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# Impact of Climate Change on Aeronautics and Aviation

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**Abstract**

The history of aeronautics and the development of commercial aircraft is extremely related to climate facts. Aircraft structures are designed on the basis damage tolerance criteria and the reference loadings are a few gust-loading spectral density data, the most famous was given by Theodore von Kármán. The dramatic climate change observed in the last decades introduce many issues in aeronautics and aviation. The appearance of unexpected loads demands heavier structures and systems, that is existing aircraft could be not able to contrast loading related to new gust spectra (airframe icing, wind shear phenomena, sand, and dust storms, jet stream changes, clear air turbulence etc). A lot of effort and investment in new technologies are needed to make aircraft greener to contribute to C02 reintroduces including both physical risks such as flight delays or airport closures and related costs, and contractual, regulatory, or legal compliance risks. A multi-disciplinary research effort by scientists, meteorologists, climatologists, and engineers, is needed to understand better the impacts of the changing climate on the entire aviation system, including aircraft and infrastructure. Thereafter, dedicated guidance material by ICAO could target climate adaptation correlated issues, based on models of best practice. Such guidance material would aim to support the risk management activities of all stakeholders, including operators and pilots, airport managers, aircraft manufacturers, governments, and regulators. In this scenario the role of space infrastructure becomes crucial. These can provide and collect the necessary data, some of these in real-time, to be used to design the above-dedicated guidance materials by referring to AI systems. Efforts should be made to put in low orbit the necessary payload/constellations to improve existing data on air traffic and climate monitoring along the aircraft routes.

**Keywords:** Aviation, Climate change, Space technology, Turbulence.

## 1. Introduction

Climate change is an interdisciplinary issue that affects nearly every aspect of our lives, including public health, energy security, food security, and water availability. Its effects on the environment, society, and the economy are far-reaching and cannot be overlooked. Understanding the science behind the issue, taking steps to reduce our contributions to it, and supporting policies to help alleviate its effects are all critical. This urgent and worldwide crisis stems from human activities such as burning fossil fuels, deforestation, and agriculture that emit greenhouse gases, leading to extreme weather events like floods, droughts, and hurricanes. Its impact is already being felt by communities worldwide, and as temperatures rise, the situation is expected to worsen.

The aviation industry is deeply affected by the issue of climate change, even though air travel is among the fastest-growing contributors to greenhouse gas emissions. In fact, international aviation emissions are projected to increase significantly in the coming decades, making it a major concern [1]. To address this, the industry is actively seeking out new technologies and alternative fuels, alongside initiatives such as carbon offsets and fuel efficiency standards, to decrease the environmental impact of air travel. Additionally, implementing policies that encourage airlines to adopt sustainable practices and lower their emissions is crucial. It's worth noting that aircraft performance is heavily influenced by environmental factors, so climate change can have a substantial effect on the aviation industry.

The effects of climate change on the aviation industry are complex and multi-faceted. For example, changes in temperature and air density can affect the performance of aircraft engines and the lift generated by wings, potentially leading to flight disruptions or cancellations. Additionally, extreme weather events such as storms, hurricanes, and flooding can damage airport infrastructure and cause flight delays or cancellations. These disruptions can have significant economic and social impacts, particularly in regions that depend on air travel for tourism or trade.

Moreover, the aviation industry is also vulnerable to the physical impacts of climate change, such as sea-level rise and coastal erosion, which can threaten the infrastructure of coastal airports and runways. This can lead to costly repairs, relocations, or even closures of airports, which would have far-reaching effects on global transportation and trade.

Considering these challenges, the aviation industry is working to develop resilience strategies to adapt to the impacts of climate change, such as building sea walls, improving drainage systems, and diversifying airport locations. Addressing the issue of climate change is essential for the aviation industry to continue to thrive sustainably in the future.

