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LETTER

Clear-air turbulence-aware flight routing over the North Atlantic using weather regimes

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Abstract

Clear-air turbulence (CAT) is one of the most significant hazards to aviation during the cruise phase. Under climate change, CAT is projected to increase in frequency and severity in certain key areas for aviation, posing growing challenges for flight safety and operational efficiency. This study focuses on the North Atlantic region and investigates how large-scale atmospheric circulation characterised by weather regimes influences the spatial distribution of moderate-or-Greater CAT (MOG-CAT) occurrences. Using ERA5 reanalysis data from 1979 to 2020, we classify daily winter circulation into four weather regimes and compute the MOG-CAT climatology associated with each regime. We then integrate this information into a flight planning model to minimise fuel consumption whilst avoiding areas subject to frequent MOG-CAT. The flights between London Heathrow and New York JFK airports are used as an example. Results show strong regime-dependent variations in MOG-CAT occurrence, reflecting shifts in jet stream position and intensity. For three of the regimes (the negative phase of the North Atlantic Oscillation NAO−, Atlantic ridge and Scandinavian blocking), CAT-aware routing offers turbulence avoidance with minimal fuel and time penalties. In contrast, under NAO+, avoiding MOG-CAT areas can increase round-trip fuel consumption by up to 8%, highlighting a trade-off between safety and efficiency in this high-hazard regime. This regime-based approach has the potential to support CAT hazard assessment and flight route optimisation weeks in advance, thus opening new opportunities for safer and more fuel-efficient flight route planning.

1. Introduction

Aviation is both a driver of climate change and is increasingly impacted by it. The sector currently accounts for approximately 2.4% of anthropogenic CO_2 emissions and 3.5% of total radiative forcing when including non-CO_2 effects such as contrail formation, which are still subject to large uncertainties (Grewe *et al* 2019, Lee *et al* 2021). Aviation has experienced substantial growth in recent decades, and in the absence of significant mitigation measures, its associated greenhouse gas emissions are expected to continue to increase by mid-century (ICAO 2025). In response, international organisations such as the International Civil Aviation Organization have committed to the ambitious climate goal of net-zero CO_2 emissions by 2050 (ICAO 2022). The aviation sector must now explore a range of strategies to achieve this goal. While emerging technologies such as sustainable aviation fuel and hydrogen propulsion hold long-term promise, they remain costly and require further technological development and policy support before they can be deployed at scale—likely not before 2040–2050. In the meantime, operational improvements, particularly optimised flight trajectories, offer immediate and cost-effective reductions in emissions using current aircraft and infrastructure (e.g. Rodionova *et al* 2014, Ahmed *et al* 2021, Wells *et al* 2021, 2023, Boucher *et al* 2023). For example, Wells *et al* (2023) demonstrated that wind-aware routing can reduce fuel use by 4.2% on transatlantic flights, saving up to 16.6 million kg of CO_2 in a single winter season.

Aviation must also adapt to the growing challenges posed by changing climate, both at ground level and at cruising altitudes (Gultepe *et al* 2019, EUROCONTROL 2021, EASA 2025, WMO 2025). Increasing surface temperatures can reduce air density, leading to weight restrictions at take-off in some airports (Coffel *et al* 2017, Gratton *et al* 2020, Gallardo *et al* 2023, Williams *et al* 2025). In the upper troposphere, wind changes can alter flight times and fuel use (Irvine *et al* 2016, Williams 2016), while increased wind shear in jet streams is projected to increase the frequency and severity of clear-air turbulence (CAT) (Williams and Joshi 2013, Storer *et al* 2017, Williams 2017, Kim *et al* 2023, Foudad *et al* 2024). CAT is a type of atmospheric turbulence that cannot be detected visually by pilots or by using onboard radar. It is the leading cause of weather-related in-flight injuries in commercial aviation, and can lead to abrupt altitude changes, speed adjustments, and therefore, increased fuel consumption (Sharman and Lane 2016).

Several studies have reported increasing CAT trends in recent decades in mid-latitude flight corridors (Jaeger and Sprenger 2007, Prosser *et al* 2023, Lee *et al* 2023a, Foudad *et al* 2024). Using 11 CMIP6 models and a large initial-condition ensemble of the CNRM-CM6.1 model, Foudad *et al* (2024) demonstrated that in several regions of the Northern Hemisphere—for example, East Asia—the observed positive CAT trends are attributable to anthropogenic forcing. However, in certain regions, such as the North Atlantic, internal climate variability plays a dominant role in shaping CAT trends. These findings highlight the importance of characterising patterns of internal variability, particularly those related to large-scale atmospheric circulation, in order to better understand turbulence hazard and inform flight routing strategies.

