average temperature and precipitation in the different regions vary. In general, average temperatures in Baku and surrounding regions reach approximately 27°C during the summer months of July and August, while the temperature remains between 15°C and 20°C in the mountainous areas in the northern and western parts of the country. During the winter period from December to February, the average temperature in Baku is about 3°C and 4°C, whereas in the western and northern zones, it is below 5°C and 10°C. Furthermore, while the average rainfall is above 40 mm in the whole Azerbaijan, in Baku it remains below 25 mm per month on average.

According to World Bank analysis based on new climate models, the mean temperature will increase by 0.3 °C per year from 2021 to 2050 indicating a rise from 1.4°C to 2.8°C in the middle of this century and that precipitation will increase by about 10-20% compared to the period from 1961 to 1990 (World Bank, 2012). From 1961 to 1990, the average temperature increase was 0.15°C to per decade and it increased by 0.4°C per year until 2020. Projected future climate by 2050 in Azerbaijan and the surrounding regions, it is expected that the intensity of rainfall will increase followed by flooding, which will cause the Caspian Sea level to rise by 1.5-2 meters. (Karimov, 2020). This is of particular concern for Heydar Aliyev airport, whose elevation above the Caspian Sea is only 3 meters.

1.3. Aircraft performance and operational degradation impact, in result of climate change

The exhaust gas temperature (EGT) value is a critical parameter for aircraft engines; therefore, monitoring of the trend variations allows airlines to effectively predict the aircraft take off performance (Qiang and Ding, 2014). The EGT value during takeoff depends on the ambient temperature and thrust settings. If the outside air temperature exceeds the given limit, the EGT increases while the available engine thrust decreases and the engine EGT is regulated by the electronic engine control system.

The turbine section is more susceptible to engine deterioration as a result of high EGT, which lowers the performance of the engine main modules, particularly the compressor. In order to maintain the rotor speed and allowable thrust level, additional fuel flow to the combustion chamber is required to balance the compressor pressure ratio (Balicki et al., 2014). Precise estimation of the engine fuel flow is important for defining the operational characteristic and thrust of the aircraft as well as emission calculations (Chati and Balakrishnan, 2013).

Turbofan engines are comprised of six main components, namely a Fan, Low pressure (LP) compressor, High-pressure (HP) compressor, Combustion chamber, High-pressure turbine (HPT), and Low-pressure turbine (LPT) (Gharoun et al., 2019, Chao et al., 2019). Allowable operating limit of the any aero engine depends on the condition of the combustion chamber (Fuel Burn) and turbine section (EGT) as well as the fan blades (N1) (Figure 3).

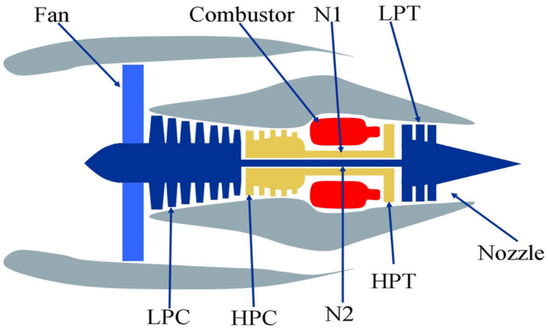

Figure 5. A simplified diagram of a twin-spool turbo-fan engine: Source (Chao et al., 2019)

The EGT provides a direct indication of engine health including wear of the compressor and turbine blades caused by aging, which increases the clearance between blade tips and turbine casing and amount of hot stream air leaking, which minimizes the allowed EGT margin used to estimate the average remaining life cycle and time on-wing (Garg, 2013; Balicki et al., 2014; Bonnet 2017). Intense climate change has a direct impact on these three engine parameters, respectively influencing auxiliary parameters such as pressure and temperature and oil consumption, vibration, termosensors and fuel control components.

T. Zhou et al. (2018) stated that the global warming of 1.5 -2°C in China will impact the planning of future flight and weight restrictions during the summer period, consequently reducing the takeoff weight of aircraft, especially in Beijing (PEK), Shanghai (SHA), and Lasa (LXA) airports. In addition, the study by Y. Zhou et al. (2018) showed that climate change causes the temperature and barometric altitude increase and in return increases the takeoff distance and reduces climb rate in summer, suggesting that an additional 3m to 170 m of increase in runway lengths will be required in future hot seasons.

