A PRELIMINARY METHODOLOGY TO ASSESS GUST SPECTRA VIA SATELLITE DATA

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Abstract

The wind gust represents one of the most unpredictable and critical phenomena in the field of aviation. The transient nature and elusive detection of wind gusts present significant challenges, which are further compounded by the impacts of climate change. This study demonstrates the capacity of satellite data to reveal the complexities of gust behavior. The authors exploit data from the Aeolus ESA satellite to reveal annual and seasonal fluctuations in gust patterns along a section of the transatlantic route, a pivotal corridor in aviation. These findings underscore the transformative potential of satellite technology to study the repercussions of climate change on air travel, with implications extending to global aviation.

Keywords: Climate change; Aviation; Satellite

1. Introduction

Aviation represents a marginal 2.4% of global CO_2 emissions [1], however, the sector has witnessed a 32% growth rate in recent years [2]. This rapid expansion, in conjunction with the projected future growth of the sector, presents a complex set of challenges for the aviation industry as it endeavours to mitigate its environmental footprint [3]. Concurrently, the effects of climate change significantly impact Aviation and Aeronautics, affecting the operational aspects of flight and the resilience of the associated infrastructure and the airline's work [4].
The effects of climate change on aviation are multifaceted. Coastal airports and runways face direct threats from rising sea levels and coastal erosion [5]. This poses integrity issues necessitating resource-intensive interventions like repairs, relocation, or even closures, with far-reaching implications for global transportation and trade. Extreme weather events, such as storms, hurricanes, and floods, pose significant threats to airport infrastructure, particularly affecting regions reliant on air travel for commerce and tourism [6]. Among the effects of climate change, the increase in gusts is particularly concerning, posing significant hazards in aviation [7]. These hazards can lead to injuries, significant financial losses due to increased aircraft maintenance needs, and compensation for injured passengers. Paul D. Williams' analysis highlights longer flight times on transatlantic routes due to shifting wind patterns induced by climate change, resulting in increased fuel consumption and costs [8]. In addition, passenger safety and comfort are affected by increased gust intensity. There has been an increase in turbulence-related incidents in recent years [9, 10]. More recently the accident on May 21, 2024, when the Boeing 777-300ER from London to Singapore experienced severe turbulence that caused several injuries. In addition, studies indicate an alarming escalation in vibration levels during flight, attributed to increased atmospheric disturbances over the past decades [11]. These interrelated effects underscore the multiple challenges climate change poses to the aviation industry.
From an aeronautical perspective, climate change profoundly affects every phase, from design to maintenance. Rising surface temperatures and changing wind profiles may increase the required

takeoff and landing distances, posing challenges for airports with limited runway lengths [12]. According to [13], the take-off length runaway may increase of 6.2% due to the effects of global warming. This aspect has to be taken into account in case of the design of novel aircraft whose entry to service is expected in the near future. Additionally, aircraft are designed to withstand specific loads during various flight phases, with these limits detailed in load and envelope diagrams [14]. These diagrams are based on atmospheric conditions, including gusts. Climate change affects these conditions, impacting the diagrams and, consequently, the aircraft design, particularly concerning gust response [15]. Wind gusts, characterized by sudden and brief increases in wind speed and direction, play a critical role in aircraft design. Their unpredictable nature imposes unique challenges that must be addressed to ensure modern aircraft's safety, performance, and efficiency. The presence of a gust generates a variation of the lift of the aircraft, in fact, in case of horizontal gust a variation of dynamic pressure occurs, whereas, in case of vertical gust, a variation of aerodynamic incidence occurs. As a result, in both case the lift generated by the aircraft changes, and this influences aircraft dynamics and structures. From one hand, a variation of lift should be counteracted by the aircraft autopilot and stability augmentation systems in order to maintain a safe level flight; however, to accomplish this goal, modelling of the aircraft response to the presence of a gust has to be carried out during the aircraft design process. On the other hand, variation of lift generates a randomized load on the wing which have detrimental effects on aircraft structural life. In this regard, active control methods to alleviate loads acting on aircraft structures are currently investigated [16, 17, 18].

