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Impacts of Changing Atmospheric Circulation Patterns on Aviation Turbulence Over Europe

Key Points:

- Changing atmospheric circulation due to climate change increases turbulence over Europe
- Turbulence peaks in winter, linked to wind shears from the subtropical jet stream over the Southern Mediterranean
- Most increasing episodes are related to clear air turbulence, occurring unexpectedly at flight cruise altitudes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Addressing aviation turbulence not only enhances passenger comfort but also help to reduce fuel consumption and environmental impact, supporting aviation sustainability. By using ERA5 reanalysis data we explore how changing atmospheric circulation, monitored via sea level pressure trends, impacts aviation turbulence over Europe. Our results show coherent climate anomalies, with rising turbulence intensity over the UK and Northern Europe where most events involve clear air turbulence, which occurs unexpectedly and without warning, particularly at flight altitudes. We also highlight a clear seasonal patterns in moderate-or-greater turbulence encounters, most frequent and intense in winter, with a key role of wind shears due to the subtropical jet position over Southern Mediterranean. Our approach adds to previous studies on the same topic by analyzing individual atmospheric circulation pattern changes and their effects on turbulence-related factors. This offers insight into how climate change affecting atmospheric dynamics may contribute to increased aviation turbulence.

Plain Language Summary This study investigates how climate change can affects aviation turbulence over Europe, which is crucial for improving passenger comfort, reducing fuel consumption, and promoting sustainable aviation. Our findings indicate an increase in turbulence, particularly over the UK and Northern Europe with a significant portion of this increase involving clear air turbulence. This is particularly hazardous as it occurs without warning and cannot be detected visually, especially at cruising altitudes. We also found that turbulence is more frequent and intense during winter with a seasonal pattern influenced by wind shears associated with the position of the subtropical jet stream over the Southern Mediterranean. Finding ways to face with turbulence could make flights smoother, safer, and more environmentally friendly.

1. Introduction

The unprecedented changes in Earth's climate are reshaping atmospheric dynamics on a global scale (Masson-Delmotte et al., 2021), with profound implications for various sectors, including aviation (Shaw & Miyawaki, 2023; Williams & Joshi, 2013). Atmospheric patterns changes modify the weather and, in synergy with global warming, enhance extreme events (e.g., storms, precipitations, heatwaves, droughts, Christidis and Stott (2021); Gudmundsson et al. (2017); Bevacqua et al. (2019)), affecting different sectors (e.g., industry, agriculture, tourism, Ortiz-Bobea et al. (2021); Scott et al. (2012)). As anthropogenic activities continue to drive climate change, understanding the specific regional manifestations of these alterations becomes imperative, particularly over Europe which is marked by densely populated urban centers, major economic activities, and extensive air traffic networks (D. S. Lee et al., 2009). Indeed, one of the most evident consequences of global warming is the intensification of convective phenomena (Seneviratne et al., 2021). As temperatures increase, also the moisture content in the atmosphere increases, leading to convective processes and fostering the development of thunderstorms and intense rainfall events (Dayan et al., 2015). These convective systems can also generate strong wind shears, contributing to atmospheric instability and turbulence, particularly in the lower atmosphere where most commercial aircraft operate (Sharman & Lane, 2016).

European climate features a rich meteorology, with its diverse geography, orography, and micro-climates, which is greatly impacted by climate change (Naumann et al., 2021). Of particular interest is the heightened potential for increased aviation turbulence, with direct consequences for flight operations, fuel efficiency, passenger comfort,

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and overall safety (Gratton et al., 2022). Indeed, atmospheric turbulence poses a significant risk to the aviation industry, accounting for 71% of all weather-related aircraft accidents among regularly scheduled air carriers (Gultepe & Feltz, 2019). Among different types (Storer et al., 2019; J.-H. Kim & Chun, 2010; Lane et al., 2012; Trier et al., 2022) clear-air turbulence (CAT), defined as high-altitude aircraft bumpiness occurring away from significant cloudiness and thunderstorm activity, is, surprisingly, the half of all encounters with turbulence (Williams & Storer, 2022). Recent studies (Storer et al., 2017; Williams, 2017; Williams & Joshi, 2013) have shown a significant increase in turbulence levels over the last decades which are projected to further increase according to climate models (Smith et al., 2023) by mid-century in various regions, including the North Atlantic, North America, and Europe (Wolff & Sharman, 2008; Storer et al., 2017; S. H. Lee et al., 2019). Given the wide spectrum of aviation-related weather impacts and the inherent challenge in accurately simulating them through a singular or a set of models (as global climate models Smith et al. (2023)), a holistic approach is helpful to discern increasing or decreasing trends in the frequency of occurrence of atmospheric circulation patterns (Faranda, Messori, et al., 2023a; Faranda et al., 2023b). Indeed, the interconnected nature of meteorological events across the European aviation sector requires for an integrated analysis, in which different atmospheric observables are jointly considered to account for both phenomena and impacts.