Fuel consumption is the primary airline operating cost of commercial aircraft, which is based on a variety of factors in including price escalation growth, political situations and technical issues, which add to the abovementioned global warming challenges (Dankanich and Peters, 2017).

In this paper, Section I presents a brief introduction about climate change and aircraft performance. Section II contains the methodology, data collection procedures and techniques, description of used equipment, as well as analysis of accumulated information. Section III provides detailed results of the study. Section IV and Section V include the discussion and conclusion, respectively.

2. Methodology and Data Collection

Taking into account global climate change, the purpose of this study is to analyze its effect on aircraft engine performance with a specific focus on the Azerbaijan aviation system. Climate change will affect weather conditions which will cause performance degradation of aviation systems, specifically engine and flight performance. Particular weather effects on Azerbaijan aviation are discussed.

Real time data was collected and analyzed to investigate the impact of climate change on engine parameters of a Boeing 787-8 with GEnx-1B engines in Baku International Airport (GYD), Azerbaijan. Acquisition of data from the Enhanced Airborne Flight Recorder (EAFR) for this study was collected in two phases of flights for engine performance calculation:

1. Takeoff - The selection based on records at full power, when appears peak EGT and allowable Fuel Flow (FF) values, on particular engine model and used for estimation of the EGT/FF performance variation on raised ambient temperature.

2. Cruise - The selection is made taking into account the fact that the engine and aircraft system operations are stabilized at cruise altitude, which allows any changes in parameters to be observed if they occur.

2.1. Data Collection Source and Techniques

To conduct the intended research, the airport in Baku was chosen due to its close proximity to the coast of the Caspian Sea with low elevation of 3 m (10ft) AMSL, where the average atmospheric temperature is higher and weather conditions are different to other airports on given days (Table 2). Azerbaijan currently operates 7 International airports for commercial purposes: Baku, Ganja, Nakhchivan, Lankaran, Gabala, Khojaly and Zaqatala. The characteristics of the airports are shown in Table 2. Average weather conditions at GYD airport are given in Table 3.

Table 2. Characteristics of Azerbaijan's airports

Airports (INT)	Runway Length	Runway Heading	Runway length (m)	Elevation (m)
Baku	16/34	162°/342°	4000 x 60	3
	18/36	175°/355˚	3200 x 45	3
Ganja	12L/30R	124˚/304°	3300 x 44	330
Lankaran	15/33	140°/320˚	3300 x 45	9
Gabala	16/34	162°/342˚	3600 x 60	344
Zaqatala	15/33	152°/332˚	3000 x 60	390
Nakhchivan	14R/32L	138°/318˚	3300 x 45	873
Khojaly	05/23	-	2178x37	610

Table 3. Average weather condition data at GYD Airport for March and August 2021. (Source: weather-atlas.com)

Weather	March 2021	August 2021
Avg temperature	10 °C	30 °C
Avg. Highest temperature	11.3 °C	29.5 °C
Avg. Lowest temperature	6.5 °C	25.3 ˚C
Wind speed	23.2 km/h	19.2 km/h
Air pressure	1017.6 mbar	1011.4 mbar
Rainfall	13 mm	4 mm
Snowfall	7 cm	0
Humidity	72%	54%
Visibility	10 km	10 km
Cloud cover	36%	13%
UV Index	3	7

Baku airport has high traffic loads due to its role as a hub of international flights for transporting passengers and cargo (Figure 6).

The data from the Enhanced Airborne Flight Recorder (EAFR), 20 flight records have been chosen where 10 flights are take-off and 10 are cruise flights. Their parameters are analyzed in comparison to ambient conditions which are also recorded in EAFR. The parameters of each flight data, including air temperature at sea level, were obtained from the EAFR Boeing 787-8 with GEnx-1B engines on different routes and time periods. The data are focused on winter and summer weather conditions, including March and August 2021, when air temperatures are relatively different.

Figure 6. Heydar Aliyev International Airport (drzewiecki-design.net,2021)

2.2. Digital Flight Data Recorder Input and Output Parameters

The Flight Data Recorder (FDR) is the general term used for an avionic instrument on each aircraft, which records the key parameters of the aircraft system and engine variables from takeoff to touch down. The Enhanced Airborne Flight Recorder (EAFR) is one of the advanced FDR systems, which has the capability to provide necessary crash protected recorder functions that include combinations of the Digital Flight Data Recorder (DFDR), the Cockpit Voice Recorder (CVR), the Data Link recording (DLR), and Image Recording (IR) functions and also ensures that the Flight Data Acquisition Unit (FDAU) functions to collect flight data parameters for subsequent storage. The Digital Flight Data Recorder (DFDR) function records aircraft flight data and engine parameters linked from the sensors, switches, transmitters, and indication devices (GA Aviation, 2018).