Another critical aspects of aircraft design influenced by wind gusts is the management of fatigue loads. Fatigue refers to the progressive and localized structural damage that occurs when a material is subjected to cyclic loading [19]. Wind gusts contribute to this cyclic loading by introducing variable stress patterns. Repeated exposure to gust-induced loads can initiate and propagate cracks in structural components, ultimately leading to material fatigue. This growth of cracks is addressed during the maintenance phase of the aircraft using a damage tolerance approach, which relies on historical data collected and modelled based on transatlantic route gusts [20].

In the 1930s, detecting and modeling gusts required organizing special flight campaigns, selecting specific routes, and flying a fleet of aircraft to collect the necessary data [21]. This process often involved substantial financial outlays and extended timeframes, with data typically limited to specific geographic areas. The influence of climate change on gust patterns necessitates implementing more comprehensive and adaptive strategies for understanding and mitigating their effects on aircraft design and operation.

Satellites with various sensors and instruments offer a comprehensive dataset that could revolutionize aviation's approach to climate change and hazard detection (i.e. clear air turbulence, wind shear hurricanes and thunderstorms). Advanced predictive models that employ real-time observations of temperature, humidity, wind dynamics, and atmospheric stability can anticipate turbulence-prone zones with unprecedented precision compared to today's radar on the board of aircraft [22, 23]. Real-time monitoring through satellites, such as RainCube and TEMPEST-D, significantly enhances aviation hazard detection [24]. These technologies, exemplified by METEOSAT, a series of seven meteorological geostationary satellites operated by EUMETSAT, play a crucial role in predicting convective initiation and identifying clear air turbulence [25].

In this context, this article aims to highlight the capacity of satellite technology in detecting and analyzing wind gust data, leveraging its advantages to offer a substantial amount of data in a short period with almost global coverage. This work is organized as follows: Section 2 delves into the possibilities of utilizing satellite data to detect variations in wind gusts; Section 3 elucidates the methodology employed to analyze the satellite data; Section 4 presents findings, specifically examining gusts across different periods of the year, and in different years; Section 5 discusses the limitations of the approach; and finally, Section 6 offers insightful reflections and conclusions.

2. Satellite technology to forecast gust

The rise of satellite technologies has revolutionized the approach to wind gust detection. The ability to access a vast quantity of data relatively quickly and achieve near-global coverage, primarily through low-orbit satellites, is a significant advantage. This technology also allows for data collection at different altitudes with a single measurement, a capability that was previously unattainable. Moreover,

satellites can now carry multiple payloads, enabling the collection of diverse data during a single observation period. These missions extend beyond climate monitoring, showcasing the versatility of satellite technology.
Furthermore, the rapid exchange of data between satellites and ground stations facilitates real-time monitoring of weather conditions. This article showcases the potential of satellite systems, using data from Aeolus satellites, in evaluating the climatic effects of wind gusts and developing new and updated models.

2.1 Aeolus data

The European Space Agency's Earth Explorer, Aeolus, commenced its mission on August 22, 2018, marking a significant milestone in satellite-based observation. This satellite provides global insights into wind profiles from the Earth's surface to an altitude of 30 km. Aeolus employs the active Doppler Wind Lidars (DWL) method, which enables precise wind speed and direction measurements. The DWL provides indispensable data on wind profiles, offering valuable details on cloud top heights and the vertical distribution of thin clouds and aerosols. Aeolus orbits at an altitude of 320 km along a nearly polar trajectory, affording nearly global coverage, albeit not continuous monitoring of every region. Figure 1 depicts the orbit projection on a 2D map over a day.