In this study, by using the ERA5 reanalysis data (Hersbach et al., 2023) we investigate the extent to which changes in atmospheric dynamics amplify the impacts of climate change on aviation turbulence at regional scales (over North Atlantic and European sectors). Our analysis centers on the identification of weather patterns derived from the classification of daily mean sea level pressure (SLP) field (Faranda, Messori, et al., 2023a; Faranda et al., 2023b). This atmospheric variable is a good tracker of the atmospheric dynamics, at mid-latitude, and it is the most used variable for attribution studies (F. E. L. Otto, 2016; F. Otto, 2019), justifying its historical prominence in meteorological broadcasts, reanalysis products, and models of different complexity (Hersbach et al., 2023).

By focusing on the morphology of large-scale SLP patterns that are more frequently encountered during the last 4 decades in the ERA5 data (Hersbach et al., 2023) we can devise the most-encountered spatial pattern of key diagnostics (e.g., Ellrod's indices TI1 and TI2) related to aviation turbulence episodes. We observe a growing frequency of large-scale atmospheric patterns conducive to moderate-or-greater (MOG)-level turbulence over the UK and Northern Europe. Our approach complements to previous studies (e.g., Williams and Storer (2022); Storer et al. (2017); Shaw and Miyawaki (2023)) in examining long-term changing trends in atmospheric circulation patterns and their impacts on turbulence-related variables to provide a holistic understanding of how variations in atmospheric dynamics contribute to the intensification of aviation turbulence.

2. Data and Methods

2.1. Data

We use the most recent climate reanalysis data generated by the European Centre for Medium-Range Weather Forecasts (ECMWF) as a part of the EU-funded Copernicus Climate Change Service (C3S). Specifically, our focus was on the ERA5 data set, providing hourly sampled atmospheric parameters spanning from 1950 to the present, with a horizontal resolution over Europe of $0.25^\circ \times 0.25^\circ$, and at different pressure levels (Hersbach et al., 2023). We decided to focus on the satellite era (i.e., 1979-today) when widespread observations of climate variables from satellites have become available. This consistent coverage over an extended 44-year period enables us to detect temporal trends in the dynamics (from hours up to inter-annual/decadal timescales) associated with spatial patterns, also ensuring uniform spatial and temporal coverage. We focus over the European box extending between 30°W and 40°E in longitude and between 35°N and 75°N in latitude with a grid size of 281×181 cells (Hersbach et al., 2023). We use mean sea level pressure as a key indicator for analogs searching (e.g. (Faranda, Messori, et al., 2023a; Faranda et al., 2023b)), while for investigating impacts on aviation turbulence we use three different parameters: the Ellrod's indices TI1 and TI2 and the eddy dissipation rate (EDR). The Ellrod's indices, TI1 and TI2, are turbulence indices developed to help forecast CAT in the atmosphere. TI1 (in units of s^{-1}) is based on the deformation of the wind field at flight levels by combining the vertical wind shear (VWS) and the horizontal deformation (DEF), that is, $\text{TI1} = \text{VWS} \times \text{DEF}$. High values of TI1 suggest a high potential for CAT, primarily associated with wind shear zones such as jet streams (Ellrod & Knapp, 1992). TI2 (in units of s^{-1}) further incorporates convergent flow (-DIV) related to the development of frontal zones and thereby provides a more refined estimate of turbulence by considering both dynamic and thermodynamic properties of the

atmosphere (Ellrod & Knox, 2010), that is, $TI2 = TI1 - VWS \times DIV$. Like their $TI1$ counterpart, high values of $TI2$ are related to more likely CAT encounters. Finally, the eddy dissipation rate EDR (in units of $m^{2/3} s^{-1}$) represents the rate at which turbulent kinetic energy is dissipated per unit mass due to the effects of turbulent eddies ((ICAO), 2018). We indirectly derived the EDR from the cube-root of the kinetic energy estimated via the velocity field provided by the ERA5 database (Hersbach et al., 2023). Indeed, the European Center for Medium-Range Weather Forecasts (ECMWF) is being to release EDR as a product in the new reanalysis version ERA6 (Bechtold et al., 2021). For our purposes, since we cannot directly access to the inertial range of turbulence due to the standard outputs of ERA5 reanalysis, we estimate the EDR by assuming valid the Kolmogorov's second hypothesis of similarity and by employing the Taylor's hypothesis is used to express spatial increments as temporal ones. Thus,