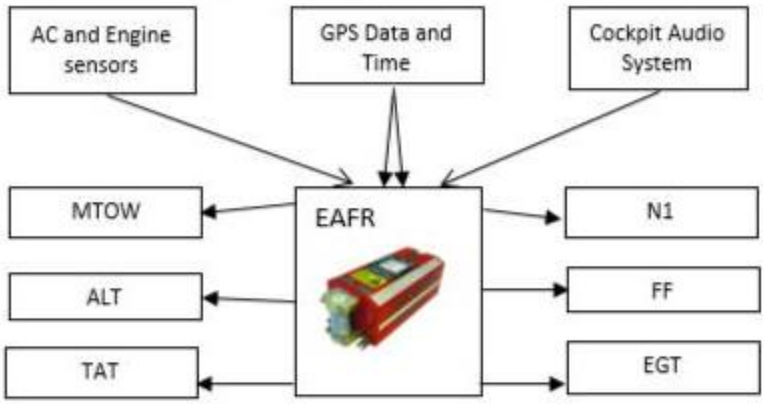

Figure 7. EAFR input and output parameters

The recorded data information can be extracted immediately from the memory using a computer interface. The Cockpit Voice Recorder records communications of crew members provided by the Flight Deck Audio System. The EAFR allows the collected data to be stored for 25 hours and the CVR recording consists of a minimum of two hours' data storage, with total recording above 1000 information (GE Aviation, 2018).

This research was conducted by using EAFR data from a Boeing 787-8 aircraft powered by a GEnx-1B engine type to study the engine performance in 2 phases of flight, with a focus on the rising trend in ambient temperature. Received flight data including Date, Time, Maximum Take-Off Weight (MTOW), fan speed (N1), altitude (ALT), fuel flow (FF), exhaust gas temperature (EGT), and total air temperature (TAT) were recorded in two flight stages (takeoff and cruise). Then, the data were compared to identify any differences and we calculated target variables for each parameter to define the impact of high ambient temperature on engine operations and their life cycles.

2.3. Aircraft and Engine Limitation Parameters

For a particular aircraft and engine (ESN: 956000; TSN 13843 FH, CSN 2635 FC CSN; TSLSV 1215 FH, CSLSV 228 FC), the Max EGT Operational Limit is defined as 924°C, which depends on the environmental conditions. Accordingly, the operating conditions represent the operating limit that described in the aircraft operation manuals, which are given in Table 4 for the engine type.

Table 4. Aircraft and Engine Limitations

Boeing 787-8 Maximum TO and Engine Exceedance Limit									
Weight, lbs	Speed, V2 Kts	Distance, m	Ceiling ft	Rang, nml	Thrust, kN	N1, RPM	N2, RPM	FF, lbs	EGT, °C
502500	165	3200	FL430	3100	280	2778	13359	N/A	1060

2.4. Main Operation Parameters of the Engine Affected by Climate Change

Power setting Is defined as the required level of jet engine thrust and is specified in two main terms which directly affect engine power. In particular, temperature rises have a greater effect on thrust performance of the engine through degradation of FF and EGT values;

1. Fuel Flow (FF) - The main factor affecting engine thrust is the amount of fuel burning. In order to obtain a higher compressor pressure ratio, it is necessary to maintain fan speed (N1) and increase fuel flow to maintain the air flow rate, which in turn leads to an unacceptably high turbine outlet temperature (TOT) and high compressor speed (N2) (Visser, 2015).
2. Exhaust Gas Temperature (EGT) - The EGT is the temperature of the gases behind the turbine section of the engines in degrees and indicates the performance status of the turbine and whole engine. A progressive increase in the EGT value caused by severe damage, surges, hot starts, or excessive fuel consumption leads to further deterioration and wear in the engines and affects the operational life cycle (Yildirim and Kurt, 2018).

In this study, by comparing the EGT and FF values obtained from the EAFR recorded at the takeoff and cruise phase of the aircraft, taking into account the MTOW value, fan speed, altitude and ambient temperature, the impacts of these values on engine performance are shown. For this purpose, data analysis of 60 flights was conducted and 20 were randomly chosen to predict the EGT and FF values in relation to the future global warming environment obtained from real flight data.