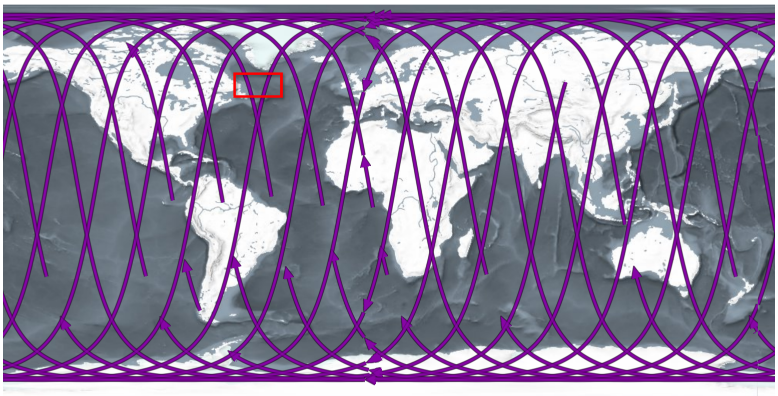


Figure 1 – Satellite projection onto the Earth's surface over a 24-hour period. Image adapted from [26]

Furthermore, radar technology enables data acquisition at various altitudes, assessing wind gust variation with altitude and specifying wing direction. As an example, Fig. 2 represents the data about vertical wing gust extracted from Aeolus data on a specific area on USA, and varying altitude form 0 to 17 km. Aeolus conducts measurements every 11.28 seconds and scans a range of 30 km with 1 km intervals, as depicted in the graph in Fig. 2. This comprehensive approach significantly advances research in atmospheric dynamics and holds promise for enhancing weather forecasting capabilities. The vast amount of data available and the ability to analyze data at any altitude and geographic location offer numerous opportunities for leveraging these datasets. Although the Aeolus mission spanned only four years, from 2019 to 2022, limiting the examination of gust evolution over time, these data serve as a foundational starting point.
While it is crucial to compare the current data with historical von Kármán and Dryden models, this alone is not sufficient for a comprehensive analysis of temporal evolution. It is imperative to compare the current data with historical datasets collected along significant flight routes. When combined, these datasets can be instrumental in deriving aircraft load diagrams and guiding regulatory updates to address non-compliance issues
Analyzing these datasets has the potential to impact aircraft structural integrity and performance significantly. Thanks to global coverage that includes previously inaccessible routes and altitudes, aircraft mission trajectory can be optimized to mitigate the detrimental effects of gusts on aircraft performance, such as fuel consumption or aircraft maintenance process. Moreover, refined data can assess vibration levels experienced by pilots and passengers, ensuring optimal comfort and reducing

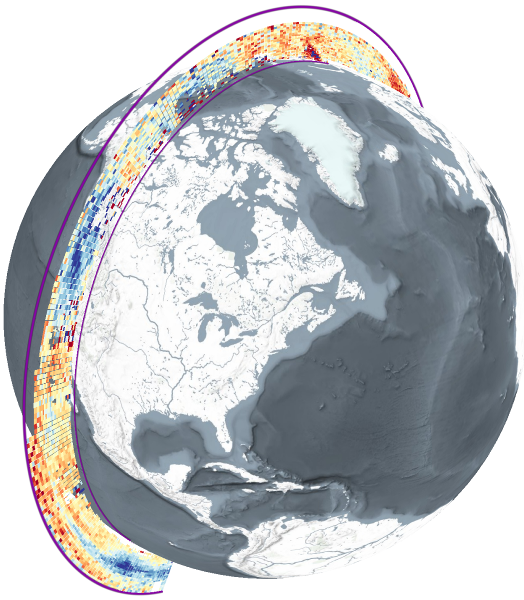


Figure 2 – Representation of the vertical wind gust collected by the satellite at various altitudes along its orbit. Each measurement interval has a height of 1 km and a width of 11.28 s. Image adapted from [26]

potential physical risks [27].