The role of the Space sector in combating climate change has become increasingly significant in recent years. Space technology offers the potential to enhance our understanding of climate change and develop innovative solutions to mitigate our greenhouse gas emissions. Satellites can provide valuable data on global temperatures, sea level rise, and other climate factors, which can help us analyze the effects of climate change. They can also track changes in atmospheric composition, including levels of carbon dioxide and ozone. Observation satellites are well-suited for collecting this data and monitoring climate events. One notable example is the NASA-led Orbiting Carbon Observatory-2 mission [2], which employs a satellite to measure carbon dioxide levels in the atmosphere. The information collected can inform policy decisions and identify areas where emissions reduction is necessary. Furthermore, space technology can also facilitate the development of new solutions to reduce our greenhouse gas emissions. For instance, solar panels on spacecraft can generate electricity, and technology designed for human exploration can be utilized to research new forms of energy on Earth, such as smaller, more efficient nuclear fission reactors [3]. These technologies hold great potential in reducing our reliance on fossil fuels and minimizing the number of polluting gases emitted.

The objective of this article is to offer a comprehensive overview of how the aviation sector is impacted by climate change, including its effects on aircraft performance. The article also explores the potential of space technologies in monitoring these effects and enhancing the accuracy of forecasting models. Section 2 provides an in-depth analysis of the major effects on aeronautics and aviation, while Section 3 delves into the repercussions on aircraft performance. The authors further discuss innovative space technologies and programs in Section 4. The paper concludes by examining potential implementation strategies and highlighting significant trends and concerns.

## 2. Effects on the Aviation sector

The impact of climate change on aeronautics and aviation is far-reaching, affecting all aspects from the design phase to traffic and airport management. Eurocontrol, the organization responsible for air traffic management in Europe, has conducted a comprehensive analysis of the effects of various meteorological changes on civil aviation in the ECAC region, which is composed of 44 member states. Sea level rise has been observed in Europe (as shown in Fig. 1), with a rising trend across the entire mainland from 1993 to 2019. This increase has resulted in a 21% rise in the number of airports at risk of flooding by 2090, with 91% of them being small airports that play a critical role in local tourism [4].

In addition, the rise in temperature has altered tourism demand, both in terms of space and time evolution. Eurocontrol [5] has evaluated these variations using a Tourism Climate Index (TCI), indicating an increase in tourists in central Europe during the autumn months (September, October, and November). Conversely, in southern Europe, there will be a slight decrease in summer tourism, but an increase in both the autumn and spring months. Other regions such as northern Spain and Scandinavia will become more favorable throughout the year. However, mountainous areas will suffer the most from temperature rise, especially ski resorts that will increasingly have to rely on artificial snow. Conversely, bathing areas will be available for a longer period, with reduced demand during the hottest months (June, July, August).

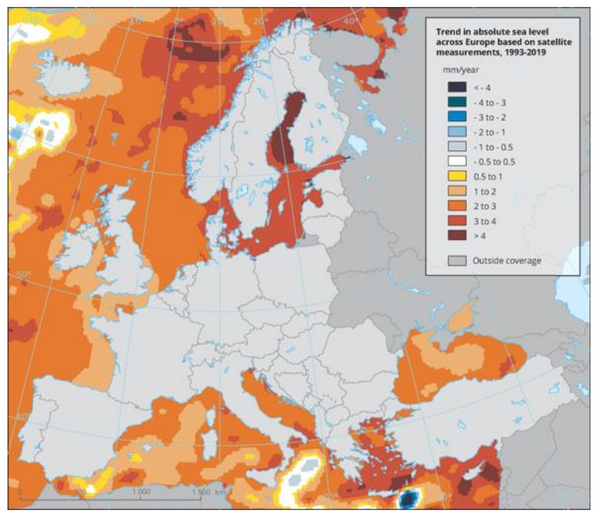


Fig. 1. Absolute Sea Level trend in Europe from 1993 to 2019. The red color indicates a rising from 2 to 4 mm/year, while in the blue zones, a decrease in sea level occurred. (Source: European Environmental Agency)

Changes in wind patterns and storm events have significant effects on aeronautics and aviation. En-route and arrival delays are often caused by convective cells, unexpected storms, and wind shear, which are more common in certain geographical areas. For instance, convective events are the most widespread cause of en-route delays in the Mediterranean zone, and these events are projected to increase in intensity in the coming years. In addition, turbulence prediction models suggest that turbulence frequency and intensity are expected to increase significantly, particularly in the tropical zone where major routes are located [6].

Furthermore, extreme rainfall days are predicted to increase across northern Europe but decrease across southern Europe, leading to longer delays. It is challenging to predict the long-term effects of these changes on traffic management, considering the variability of wind intensity and the interaction with other meteorological conditions. Nevertheless, air traffic management (ATM) must anticipate an increase in delays and act promptly to reprogram routes [7], [8].