Statistical parameters during takeoff and cruise phases and validation of the data used for analysis of EGT and FF variations are given in Tables 5–8, respectively.

Table 5. TAKEOFF data for March 2021

DATE	TIME	TOW (lbs)	TAT	ALT (ft)	N1(%)	FF (lbs/hr)	EGT (°C)
05-03-2021	07.22	286876	7	-156	75	11197	723
21-03-2021	07.01	384965	9.7	-69	83	14405	798
21-03-2021	12.10	349683	3.1	1235	80	12812	761
24-03-2021	06.47	382357	14.6	508	83	14415	813
24-03-2021	11.58	364450	6	783	81	13446	781

Table 6. TAKEOFF data for August 2021

DATE	TIME	TOW (lbs)	TAT	ALT (ft)	N1(%)	FF (lbs/hr)	EGT (°C)
07-08-2021	09.22	429671	40	294	87.3	17633	932
08-08-2021	06.49	381116	38.2	144	83.1	15025	876
09-08-2021	06.46	378350	34	89	82.9	14790	864
11-08-2021	06.54	378516	40.3	174	82.7	15019	887
14-08-2021	12.11	431993	36	123	87.2	17354	915

Table 7. CRUISE data for March 2021

DATE	TIME	TOW (lbs)	TAT	ALT (ft)	N1 (%)	FF (lbs/hr)	EGT (°C)
05-03-2021	07.41	281572	-27.2	32003	82	4410	607
21-03-2021	08.33	365885	-22.4	39999	95	5105	749
21-03-2021	13.08	337590	-22.2	37002	90	4838	695
24-03-2021	08.01	366896	-27.9	38002	91	4666	688
24-03-2021	13.06	350602	-24.2	38999	91	4452	699

Table 8. CRUISE data for August 2021

DATE	TIME	TOW (lbs)	TAT	ALT (ft)	N1(%)	FF (lbs/hr)	EGT (°C)
07-08-2021	13.06	385911	-24.3	38000	92.9	4962	712
08-08-2021	08.22	361744	-21.2	36001	90.3	5035	699.2
09-08-2021	07.56	362995	-24.6	37999	91.7	4744	699.8
11-08-2021	08.09	362277	-25.3	37999	91.4	4738	694.5
14-08-2021	13.37	413093	-13	37998	95.6	5671	785.6

Therefore, the parameters such as fan speed, gas temperature and fuel flow impact engine performance depending environmental conditions

2.5. Data Analysis

Fan speed (N1)- implies control of the turbofan aero-engine often used as a takeoff thrust setting indicator and management of the engine parameters in cruise altitude. Use of the thrust setting value is usually required to find the proper equation to estimate thrust specific fuel consumption (TSFC), which corresponds to the specified power setting value, according to the below sequential formula;

Firstly, the fuel to air ratio is calculated using the following equation (Eq) (1):

$$f = \frac{\dot{m}_f}{\dot{m}_a} \tag{1}$$

Eq (1) allows the calculation of the fuel flow rate (f) according to Eq (2)

$$\dot{m}_f = f * \dot{m}_{ba} \tag{2}$$

TSFC ((lbm/hr)/lbs or (kg/hr)/N) is the ratio of the engine fuel mass flow rate (ṁf) to the amount of Thrust (F) produced by burning the fuel and another form of the equation is specified as the fuel to air ratio (f) divided by the specific thrust (Fs):

$$TSFC = \frac{m_f}{F} = \frac{f}{F_s} \tag{3}$$

The engine inlet-exhaust gas temperature depends on ambient environment conditions, which strongly impact engine performance, especially as the static pressure and outside temperature on the ground and in-flight altitude may differ substantially at sea level conditions.

Therefore, in order to define fuel flow difference (FFΔ) rate during takeoff in different climate environments, the following equation can be used;

$$FF_{\Delta} = FF_{hot} - FF_{cold} \tag{4}$$

There are two gas generator turbines named HPT and LPT operating on independent output shafts. EGT was initially used to calculate the actual temperature at the turbine exit for each bypass ratio (Tt4), as shown in Eq 5.

$$T_{t_4} = \frac{1}{c_{pt}(1+f)}\left[c_{pc}T_{t_3} + f\eta_b h_{pr}\right] \tag{5}$$