3. Methodology

This section outlines the methodology used to analyze the Aeolus data. The satellite data available on the online ESA platforms VirES were downloaded and analyzed using Matlab. The VirES platform enables users to select data, define areas of interest, and apply filters to clean the dataset (e.g. by selecting wind direction).
The satellite operates in low Earth orbit (LEO), so once the area is selected in red as highlighted by the red rectangle depicted in Fig. 1, continuous observation of the area is not possible, and the satellite only passes over it twice a day. Accordingly, the time signal data were padded.

A Discrete Fourier Transform (DFT) was applied to the time domain data to comprehensively analyze the signal's frequency content. This mathematical technique is transformative, decomposing the signal into its frequency components and providing invaluable insight into its spectral characteristics as reported in Eq. 1.

$$X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi \frac{nk}{N}} \tag{1}$$

Here, x_n represents the value of the n-th component of the measured signal in the time domain, while N denotes the total number of samples of the signal. The term $e^{-i2\pi \frac{nk}{N}}$ corresponds to a complex sinusoid at frequency $f_k = k/N$, with k in $[0, N-1]$, and X_k represents the assocciated complex number of the signal in the frequency domain. This equation allows for the transformation of the signal from the time domain to the frequency domain. Examining the resulting frequency spectrum reveals the dominant frequencies and inherent patterns within the signal, facilitating a more nuanced interpretation of its behaviour and extracting meaningful information about its underlying structure and dynamics. In this context, the signal's Power Spectral Density (PSD) was evaluated using the following equation.

$$PSD(f_k) = \frac{1}{N} |X_k|^2 \tag{2}$$

where $PSD(f_k)$ represents the signal's power spectral density.
One of the classical mathematical models to represent the wind gust is the von Kármán model [15].

$$PSD_{vk}(f_k) = \frac{\sigma^2 L}{\pi V} \frac{1 + 8/3\left(1.339 \cdot 2\pi \frac{L f_k}{V}\right)^2}{\left[1 + \left(1.339 \cdot 2\pi \frac{L f_k}{V}\right)^2\right]^{11/6}} \tag{3}$$

where σ represents the root mean square of the signal, L stands for the length scale and V denotes the mean flight speed. The von Kármán model is calibrated using two key parameters: L and σ/V. The parameter L represents the average size of the gust in terms of distance and is influenced by factors such as altitude, and the turbulence model employed. On the other hand, σ/V represents turbulence intensity, which is affected by average wind speed and altitude. These parameters are challenging to measure and interdependent with other variables. Given the complexity and variability of these parameters within the von Kármán model, a nonlinear least mean square method was employed for fitting Eq. 4. The von Kármán model is formulated as follows:

$$\overline{PSD}_{vk}(f_k) = a \frac{1 + 8/3\,(b f_k)^2}{\left[1 + (b f_k)^2\right]^{11/6}} \tag{4}$$

with $a = \frac{\sigma^2 L}{\pi V}$ and $b = 1.339 \cdot 2\pi L/V$ the parameters to estimate. The nonlinear least mean square problem consists of estimating the parameters a and b that minimize the normalized sum of the square errors between the measured Power Spectral Density, $PSD(f_k)$ and the estimated model, $\overline{PSD}_{vk}(f_k)$. An example of this fitting performed on the dataset is illustrated in Fig. 3.

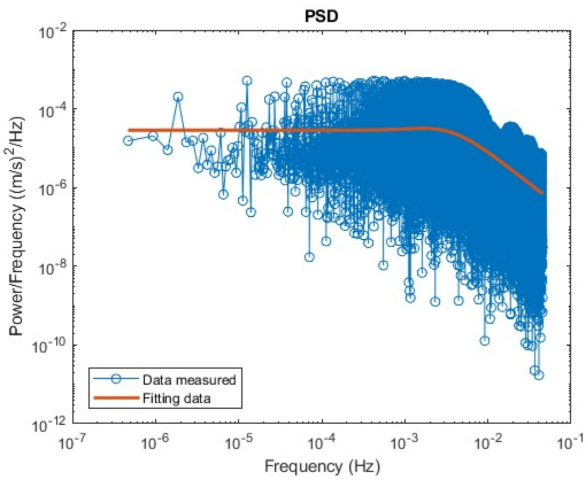


Figure 3 – Power Spectral Density and fitting of wind velocity signal observed in September 2019. The area of observation spanned 50 to 55 North latitude and 33 to 43 West longitude. The altitude selected ranged from 9900 to 10900 km. The R^2 fitting parameter is 0.11