$$EDR = \left[\frac{V'^2}{\Delta t} \right]^{1/3} \quad (1)$$

where $V' = \sqrt{\langle V^2 \rangle}$ is the root-mean square (RMS) of the velocity field and Δt is the time resolution. This is equivalent to the second-order structure function approach (Frehlich & Sharman, 2004; Kim et al., 2022) but adapted to the outputs provided by ERA5. We need to point out that our estimation can be considered as a proxy of the EDR usually adjusted for aircraft type. Indeed, our EDR is not derived from AMDAR transmissions and it is not adapted on the type of aircraft ((ICAO), 2018). However, its statistics (see Figure S6 in Supporting Information S1) is well in agreement with values reported in literature, allowing to classify aviation turbulence onto different classes/levels ((ICAO), 2018): null (EDR lower than 0.1), light (EDR between 0.1 and 0.2), moderate (EDR between 0.2 and 0.45), and severe (EDR larger than 0.45).

For our purpose we focus on the range of altitudes between 250 hPa (~34 kft) and 200 hPa (~38 kft) which includes cruising altitudes for commercial airliners (~36–37 kft) (Sharman & Lane, 2016).

2.2. Methods: Occurrence Trends of Analogs

The computation of the trends in the occurrence of atmospheric circulation patterns involves the following steps (Faranda, Messori, et al., 2023a; Faranda et al., 2023b). First of all, anomalies of the sea-level pressure field are obtained by removing a grid-by-grid point linear trend throughout the entire analysis period, to account for long-term thermodynamic trends, and a mean seasonal cycle by averaging over the corresponding calendar days. Then, Euclidean distances between these maps at different times are computed, treating one map as a reference state and measuring its distance from all others in the data set. A quantile (typically $q = 0.98$) determines which fields are considered analogs. The entire time interval is further divided into equal sub-intervals, and the number of analogs $N(t)$ within each sub-interval is counted. A linear best-fit detrending process is applied as

$$N(t) = a t + b \quad (2)$$

and the 95% confidence intervals (CI) for the slope of the fit (a) are calculated. If both the lower and upper CI bounds are positive or negative, then that SLP pattern is associated with a positive or negative trend. If the CI includes zero, the trend is considered non-significant. The robustness of the estimation is assessed by both repeating calculations for higher quantiles ($q = 0.99, 0.995$), as well as, by bootstrapping procedures (Faranda, Messori, et al., 2023a; Faranda et al., 2023b). Thus, we consider only maps displaying consistent and significant occurrence trends across all quantiles as robust circulation patterns.

Finally, since the output of the analogs searching is a list of dates they can be used to reconstruct composite maps of the SLP field or of any other field of interest (e.g., temperature, wind speed, precipitation, turbulence indices, etc.), as well as, to inspect seasonal variations in the occurrence of analogs. The detection of occurrence trends of atmospheric analogs has proved useful impactful climate extremes (Jézéquel, Cattiaux, et al., 2018; Jézéquel, Dépoues, et al., 2018; Platzer et al., 2021; Yiou et al., 2017), including heatwaves and windstorms (Faranda, Messori, et al., 2023a; Faranda et al., 2023b), Acqua Alta events in Venice (Alberti et al., 2023; Faranda et al., 2023), droughts (Faranda, Pascale, & Bulut, 2023), and off-shore wind power availability (Rapella et al., 2023). In the following we specifically focus on increasing trends, that is, with coefficients a which are positively defined within error bars, to investigate the morphology of the patterns which are expected to be most