In this equation, cpt is defined as the specific heat of the turbine and cpc is defined as the specific heat of the compressor. Hb is the adiabatic efficiency of the combustion and hpr is the enthalpy of the combustion process. Using several parameters of the engine components, including the compressor temperature (Tc), fan inlet temperature (Tfi), bypass ratio (Tbr), fuel to air ratio (Tfa), and turbine entrance temperature (Tt3) it is possible to calculate the exit temperature of the turbine (Tt5) using Eq 6,

$$T_{t_5} = T_{t_4}\frac{c_{pc}*\left(T_{t_3}-T_{t_2}\right)+BPR*c_{pc}*\left(T_{t_{13}}-T_{t_2}\right)}{c_{pt}(1+f)*\eta_m} \tag{6}$$

Consequently, Eq 7 is,

$$T_{t_5} = EGT \tag{7}$$

Where Tt13 is the temperature of the air leaving the fan. The EGT is measured at different ambient temperatures when the EGT reaches its peak value during takeoff at full rated or derated thrust, and during cruise at stable engine parameters. The values are used to compare residual values on days with higher and lower temperatures, Eq 8.

$$EGT_{\Delta} = EGT_{hot} - EGT_{cold} \tag{8}$$

This study primarily investigates FF and EGT values and their implications on operational performance due to climate change.

3. Results of the Study

3.1. Manifestation of Takeoff Parameters

During winter (March) in Baku, the daily air temperature is roughly equal, excluding snowfall and storm wind, and the average wind speed is usually above 10-15 m/sec, particularly at the airport. In summer time, the daily air temperature significantly increases above 40°C in July and August, while the air pressure at sea level is marginally positive. However, the air pressure at sea level changes due to weather conditions. The weather condition parameters of temperature, precipitation, wind speed and direction affect pressure altitude.

The results were obtained by comparing and calculating the lowest temperature in March with the highest temperature in August. Comparing each of five values for two months, we calculate the amount of fuel consumption and EGT at high temperature in the takeoff phase of the flight. In this case, the take-off weight (MTOW) is 358856 Lbs on average and the airport elevation at sea level varies slightly during take-off, as shown in Table 9.

Table 9. Delta (D) parameters of FF and EGT

Ta-Tm˚ C	Td ˚C	FFh-FFc (lbs)	FFd (lbs)	EGTa-EGTm °C	EGTd ˚C
40.3-3.1	37.2	15019-12812	2207	887-761	126
40-6	34	17633-13446	4187	932-781	151
38.2-7	31.2	15025-11197	3828	876-723	153
36-9.7	26.3	17354-14405	2949	915-798	117
34-14.6	19.4	14790-14415	375	864-813	51

The Average Fuel Flow Rate difference is more than 2700 lbs, where the Exhaust Gas temperature difference exceeds 150°C in summer in comparison to winter flights.