4. Results

This section presents the results obtained through the methodology described in Section 3. Satellite data were employed to investigate a range of observation windows and conduct comparative analyses. The cases examined focus on a segment of the transatlantic route, ranging from 56 to 51 degrees North latitude and from 33 to 43 degrees West longitude (see Fig. 4). Specifically, the following parametric analyses have been carried out:

- **Seasonal variation**: One month is selected for each season within a specific year to observe seasonal changes. Furthermore, seasonal variations are examined across different years.
- **Annual variation**: To assess annual variations, the same month is examined over four years, from 2019 to 2022.

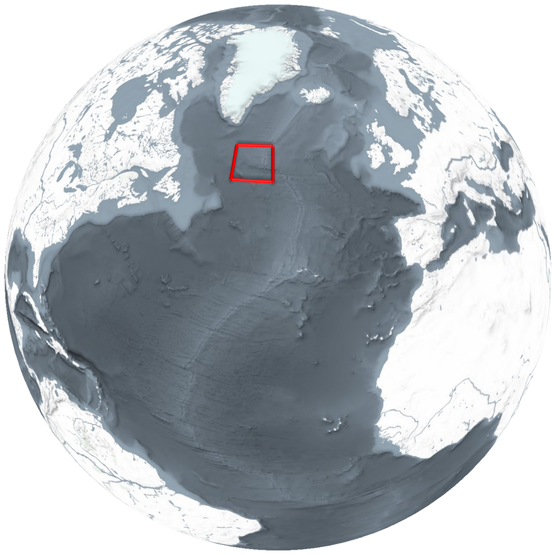
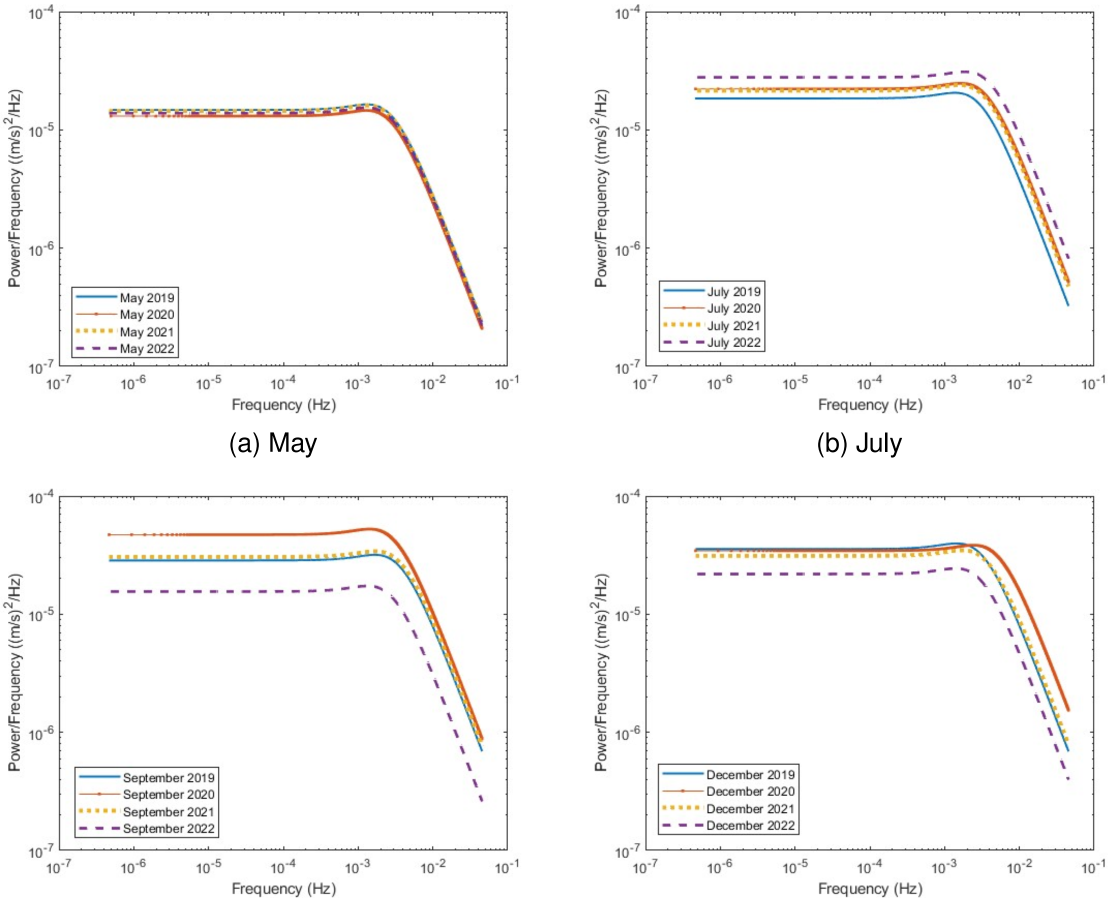