The North Atlantic is one of the world's busiest airspaces, with 2000 to 3000 flights crossing the ocean each day (NATS 2014), and is characterised by strong jet stream and storm track activity (Rivière and Orlanski 2007, Woollings *et al* 2010, Shepherd 2014). A well-established paradigm for characterising its large-scale atmospheric variability is the concept of 'weather regimes', defined as quasi-stationary, recurrent circulation patterns that dominate the modes of variability. For winter, four regimes have been identified in the North Atlantic sector: the positive and negative phases of the North Atlantic Oscillation (NAO; Hurrell *et al* 2003), the Atlantic Ridge, and the Scandinavian Blocking (e.g. Vautard 1990, Michelangeli *et al* 1995, Cassou *et al* 2004, Sanchez-Gomez and Terray 2005, Hannachi *et al* 2017).

Weather regimes have been widely used in studies of extreme weather events (e.g. Yiou and Nogaj 2004, Cassou *et al* 2005, Sanchez-Gomez and Terray 2005, Sanchez-Gomez *et al* 2008b, Cattiaux *et al* 2010, Lavaysse *et al* 2018), and sub-seasonal to seasonal (S2S) forecasting (e.g. Ferranti *et al* 2015), as well as in energy meteorology (e.g. Brayshaw *et al* 2011, Grams *et al* 2017, van der Wiel *et al* 2019, Bloomfield *et al* 2020). However, their application in aviation meteorology remains very limited. These regimes are closely linked to the variability of the eddy-driven jet stream (Woollings *et al* 2010, Hannachi *et al* 2012, Madonna *et al* 2017), and have been used to investigate climate-optimal routes (Irvine *et al* 2013, Yamashita *et al* 2021). NAO has also been used to investigate time-minimal routes and their turbulence potential (Kim *et al* 2016, 2020), and changes in atmospheric circulation patterns have been shown to increase turbulence over Europe (Alberti *et al* 2024).

Weather regimes are not intended to replace operational daily wind forecasts, but rather provide a climatological and conceptual framework to understand how large-scale atmospheric circulation patterns influence the occurrence of CAT and the associated trade-off in fuel efficiency. In addition, recent advances in S2S forecasting of North Atlantic weather regimes provide probabilistic information weeks in advance, which can complement daily forecasts by offering guidance on the likelihood of regime-related circulation patterns (e.g. Scaife *et al* 2014, Ferranti *et al* 2015, Dunstone *et al* 2016, 2023). Beyond their relevance for operational forecasting, large-scale circulation regimes also play a crucial role in the context of climate change, as projected shifts in their frequency, persistence, and intensity could alter the jet-stream climatology, with potential implications for CAT occurrence, fuel efficiency, and transatlantic flight planning. This motivates the use of weather regimes in the present study as a bridge between climatological studies and potential operational applications.

In this study, we include weather regimes occurrence and CAT-related turbulence hazards in a fuel-optimised flight algorithm. Specifically, we investigate whether the climatologies of moderate-or-greater (MOG)-level CAT (hereafter MOG-CAT), defined for each regime, can support safer and more fuel-efficient transatlantic routes. We use a dynamic programming framework developed by Wells *et al* (2023), which minimises fuel consumption on transatlantic flight routes by considering atmospheric conditions and aircraft-specific parameters. We extend this framework by including regime-dependent MOG-CAT climatologies in the optimisation algorithm, in order to evaluate the potential fuel penalties associated with regime-aware turbulence avoidance strategies.

This study focuses on transatlantic winter flights between London Heathrow (LHR) and New York John F. Kennedy International (JFK) airports using an Airbus A350 aircraft. Section 2 describes the data and method that are used to generate the results presented in section 3. A discussion of potential operational implications of the MOG-CAT-weather regime framework and its limitations is given in section 4, which is followed by conclusions and perspectives in section 5.