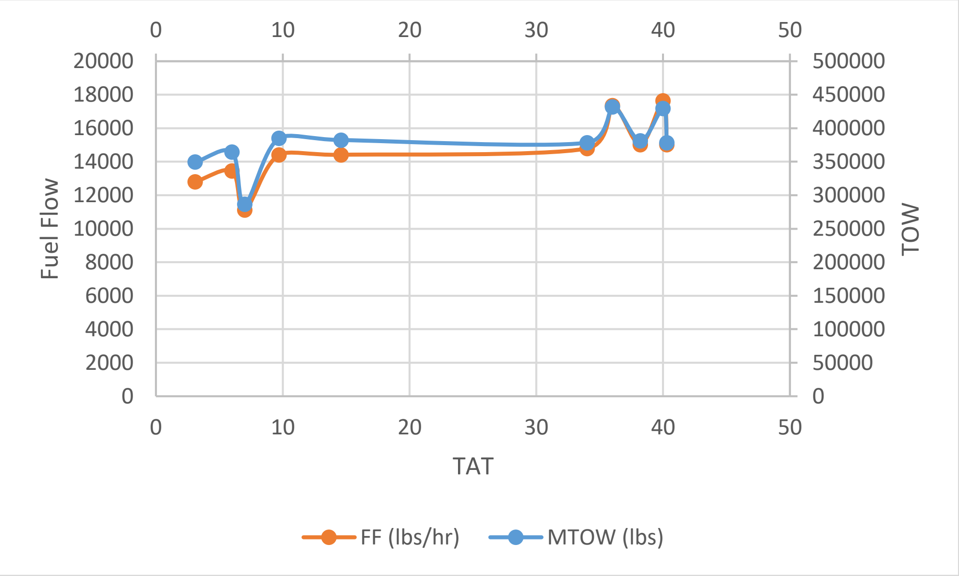

Figure 8. Fuel flow and TOW in relation to TAT during Take-off

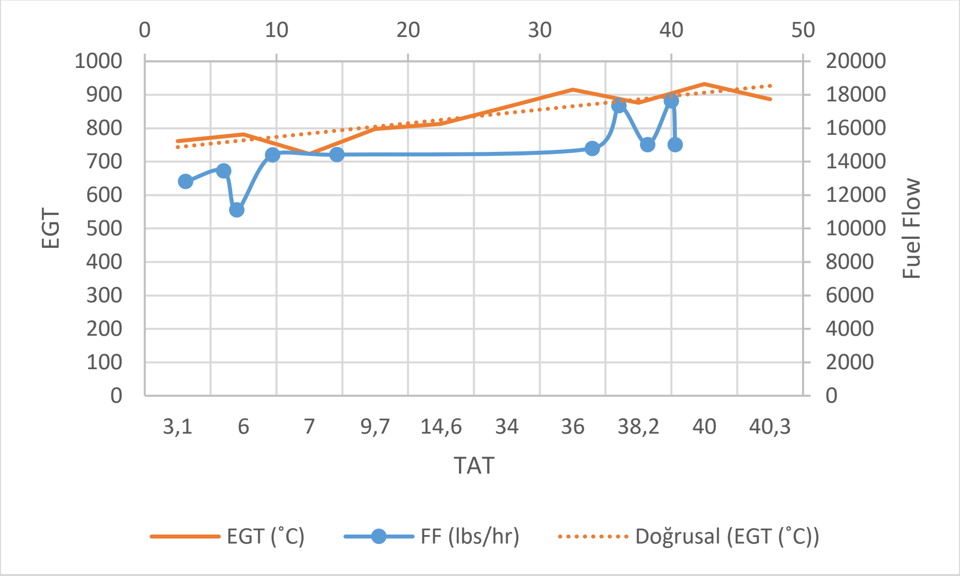

Figure 9. EGT and fuel flow in relation to TAT during Take-off

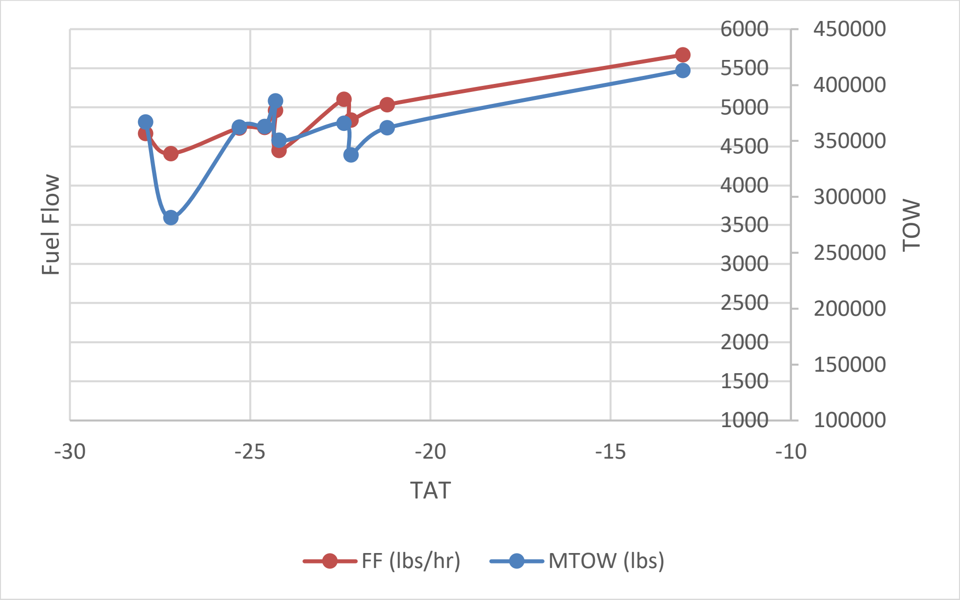

Figure 10. Fuel flow and TOW in relation to TAT at cruise altitude

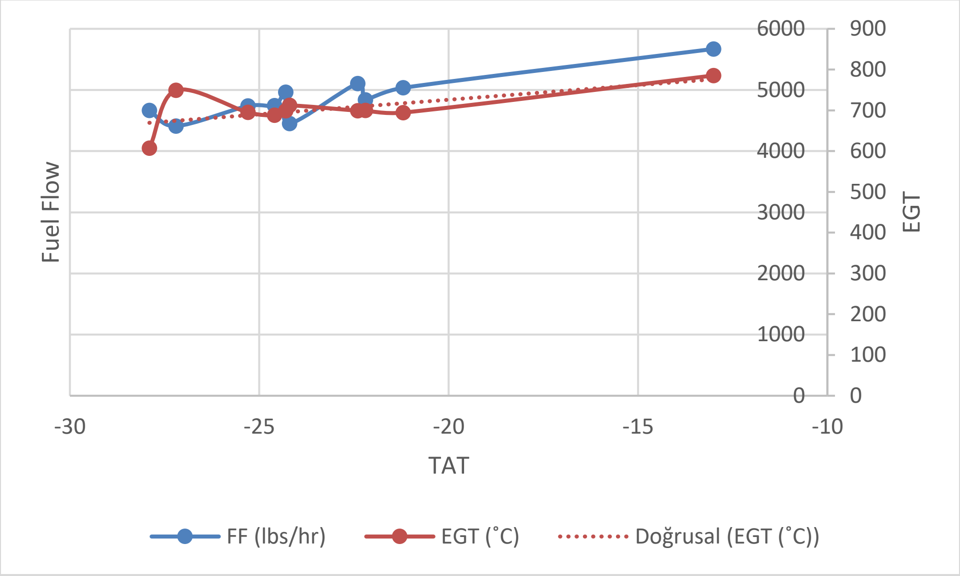

Figure 11. EGT and fuel flow in relation to TAT at cruise altitude

In fact, the increasing temperature and pressure altitude at sea level at an average of +50 m increases fuel consumption and EGT, while decreasing takeoff performance. This will result in a reduction in TO weight in order to keep the runway length constant. On the other hand, the decrease in air temperature and increase in barometric altitude can improve the performance. The results show that while the outside temperature in summer increased, during takeoff, the fuel flow increased more than 2700 lbs, while EGT increased more than 120°C.

Figure 8 shows the trend of fuel flow in different air temperatures on summer days, and the average fuel flow rate is indicated by the red bar. Additionally, Figure 9 shows the EGT trend during takeoff on the same days with relation to fuel flow, with the EGT trend indicated by the dashed lines. It is important to take into account that these parameters are directly impacting the release of emissions.