Figure 4 – Representation of the selected are. Image adapted from [26]

The analyses provide insights into wind gusts' temporal and spatial dynamics along the transatlantic route, offering valuable information for aviation safety and operational planning.
The data set encompasses satellite observations from 2019 to 2022, with an altitude range of 9.9 to 10.9 km. A notable month was selected for each year and season to capture the annual variation of wind gusts. This approach allowed for considering the significant diversity of atmospheric conditions along the route across different seasons. The outcomes are depicted in Fig. 5.
The analysis of the May data, representing the spring season, reveals a consistent pattern with no discernible variations over the observed years. In contrast, a significant increase in wind gusts is observed from 2019 to 2022 in July, particularly at lower frequencies. The autumn months, such as September, show a random trend depending on the year. In contrast, December exhibits relatively stable conditions across all years, with a slight decline observed in 2022.

A significant month was selected for each season in each year to observe seasonal variations. The results are presented in Fig. 6. As in previous analyses, a variety of trends emerge across the years. Across all four years under consideration, the spring season consistently exhibited the lowest gust intensities, followed by summer. Conversely, periods of more intense gusts correspond with the colder months, except in 2022, which showed a notable increase in gust intensity during summer.

While these observations provide valuable insights, it is essential to note that making predictions based solely on these trends is impractical due to the limited observation period. Nevertheless, they serve as a foundational starting point for subsequent analyses and comparisons with data from other satellites and historical gust records.



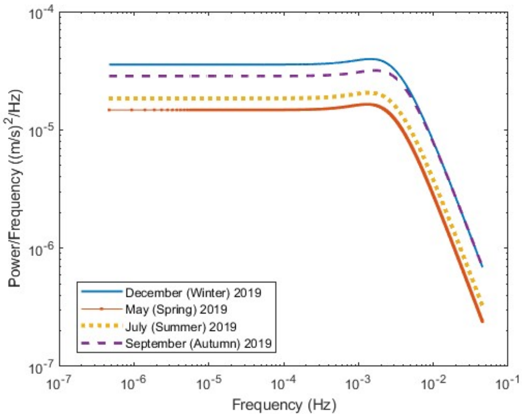
(a) May (b) July

(c) September (d) December

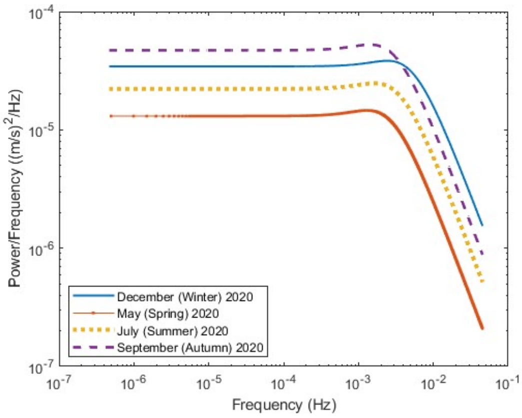
Figure 5 – Annual variation from 2019 to 2022. The area of observation spanned 50 to 55 North latitude and 33 to 43 West longitude. The altitude selected ranged from 9900 to 10900 km.