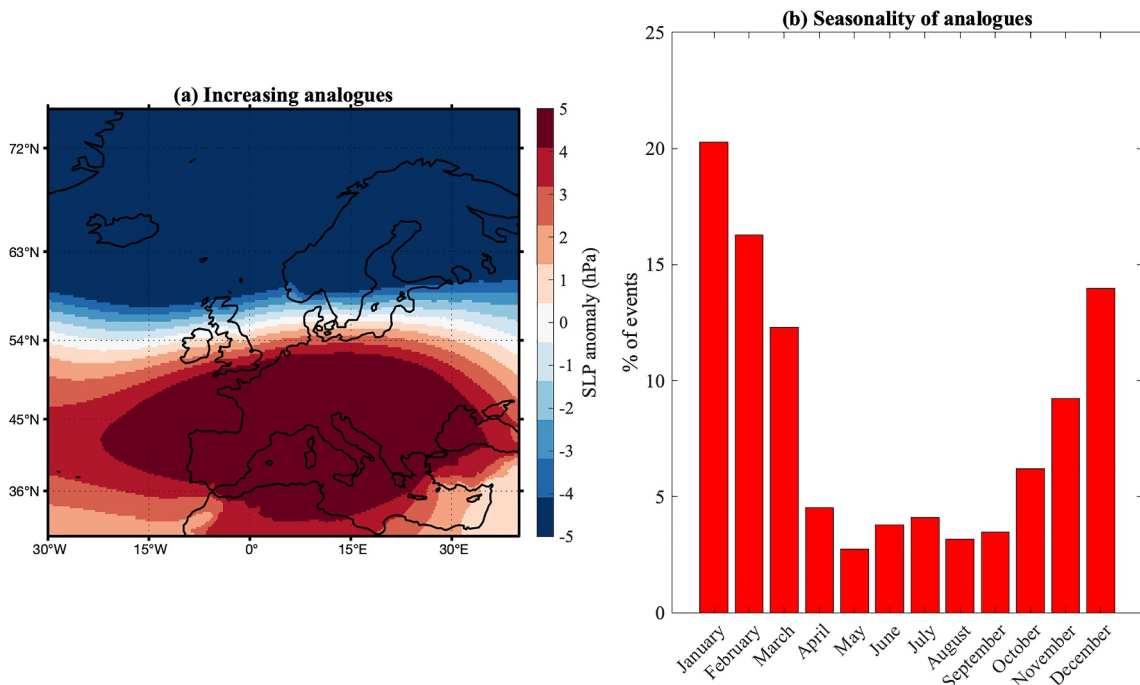


Figure 1. Composite anomalies of sea-level pressure (a) and monthly percentage distribution (b) for days with increasing occurrence trends.

encountered and whose increases can be related to climate change (Faranda, Messori, et al., 2023a; Faranda et al., 2023b).

3. Results and Discussion

When averaging over all seasons, the atmospheric circulation patterns (Figure 1) with occurrence trends show highly coherent surface climate anomalies over Europe. Specifically, more frequently occurring patterns (Figure 1a) show a north–south cyclonic–anticyclonic bipolar configuration with anomalies ranging between ± 5 hPa. Increasing analogs patterns are also associated with anomalously windy, warm, and wet conditions in Northern and Eastern Europe and moderately warm, dry conditions in Southern Europe (Faranda, Messori, et al., 2023a; Faranda et al., 2023b). Furthermore, increasing trends are mostly occurring (Figure 1b) during winter season (DJF, $\sim 50\%$), also showing a pronounced monthly variability, with occurrence reducing from 15% to 20% to less than 5% when moving from winter to summer months.

While previous studies (e.g. (Faranda, Messori, et al., 2023a; Faranda et al., 2023b; Rapella et al., 2023),) focused on meteorological variables (e.g., temperature, precipitation, wind speed) to study impacts of atmospheric circulation changes, here we are interested in variables which are strictly related with the occurrence of moderate-or-greater aviation turbulence (Sharman & Lane, 2016). As in J. H. Lee et al. (2023) we select MOG thresholds from the 95th percentiles of turbulence indices TI1, TI2, and EDR at 200 hPa. As a more conservative choice we evaluate this threshold only for increasing trends and not for the whole period (1979–today). The derived thresholds are in agreement with J. H. Lee et al. (2023), although slightly lower than Prosser et al. (2023). Nevertheless, our results are robust with respect to the selected thresholds for MOG turbulence. Figure 2 reports the composite maps for MOG turbulence of TI1 (a), TI2 (b), and EDR (c) for more frequently occurring patterns.

We can evidence that jointly larger TI1 and TI2 values are observed over the UK and the Norway, which we can link to the presence of larger vertical wind shears (see Figure S1a in Supporting Information S1), while larger TI1 and TI2 values over the North Atlantic are mainly related to both vertical wind shears and larger values for deformation. The latter, being associated with frontogenesis (J. H. Lee et al., 2023), seems to play a dominant role also over Alps and Southern Mediterranean (see Figure S1b in Supporting Information S1), which can be mainly related to thermal gradients leading to shears (Sharman & Lane, 2016). Furthermore, larger values of TI2 are also observed over the Northern France, Northern Germany, as well as, over the Alps, which we can relate to