Eurocontrol conducted an interview with 63 stakeholders in the European Aviation sector and 50 players in the European Air Traffic Management [1]. They were asked to what extent the industry was prepared to deal with climate change. According to the results shown in (Fig. 2), most respondents believe the sector has implemented some adaptation measures. Only 6% of participants believe that the sector has not analyzed adaptation. Concerning European ATM, 60% of respondents concluded that certain adaptation measures are already in existence (Fig. 3). However, a small proportion of participants claimed that European ATM has not contemplated adjustments. While awareness is increasing, it is essential to determine if appropriate measures are being implemented promptly or if actions need to be expedited.

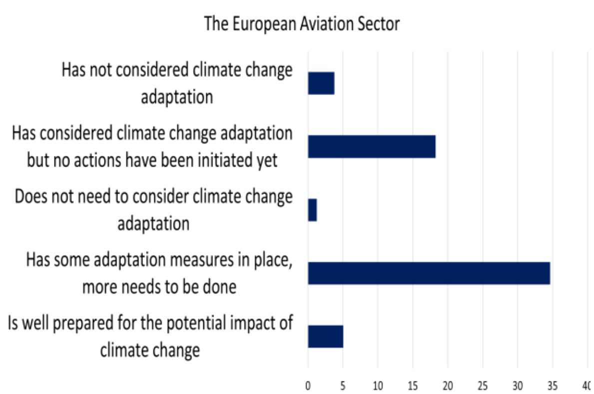


Fig. 2. Stakeholder perceptions of the level of preparedness for the potential impacts of climate change for the entire European Aviation sector

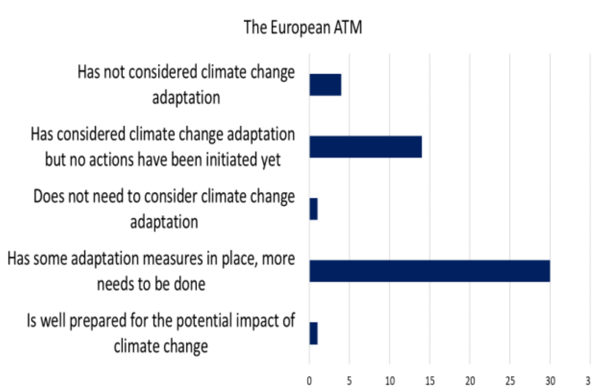


Fig. 3. Stakeholder perceptions of the level of preparedness for the potential impacts of climate change for the European Air Traffic Management (ATM).

## 3. Aircraft performances

Environmental phenomena significantly impact aircraft performance, making it heavily reliant on climate conditions. Therefore, climate change and its effects on the environment pose significant challenges for the aviation industry. Rising temperatures, changes in precipitation patterns, and variations in wind patterns can all affect aircraft performance. For example, an increase in temperature can reduce air density and increase the required take-off distance. Changes in wind patterns and turbulence intensity can also cause structural issues and impact the efficiency of propulsion systems [9].

To mitigate these risks, it is important to have a precise understanding of the loads to which aircraft are subjected, both during the design phase and in operation. Inadequate design or maintenance policies can lead to significant safety risks and operational inefficiencies. Furthermore, more data is necessary to understand how climate change and gust intensity are correlated. Variations in gust intensity can alter the loading conditions on an aircraft, impacting its envelope flight diagram. Consequently, maintenance policies must be updated, and new structural design solutions must be devised to address the changes. This may entail the introduction of new flight regulations and the establishment of specific load conditions for each aircraft, (Fig. **4.** Effects of turbulence changes on the aircraft design and regulationFig. 4). More turbulence data and accurate forecasting models are necessary to provide information for developing new aircraft design and operation strategies that are better suited to the challenges posed by climate change.