Figure 10 shows that the fuel flow and TOW is in a direct relation, where increasing TOW, where increase in the TOW directly increases FF. the second data in the graph which have a relatively low FF is the one performed at the lowest ceiling of the all data. Figure 11 shows that even at the cruise altitude of 38.000ft, high temperatures are experienced and it has a direct effect on fuel flow and EGT. Although expected ISA temperature conditions for that altitude is around -56°C, -13°C is recorded. Thus approximately 200°C increase has been experienced on EGT.

3.2. Manifestation of Cruise Parameters

The fuel consumption rate and the exhaust gas temperature are observed to follow similar trends, and apart from the engine condition, the exhaust gas temperature is dependent on fuel flow rates. During the climb phase up to cruise, these parameters decrease gradually with altitude under the influence of atmospheric pressure and air density, Table 12.

Table 12. Fuel Flow and Exhaust gas Temperature at Cruise Altitude

TAT ˚C	ALT ft	FFh-FFc lbs	FFd lbs	EGTa-EGTm ˚C	EGTd °C
-27.9/-25.3	380FL	4738-4666	72	694.5-688	6.5
-27.2/-24.6	380FL	4744-4410	334	699.8-607	92.8
-24.2/-24.3	380FL	4962-4452	510	712-699	13
-22.4/-21.2	390FL	5105-5035	70	749-699.2	49.8
-22.2/-13	380FL	5671-4838	833	785.6-695	90.6

The change in average Fuel Flow rate is 363 lbs in cruise altitude, where the change in Exhaust Gas Temperature is around 50°C. As expected, the FF and EGT are higher during the takeoff phase, and continue during climb, then are slowly reduced when crossing the transition level, and become stable at cruise altitude. There is a significant difference between the FF and EGT values at takeoff and cruise as expected. At takeoff, the values are 2200 lbs FF and EGT of 150°C, while the cruise figures are 361 lbs FF and 50°C EGT.