5. Limitations of the approach

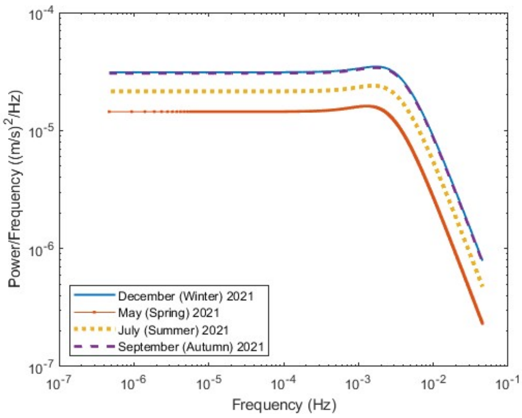
While the analysis of turbulence sources and the use of Aeolus satellite data demonstrate significant potential for detecting and analyzing wind gusts, several limitations to this approach must be considered. The Aeolus satellite operates in low Earth orbit (LEO), which means it does not provide continuous coverage of any single area. Therefore, there are gaps in the data, as the satellite only passes over each region at specific times. Consequently, the time signal data must be completed by inserting zeros when the satellite does not cover the region of interest, potentially introducing inaccuracies, due to noise signal. Integrating historical data with current satellite observations is crucial for understanding long-term trends and the impacts of climate change on wind gusts. However, discrepancies in data quality, resolution, and coverage between historical and current datasets can pose challenges for accurate analysis and comparison. Making predictions solely based on this limited dataset is not feasible. Despite these limitations, integrating satellite technology in the analysis of wind gusts represents a significant advancement in aviation safety and efficiency. Continued research and development, technological improvements, and more comprehensive data collection will help mitigate these limitations and enhance this approach's predictive capabilities.



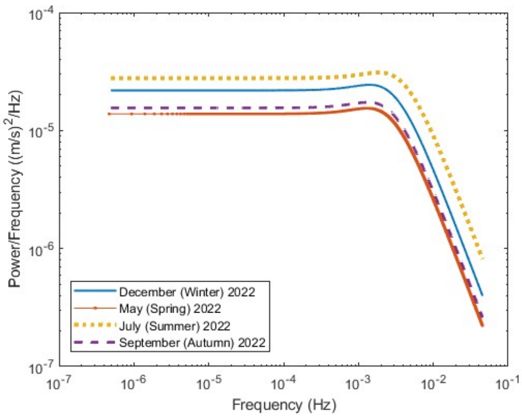
(a) Seasons in 2019



(b) Seasons in 2020



(c) Seasons in 2021



(d) Seasons in 2022

Figure 6 – Seasonal variation from 2019 to 2022. The area of observation spanned 50 to 55 North latitude and 33 to 43 West longitude. The altitude selected ranged from 9900 to 10900 km.