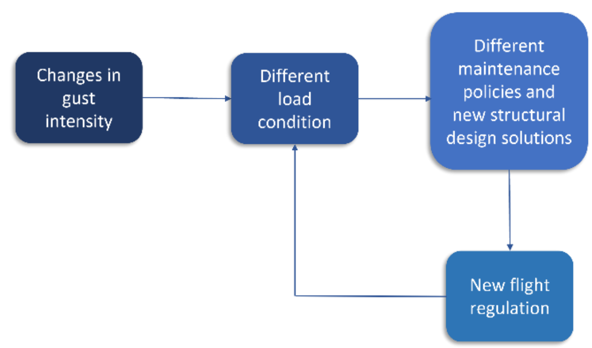


Fig. 4. Effects of turbulence changes on the aircraft design and regulation

To explain the consequences of the turbulence intensity changes, the responses of a model with 2 degrees of freedom subjected to different gust intensity, was evaluated. As turbulence model, von Kármán gust was considered, with the corresponding Power Spectral Density

$$\Phi(\Omega) = \sigma_g^2 \frac{L}{\pi} \frac{1+\frac{8}{3}(1.339L\Omega)^2}{[1+(1.339L\Omega^2]^{\frac{11}{6}}} \quad (1)$$

Following the military norm MIL-STD-1797, light, medium and sever gust were evaluated, changing $\sigma_g$, the root mean square of the gust speed. The response of the aircraft varies related to the gust intensities, specifically the peaks in the response increase when the gust speed rise (Fig. 5, Fig. 6), these effects could be intensified by climate change affecting the crew comfort during the cruise, but more importantly altering our knowledge about the fatigue life of the structure.

## 4. Space technology support

Aviation is one of the sectors that benefit from space technologies and Earth observation missions collecting and providing climate data. These data are not only useful for aviation but also for other sectors such as agriculture and meteorological stations. Real-time monitoring is essential in managing potential catastrophic events, such as tsunamis, floods, and landslides, and to act on time, limiting the victims. Numerous missions are being developed to monitor sudden and powerful events, such as convective cells. Raincube, a 3U CubeSat, employs a Ka-band radar antenna to detect convective cells by measuring their brightness temperature [10]. However, it has a drawback in that it lacks a system to locate and track the cells, so the radar can only detect the cell when the satellite flies over it. Moreover, Raincube operates in LEO, so it can only study the instantaneous situation and not the system's evolution. Another mission, TEMPEST-D, launched in 2018 and was operational until 2021. This 6U CubeSat was equipped with a microwave radiometer to observe the evolution of storm clouds and assess their intensity and hazard potential. Unlike Ka-band radar, TEMPEST-D measured brightness temperature with less accuracy but with a wider swath of 825km. The mission's ultimate objective was to validate the payload's performance and enable the development of a TEMPEST constellation in LEO to examine not only the intensity but also the time evolution of short events such as convective cells [11], [12].

Over the years, many other missions have been developed to study meteorological events and remarkable improvements are being done on payloads in LEO. By Using satellite data estimation in turbulence intensity and frequency could be performed. By using an IR sensor, it is possible to detect clear air turbulence (CAT) observing anomalies in the water vapour in the atmosphere [13]. Clear Air Turbulence (CAT) is a type of turbulence that occurs in clear skies, without any visible indication of clouds or other atmospheric disturbances. It is a significant safety hazard for aircraft because it can occur unexpectedly and is difficult to detect and avoid.

Infrared observations of water vapor can be used to detect areas of CAT, as the turbulence is often associated with variations in atmospheric humidity. The technique involves measuring the temperature of water vapor in the atmosphere using infrared sensors. As air flows through areas of turbulence, the temperature and humidity can change rapidly, producing detectable variations in the infrared signal [14].

Using infrared observations to detect CAT has the potential to improve flight safety by providing advance warning of turbulence, allowing pilots to take appropriate action to avoid it.

Space technology has proven to be a valuable tool for detecting and studying turbulence in the Earth's atmosphere and monitoring the effects of climate change. Satellites equipped with sensors and instruments such as radar and radiometers have allowed scientists to observe and analyze atmospheric conditions, which can lead to more accurate turbulence forecasts and ultimately improve aviation safety. In addition, the use of CubeSats and other small satellites is becoming increasingly popular for turbulence detection, providing a cost-effective and flexible solution for monitoring weather patterns. As technology continues to advance, it is likely that space-based observations will play an even greater role in our ability to predict and prepare for turbulence events.