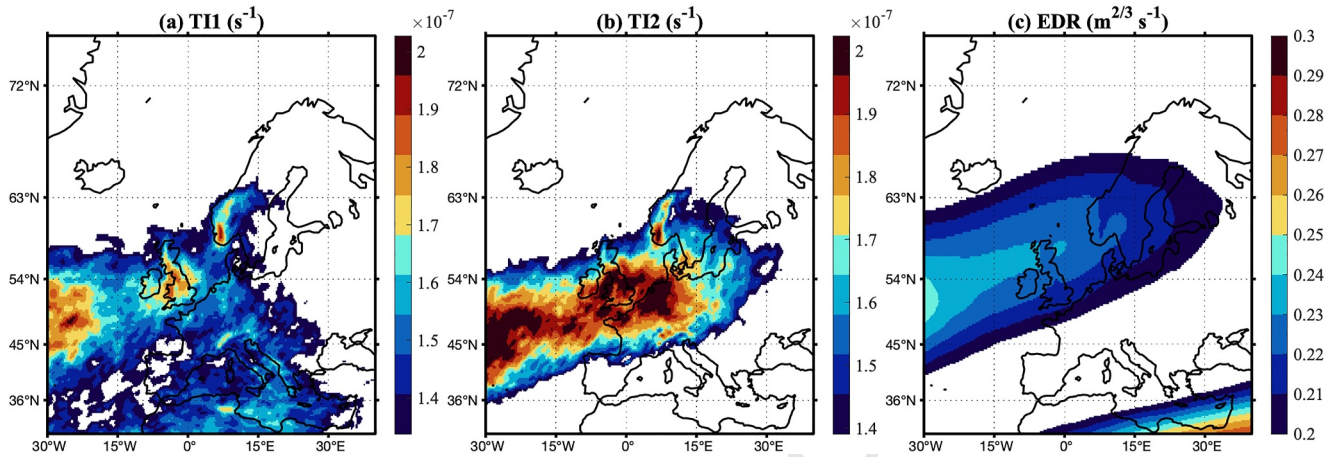


Figure 2. Composite maps averaged between 250 hPa and 200 hPa of TII (a), TI2 (b), and EDR (c) for more frequently occurring patterns corresponding to MOG turbulence.

development of upper-level frontal zones (TI2 indeed also consider the divergence as an additional term with TII, see Figure S1c in Supporting Information S1). Finally, larger EDR values are found in close correspondence of the south-east part of the European domain, close to the subtropical jet position, while lower values are encountered over the North Atlantic, UK, and Scandinavian regions.

By further inspecting the seasonal behavior of the observed patterns we can see that during winter months (Figure 3) the spatial extension as well as also the strength of turbulence is generally higher with respect to summer months (Figure 4).

In detail, we can see that during winter (Figure 3) TII and TI2 display similar spatial patterns with the composite maps (Figure 2), although with slightly overall larger values, as well as, also with localized differences. As an example, over Southern Mediterranean and Northern Africa we observe larger values for TII that could be linked with frontogenesis (see Figures S2b in Supporting Information S1) located on the cyclonic shear side of the subtropical jet stream (Ellrod & Knapp, 1992). The larger values can be indeed explained by the generally stronger jet in the winter due to the more pronounced temperature gradient between the equator and the poles. Furthermore, the presence of cold air masses distinct from warm air ones creates favorable conditions for a steeper pressure gradient that strengthens the jet, leading to more frequent and intense weather systems often bringing wet and stormy conditions over Southern Mediterranean. Additionally, stronger MOG episodes can be detected over the Alps which can be related to the presence of jet streaks, more common in winter, and able in creating localized

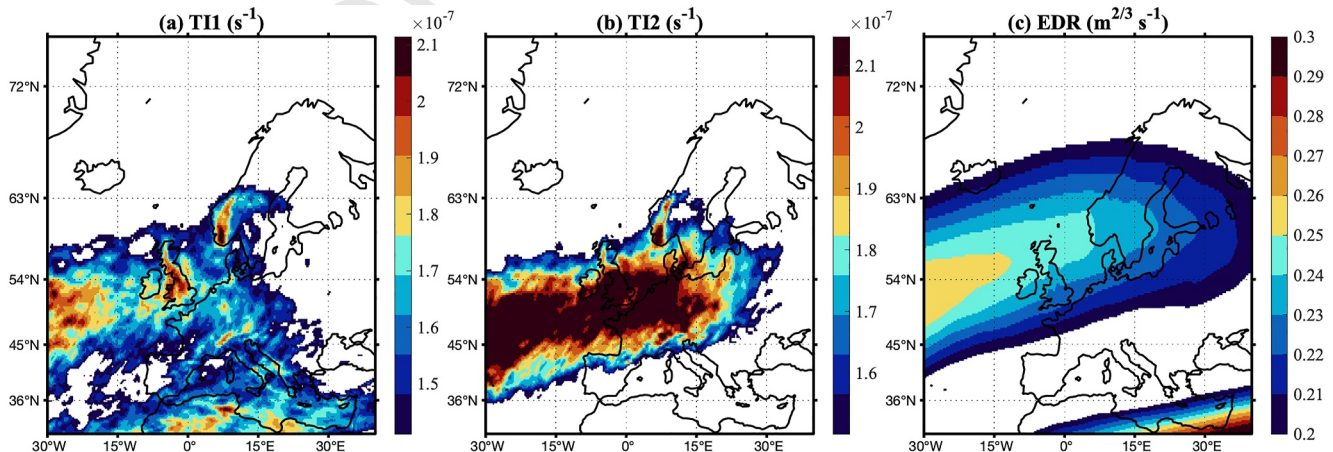


Figure 3. Composite maps averaged between 250 hPa and 200 hPa of TII (a), TI2 (b), and EDR (c) for more frequently occurring patterns corresponding to MOG turbulence during winter.