2. Data and methods

2.1. ERA5 reanalysis

We used the ERA5 reanalysis (Hersbach *et al* 2020) from the European Centre for medium-range weather forecasts (ECMWFs) to characterise the variability of large-scale atmospheric circulation and CAT over the North Atlantic region. The dataset covers 42 winter seasons (December–January–February (DJF)) from 1979 to 2020, and provides daily mean fields interpolated on a $1^\circ \times 1^\circ$ grid. We use sea-level pressure (SLP) fields to classify weather regimes, and horizontal wind components, geopotential height, and temperature at 200 and 250 hPa to characterise the jet stream variability, and for the computation of turbulence diagnostics.

2.2. Classification of weather regimes

North Atlantic weather regimes are defined as recurrent and quasi-stationary patterns of large-scale atmospheric circulation that strongly influence daily weather in the North Atlantic–European sector (Vautard 1990). To identify weather regimes, we apply the *k*-means clustering algorithm (Michelangeli *et al* 1995), following the classification method of Cassou (2008). The classification is based on the daily SLP anomalies from ERA5 reanalysis in the North Atlantic domain (90° W–30° E, 20°–80° N) (Sanchez-Gomez *et al* 2008a), focusing on the DJF winter, and classically identifies four regimes: the positive and negative phases of the (NAO+ and NAO−, respectively), the Atlantic Ridge (AR), and the Scandinavian Blocking (BL). While focusing here on the *k*-means classification, many studies have shown that the four-regime framework (NAO+, NAO−, AR, BL) is robust and reproducible across different clustering methods (e.g. Cassou *et al* 2004, Hannachi *et al* 2017, Madonna *et al* 2017). In this study each winter day is assigned to one of the four North Atlantic weather regimes (NAO+, NAO−, AR, BL).

Each of the four North Atlantic weather regimes has a distinct large-scale pressure pattern and jet stream response in winter. Figures 1 and 2 show the composites of SLP anomalies and 250 hPa wind speed anomalies, respectively, associated with each regime, based on daily ERA5 data from 1979 to 2020. NAO+ and BL are the most frequent regimes, occurring on 29% and 27% of winter days, respectively. NAO− and AR have a smaller contribution; they account for 21% and 23% of winter days, respectively. This is in good agreement with previous studies using different reanalysis data (e.g. Cattiaux *et al* 2010, Michel and Rivière 2011, Madonna *et al* 2017).

2.3. Turbulence Index and MOG-CAT

CAT is diagnosed using the Turbulence Index 1 (TI1; Ellrod and Knapp 1992), which has been shown to be one of the best-performing diagnostics for the prediction of upper-level turbulence (Sharman and Pearson 2017). Following the methodology of Foudad *et al* (2024), TI1 is calculated in the atmospheric layer between 200 and 250 hPa, corresponding to typical cruise altitudes for commercial aircraft. Vertical wind shear (VWS) is defined as the difference in wind fields between the pressure levels 200 and 250 hPa, divided by the vertical distance between these two levels, computed from the geopotential height field at each grid point.

The TI1 diagnostic is widely used operationally and has been implemented in several turbulence forecasting algorithms (Sharman *et al* 2006, Sharman and Pearson 2017). To focus on turbulence relevant for aviation safety, MOG CAT occurrences are defined as daily TI1 values that exceed the 99th percentile computed from the winter probability density function during the 1981–2010 reference period (Foudad *et al* 2024). MOG-CAT frequency is then calculated at each grid point as the percentage of days that exceed this threshold. It is worth noting that the spatial distribution of MOG-CAT frequency and its climatological patterns are weakly sensitive to the choice of the threshold (Lee *et al* 2020, Foudad *et al* 2024) and that the 99th percentile is a classical threshold choice in the literature (Williams and Joshi 2013, Foudad *et al* 2024).

2.4. Flight trajectory optimisation

To find fuel-minimal routes across the North Atlantic between LHR and New York JFK airports, we use a dynamic programming approach that solves the Hamilton–Jacobi–Bellman (HJB) equation for a fuel-minimal flight, following the formulation of Wells *et al* (2023). The optimisation is applied in a horizontal domain covering the North Atlantic, and discretised both in space and time. It minimises total fuel consumption by adjusting the aircraft's heading and airspeed at each time step, allowing the trajectory to