## *5.* Conclusions

It is clear that climate change is already affecting the aviation industry, and the situation is expected to worsen in the future. The use of space technology is becoming increasingly important to monitor and mitigate the effects of climate change on the aviation industry. Despite the challenges and costs associated with developing and managing satellite constellations, the benefits of high-accuracy and real-time data are undeniable. Moreover, by investing in sustainable practices and utilizing space technology, the aviation industry can work towards reducing its environmental impact while continuing to operate safely and efficiently. It is important for both the private sector and governments to recognize the urgency of the situation and take proactive measures to address climate change and its impact on the aviation industry.

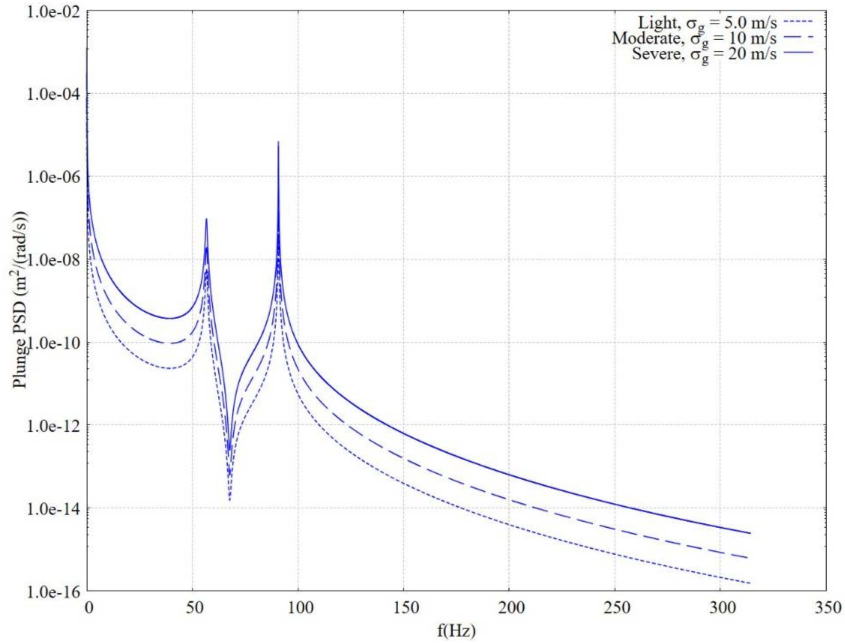


Fig. 5. Plunge Power Spectral Density of the system when subjected to three different turbulence intensities.

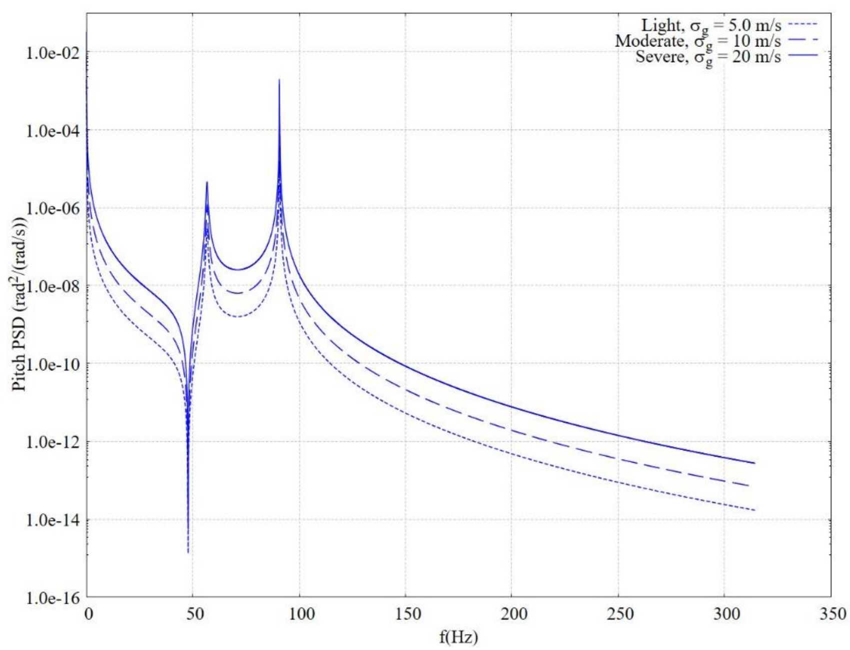


Fig. 6. Pitch Power Spectral Density of the system when subjected to three different turbulence intensities.

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