3.3. Comparison of Total Air Temperature with ICAO Standard Values at 380 FL

In this study, significant attention has been drawn to the value of the TAT at an altitude of 380 FL obtained from the EAFR as a result of 10 flights. At this altitude, the outside air temperature has an average of -23.2°C and ranges from -13°C to -27. 9°C, which seems significantly different from the data presented in the ICAO document for determining the average level of atmospheric conditions in terms of temperature, pressure and density, which are given in Table 13. When the operational outside air temperature obtained from EAFR and the ICAO standard atmosphere values are compared, a significant difference is observed.

Table 13. Cruise TAT operational values versus ICAO standard values.

TAT °C, Actual	H (ft) ICAO	H (ft) EAFR Readings
-13	14200	37998
-21.2	18200	36001
-22.2	18800	37002
-24.2	19800	38999
-24.6	20000	37999
-25.3	20400	37999
-27.2	21600	32003

Between 32000-38000 feet at pressure altitude, EAFR recorded an average TAT of around -23.2°C. According to Manual of the ICAO standard atmosphere Doc 7488/3 issued in 1993, the outside air temperature value should be around -56.5 °C. The TAT that recorded by the EAFR corresponds to a temperature altitude of 19000 ft.

4. Discussion

Relatively small contributions to anthropogenic CO2 emissions from aviation consist of around 2% which are injected into the upper free troposphere and lower layer stratosphere. The Intergovernmental Panel on Climate Change (IPCC) has estimated that this will rise to about 3.5% due to increasing air traffic volume in the next decade. The emissions produced by aircraft are generated by the burning of jet fuel and aviation gasoline (Winther and Rypdal, 2019). The results of the study indicate that temperature and barometric altitude significantly affect takeoff performance of the aircraft during summer, since fuel consumption influence the temperature of exhaust gas turbine output. It is shown in this study that increasing temperature and EGT during takeoff is obvious and the residual fuel flow and EGT are consistently 2700 lbs, and 150 □C in summer, respectively, unlike in winter. In fact, Baku has adapted to unstable weather conditions, with regular climate changes driven by permanent high wind velocity, spring lightning and fog clouds which complicate flight operations. Local operators need to use priority engine condition monitoring software for the early prediction of engine health and take proper action to avoid early engine failure and huge expenses.

Regarding the possible sea level rise, it is recommended that the Azerbaijan Aviation Authority should consider relocating scheduled flights and cargo transportation to Ganja, Gabala, and Nakhchivan, taking into account the airport elevation and relatively low air temperature. This will contribute to the growth of the regional economy, and flat distribution of traffic load, while relieving the city of Baku city from the emissions of carbon dioxide and ground traffic density. There is an illogical trend, which is the significant difference between the actual total air temperature (TAT) at pressure altitude withdrawn from EAFR and the ICAO standard values in terms of geometrical altitude. Given such differences, a detailed investigation is needed.

5. Conclusion

This paper analyzed the variation in Fuel Flow and EGT real parameters using statistical data from 20 daily flight of 2021 extracted from the Enhanced Airborne Flight Recorder (EAFR) of a Boeing 787-8 with GEnx-1B engines. This research covered takeoff and cruise altitude phases in different seasonal periods during winter and summer. Comparing these 20 daily flight parameters and studying the trends of global warming showed that the rise in temperature influences the characteristics of the aircraft and engine, especially during summer, with a significant impact on the increase in fuel consumption and EGT. These analyses reveal the ability to determine degradation of engine performance by increasing of outside air temperature, which allow predicting EGT output parameters during the takeoff phase and at cruise altitude. Based on the calculation of the difference between winter and summer periods, the residual value EGT and FF confirm the impact of high temperatures on the engine life cycle. The ambient temperature in cruise altitude at 380 FL detects an anomalous tendency in differences in different seasons. It is seen that the temperature altitude is changed in a noticeable rate with comparison to ICAO ISA table. The deviation of the temperature from the expected values give rise to the EGT temperatures of around 200°C.

The main advantage of this study is the use of real flight data taken from EAFR that allows maintenance and engineering personnel to detect early malfunctions in aircraft engines and rectify such deterioration. TAT has a direct influence on EGT and in return to the aging of the engine. With increasing TAT, the FF also increases which means the flights in summer are more costly. Depending on the data it can also be concluded that the climate change will cause a direct cost increase with the higher TAT at cruise altitude.

As stated earlier, this is the first study focused on the impact of climate change in the aviation sector in Azerbaijan. It is suggested that future research is conducted on the impact of global warming on other regional airports with respect to the influence of air temperature on aircraft and engine parameters, particularly in terms of Fuel Flow and EGT using the same method.

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