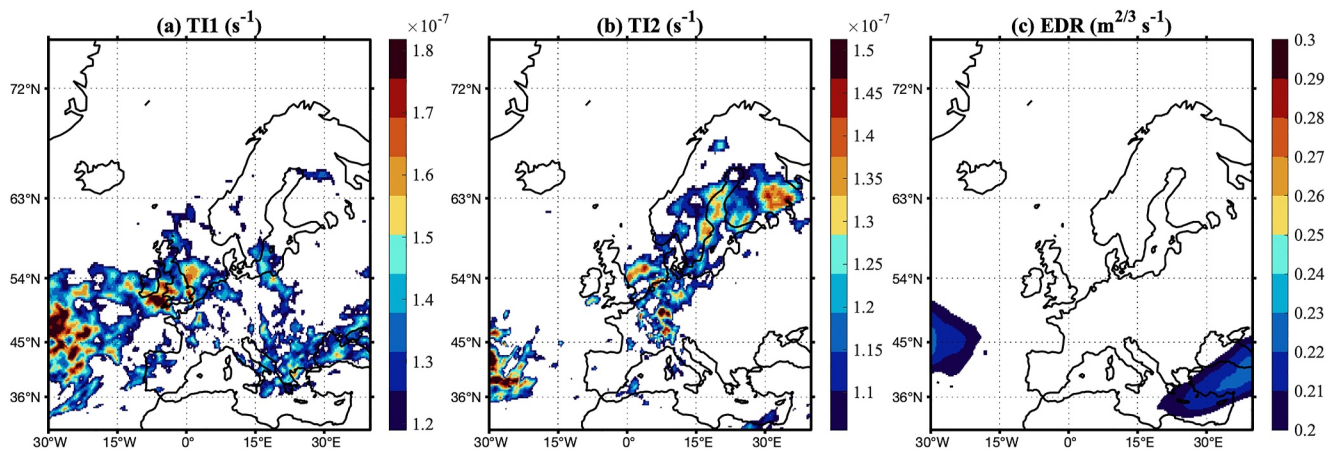


Figure 4. Composite maps averaged between 250 hPa and 200 hPa of TI1 (a), TI2 (b), and EDR (c) for more frequently occurring patterns corresponding to MOG turbulence during summer.

areas of intense wind shear and horizontal deformation, further increasing the TI1 index. Overall, by looking the spatial extension of TI2 associated with MOG turbulence does not change in winter as compared with the overall seasons, although we can clearly evidence larger values which can likely produce stronger turbulence. Indeed, by further inspecting the EDR we evidence larger values in winter, meaning stronger MOG turbulence levels when flying within Europe.

Conversely, during summer the spatial extension of MOG turbulence significantly reduces (Figure 4), as well as the observed values for all metrics, with a significant reduction especially for TI2. Small-scale localized increases in TI1 are only observed again over the North Atlantic, related to deformation likely developing on the shear side of cyclonic jet stream (see Figure S3b in Supporting Information S1) and over the North Sea, between UK and Scandinavian region. We do not evidence MOG turbulence over Southern Mediterranean region, although in the summer, the subtropical jet stream shifts northward. Indeed, its strength is typically weaker in the summer with southern parts of Europe, such as the Mediterranean region, experiencing drier and more stable weather, with effects usually less intense than in the winter. TI2, instead, showing a northward extension of localized larger values toward Sweden and Finland, likely linked to slight increases in vertical wind shears (see Figure S3a in Supporting Information S1). Finally, also the EDR evidence generally lower values and low-extended regions for MOG encounters. However, we need to point out that, given the use of CAT diagnostics (TI1 and TI2), the occurrence of CIT during summer could be missed (e.g., J.-H. Kim and Chun (2011); S.-H. Kim et al. (2021)), although we clearly identify a different role of VWS and DEF in leading TI1 patterns between summer and winter.