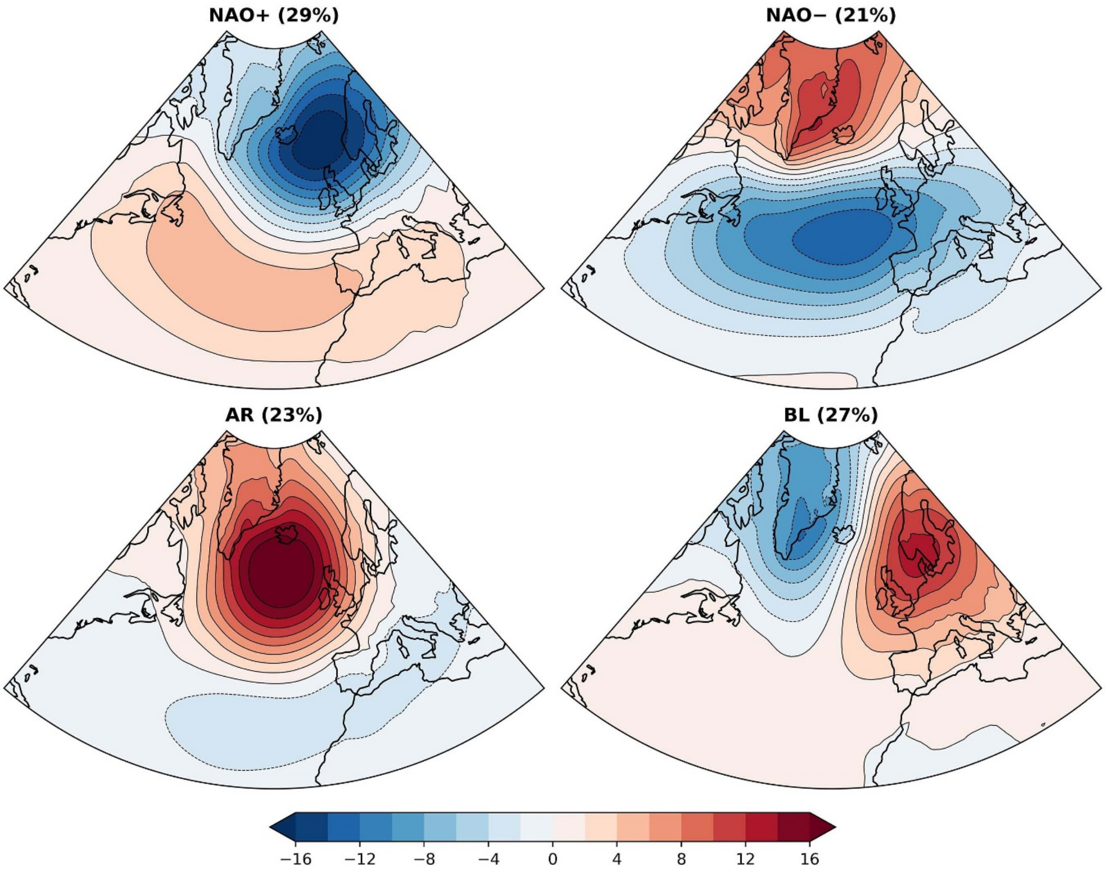

Figure 1. The four winter regimes of the atmospheric circulation over the North Atlantic sector during 1979–2020, derived from ERA5 reanalysis. The colours indicate SLP anomalies (hPa). Contour interval is 2 hPa. The mean frequency of occurrence for each weather regime during the DJF winter is shown in brackets.