6. Conclusion

Climate change has brought significant challenges to the aviation sector. Among the effects—such as rising temperatures and changes in wind patterns—the increase in wind gust intensity is a major concern highlighted in this article. The rise in gust intensity poses significant issues for aviation since it exacerbates structural fatigue and impacts aircraft performance. In this context, satellite technology can play a crucial role in detecting and analyzing climatic conditions, especially changes in wind gust patterns. This work reveals the potential and capabilities of satellite technology in detecting and analyzing wind gusts through a comprehensive analysis of turbulence sources and the Aeolus satellite's wind gust data. The generalized harmonic analysis, or power-spectral analysis, of wind gust has been used to assess wind gust power spectrum according to the well-known Von Karman model. Satellite data was used to show seasonal and annual variations in gusts between 2019 and 2022 over a portion of the transatlantic route. Additionally, variations in gust intensity at different cruising altitudes were observed. The analysis demonstrated that significant variations in some cases between different years and seasons can be detected and lays the foundation to monitor, in the forthcoming years, how the wing gust power spectrum is affected by climate change. This aspect is of paramount importance to aircraft manufactures since it will influence design and maintenance of aircraft designed to enter into service in the next coming years. To improve predictive models and understand the variations and effects of climate change on gust patterns, it is essential to analyze both recent and historical data for meaningful comparisons continuously. Expanding the scope of analysis to include other regions for comparative purposes would be beneficial. Furthermore, studying gust behaviour at sea level could provide valuable insights, particularly during critical phases such as takeoff and landing.

7. Appendix

The tables in this section contain data on the fitting parameter and the subsequent von Kármán model parameters.

Year	a $[m^2/s]$	b $[s]$	R^2	L $[m]$	$\sigma[m/s]$
2019	1.47E-05	470	0.25223	13057.1702	9.10E-04
2020	1.31E-05	473.9	0.137146	13165.517	8.54E-04
2021	1.44E-05	473.2	0.137974	13146.0701	8.98E-04
2022	1.38E-05	473	0.174725	13140.5139	8.79E-04

Table 1 – the parameters of the curves depicted in Fig. 5a, representing the month of May, with an altitude ranging from 9.9 to 10.9 km, M = 0.78, and a cruise speed of 233.61 m/s.

Year	a $[m^2/s]$	b $[s]$	R^2	L $[m]$	$\sigma[m/s]$
2019	1.84E-05	447.3	2.11E-01	1.24E+04	1.04E-03
2020	2.22E-05	377.3	1.61E-01	1.05E+04	1.25E-03
2021	2.15E-05	389.5	1.92E-01	1.08E+04	1.21E-03
2022	2.78E-05	328	1.06E-01	9.11E+03	1.50E-03

Table 2 – the parameters of the curves depicted in Fig. 5c, representing the month of July, with an altitude ranging from 9.9 to 10.9 km, M = 0.78, and a cruise speed of 233.61 m/s.

Year	a $[m^2/s]$	b $[s]$	R^2	L $[m]$	$\sigma[m/s]$
2019	2.85E-05	368.2	1.06E-01	1.02E+04	1.43E-03
2020	4.71E-05	430.7	1.10E-01	1.20E+04	1.70E-03
2021	3.05E-05	360.5	8.14E-02	1.00E+04	1.50E-03
2022	1.56E-05	459.9	1.92E-01	1.28E+04	9.45E-04

Table 3 – the parameters of the curves depicted in Fig. 5d, representing the month of September, with an altitude ranging from 9.9 to 10.9 km, M = 0.78, and a cruise speed of 233.61 m/s.

Year	a $[m^2/s]$	b $[s]$	R^2	L $[m]$	$\sigma[m/s]$
2019	3.56E-05	422.3	2.12E-01	1.17E+04	1.49E-03
2020	3.44E-05	254.2	1.00E-01	7.06E+03	1.89E-03
2021	3.12E-05	359.1	1.66E-01	9.98E+03	1.51E-03
2022	2.19E-05	437.9	2.40E-01	1.22E+04	1.15E-03

Table 4 – The parameters of the curves depicted in Fig. 5b, representing the month of December, with an altitude ranging from 9.9 to 10.9 km, M = 0.78, and a cruise speed of 233.61 m/s.

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9. Copyright Statement

10. Acknowledgment

This study was carried out within the Space It Up project funded by the Italian Space Agency, ASI, and the Ministry of University and Research, MUR, under contract n. 2024-5-E.0 - CUP n. I53D24000060005.

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