Similar scenarios to winter, although with lower values for all turbulence-related metrics, are also found for the European spring (see Figure S4 in Supporting Information S1), with also higher values for TI1 over Central and Southern Mediterranean, where it is expected to observe wind shears likely related to the increased convective activity, including thunderstorms, which can generate localized wind shear. Concerning EDR, we observe lower values over the northern part of the domain, while similar (high) values are observed for the south-eastern part, likely to be attributed to the sub-tropical jet stream. Conversely, particularly for the TI1 index, autumn season (see Figure S5 in Supporting Information S1) is quite similar to the summer time, although with larger extension of regions where TI2 assumes high values. Finally, EDR is mostly characterized by values close to 0.22, with a similar spatial extent of the winter and spring seasons. The different behavior over seasons compliments a recent study by Prosser et al. (2023) who found a larger absolute increase in winter times with respect to summer ones for MOG turbulence, as well as, also an increase of the time spent in MOG conditions.

Overall, by looking at the statistics for the EDR (see Figure S6 in Supporting Information S1) we depict an overall increase in its values for more-frequently encountered patterns with respect to the average, together with an increase in the fraction of MOG turbulence likely due to the increased role of climate change of the last 4 decades (Faranda, Messori, et al., 2023a; Faranda et al., 2023b).

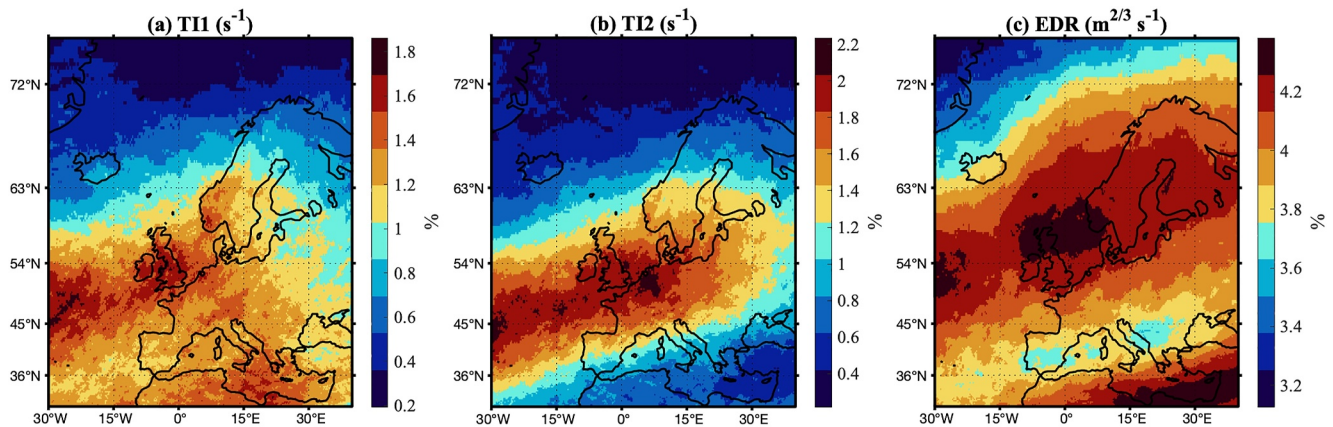


Figure 5. Composite maps of the probability of occurrence of MOG turbulence based on TI1 (a), TI2 (b), and EDR (c) for more frequently occurring patterns.

As a further step, the main question to address is where it is more probable to encounter MOG turbulence over the European domain, as well as, whether increasing or decreasing trends are also associated with increased turbulence strengths. Thus, we evaluate the fraction of time spent above the MOG threshold evaluated as the 95th percentile over the full record (1979–2023, not only on the subset of positively increasing trends) as reported in Figure 5.

The most striking feature that emerges is a significant higher chance to encounter MOG turbulence episodes close to the subtropical jet position. This suggests that the subtropical jet stream is still the main pattern enhancing turbulence episodes over the Southern regions of the European airspace; however, its role has been enhanced, in terms of probability of occurrence and intensity, due to long-term climate trends. Indeed, the probability of encountering MOG turbulence due to the subtropical jet stream moves from about 1.5% during decreasing trends up to 4% for increasing trends. This finding on the role of enhanced jet streams in leading more intense turbulence is in agreement with previous works on this topic (Prosser et al., 2023; Shaw & Miyawaki, 2023; Williams & Joshi, 2013). However, the main result is that there is a complimentary behavior for increasing trends when focusing over Europe for encountering MOG turbulence. While increasing levels have been previously reported over the North Atlantic (Williams & Joshi, 2013), here we show that also flying within the European airspace (e.g., toward central-to-northern regions or crossing southern Mediterranean during winter) can lead to more MOG turbulence episodes. This MOG turbulence tends to occur more frequently over a larger spatial area, extending from North Atlantic up to Scandinavian regions, or toward Central and Southern Mediterranean (depending on the season).

4. Conclusions

Our analysis reveals significant shifts in atmospheric circulation patterns over Europe and their implications for aviation turbulence. Consistent with prior studies (Faranda, Messori, et al., 2023a; Faranda et al., 2023b), we observe that increasing analog patterns correlate with windy, warm, and wet conditions in Northern and Eastern Europe. Furthermore, our analysis reveals a pronounced change in the seasonality of analog occurrence, indicative of an underlying trend attributed to climate change. Increasing trends predominantly occur during winter months, suggesting a notable shift in weather patterns.

Importantly, our study focuses on dynamic variables directly related to aviation turbulence, providing insights beyond traditional meteorological variables (Faranda, Messori, et al., 2023a; Faranda et al., 2023b). We observe distinct patterns in turbulence indicators as TI1, TI2, and EDR, indicative of evolving turbulence conditions as a consequence of varying atmospheric circulation patterns. Our analysis suggests that occurrence of MOG turbulence over the UK, Norway, and the North Atlantic can be linked to vertical wind shears and deformation. Conversely, in Southern Mediterranean MOG turbulence is associated with thermal gradients and wind shears, with the subtropical jet playing a significant role. MOG turbulence is more intense in winter, with larger values of TI1 and TI2, particularly over the Southern Mediterranean and Alps, due to stronger jet streams and weather systems. In summer, MOG turbulence is reduced, with smaller areas affected, mainly over the North Atlantic and

North Sea. Our results indicate that the subtropical jet enhances turbulence, especially in Southern Europe, and long-term climate trends indicate an increasing likelihood (up to 4%) of encountering MOG turbulence due to stronger jet streams. Over the past four decades, turbulence intensity and frequency have risen, particularly in winter over the North Atlantic, Europe, and the Mediterranean.

Our study also highlights the potentials of the use of analogs to provide a different but complimentary approach with respect to the existing literature on the link between climate change and turbulence impacts on aviation (e.g., Williams (2017); Williams and Joshi (2013); Williams and Storer (2022); J. H. Lee et al. (2023)). Indeed, previous works focused on a range of parameters (up to 21) which can be directly related to turbulence. Then, to investigate the role of climate change, both using reanalysis data and climate model simulations, a temporal trend is extracted from each grid box during a selected time interval of interests (for historical records typically from the beginning of satellite observations, i.e., 1979). Thus, long-term trend variability is inspected as a linear trend over certain regions. Our approach rests in a different way that can be used for a single event or a set of similar (analog) events, and it is the core of the ClimaMeter framework (Faranda et al., 2023). It is based on looking for weather conditions similar to those that caused the extreme event of interest with statistical algorithms based on dynamical system metrics. The object studied is a surface-pressure pattern over a certain region and the estimation of trends is based on the number of similar patterns (analog) to each of the considered one in the data set. Then, once we have dates for increasing occurrence trends we explore composite maps of turbulence-related variables. Thus, we use SLP field to diagnose atmospheric circulation changes due to climate change and then hazard variables (TI1, TI2, and EDR) to explore effects on turbulence-related metrics. Finally, beyond the set of variables that can be used to assess turbulence strength (Williams & Joshi, 2013) we focus on these three one since they can provide easy metrics to directly determine turbulence levels as well as the main physical source mechanisms of the observed episode (CAT, weather systems, etc.).

Understanding differences and similarities within European airspace is crucial for mitigating risks and ensuring safe travel and efficient forecasting in different regions, particularly given the increasing turbulence features we reported over continental Europe. In light of our findings on the increasing occurrence of moderate-or-greater turbulence episodes in European airspace, there are significant economic implications for airlines. Indeed, while turbulence episodes rarely lead to crashes, they can damage cabin components such as seats and overhead bins, resulting from items falling or passengers colliding with them. These incidents not only necessitate repairs but also lead to flight delays and potential injuries to passengers and crew. Collectively, the expenses related to turbulence-induced damages, delays, and injuries can amount to up to 500 million euros for airlines each year (Sharman & Lane, 2016). With the increasing trend in turbulence episodes, airlines may face even greater financial burdens in the future, claiming for enhancing turbulence forecasting and mitigation strategies to minimize economic losses and ensure passenger safety, as well as, to improve routing and provide a way to make more sustainable aviation. Clearly, our study offers a starting point of using analog-based methodologies (Jézéquel, Dépoues, et al., 2018; Platzer et al., 2021; Yiou et al., 2017) for studying impacts of changing atmospheric circulation patterns on aviation turbulence, since data we used in this study representing turbulence in a parametric way (Hersbach et al., 2023). Further investigations will be devoted to study high-resolution resources (as meteorological satellites) over specific events and/or routes as well as convection-permitting numerical models to investigate both smaller spatial and projections to future climate scenarios (Coppola, Raffaele, et al., 2021; Coppola, Stocchi, et al., 2021).

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Data Availability Statement

Data is available at Hersbach et al. (2023).

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