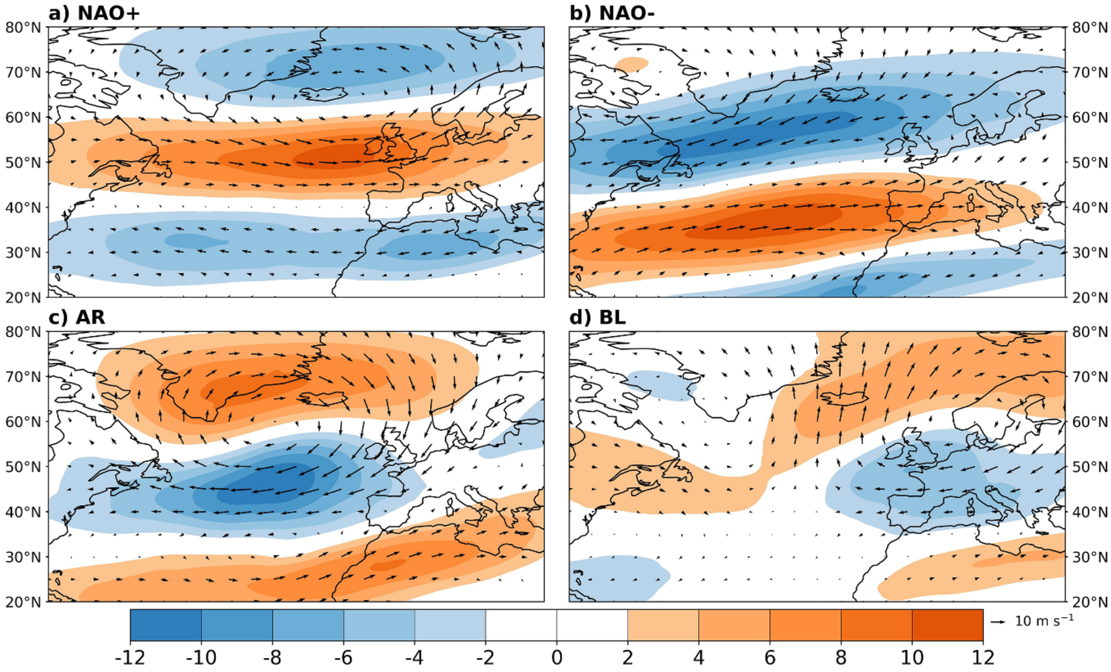

Figure 2. Anomalies of horizontal wind speed (shading; m s^{-1}) and wind vectors at 250 hPa in the North Atlantic sector during the winter season for (a) NAO+, (b) NAO−, (c) AR, and (d) BL, based on daily mean wind data from ERA5 reanalysis for the period 1979–2020.

follow the most fuel-efficient path through wind and temperature fields derived from ERA5 reanalysis data.

The continuous form of the HJB equation can be expressed as

$$\nu(x) - \inf_{\alpha \in A} \{g(x,\alpha) + f(x,\alpha) \cdot \Delta\nu(x) - [g(x,\alpha) - 1]\,\nu(x)\} = 0 \quad x \in \mathbb{R}^n \backslash C, \quad (1)$$

$$\nu(x) = 0 \quad x \in C, \quad (2)$$

where $\nu(x)$ is the value function, describing the 'usefulness' of each aircraft grid position, given the optimal choice of control variables. Here, $f(x,\alpha)$ is the dynamical system, describing the rate of change of latitude, longitude, and aircraft mass; $g(x,\alpha)$ is the fuel-burn rate; α is the vector of control variables; A is the set of all plausible combinations of control variables; and C denotes the target region.

The numerical solution is obtained using a semi-Lagrangian scheme, in which $\nu(x)$ is iteratively updated at each grid position i and iteration m according to

$$[\hat{\nu}]_i^{m+1} = \min_{\alpha \in A} \{I[\hat{\nu}]_i^m (x_i + \Delta t f(x_i,\alpha)) + \Delta t g(x_i,\alpha)\,(1 - \hat{\nu}_i^m(x_i))\}, \quad (3)$$

where $I[\hat{\nu}]$ represents the linear interpolant used to evaluate the value function at the new off-grid position. The algorithm iterates until convergence, yielding the minimal-fuel trajectory between departure and arrival airports. The full derivation and implementation of the optimisation framework are provided in Wells (2023), and a schematic of the iterative procedure is provided in the supplementary material (figure S5).

The analysis focuses on the cruise phase, here defined as starting from 225 km distance from LHR and JFK airports. Simulations are performed at a fixed pressure level of 250 hPa, approximately corresponding to typical cruising altitudes (34 000–36 000 feet) and to the core of the jet stream. Aircraft fuel consumption is modelled with a physics-based function that accounts for aircraft mass reductions as fuel is burned. The fuel-burn rate is calculated considering atmospheric conditions and the position, airspeed, and mass of the aircraft as well as aircraft-specific parameters (Poll and Schumann 2021a, 2021b). The aircraft used in the simulations is an Airbus A350–1000.

To include turbulence avoidance as a criterion of analysis, trajectory optimisation is based on regime-dependent atmospheric composites. For each of the four weather regimes (NAO+, NAO−, AR, and BL), the algorithm uses mean wind and temperature fields, together with a turbulence mask derived from the proportion of MOG-level CAT days associated with each regime. At each grid point, this proportion indicates the number of MOG-level CAT days that occur under a given regime. The turbulence constraint is then implemented by excluding grid cells where this proportion exceeds 40%, thereby retaining only regions where MOG-CAT occurrence is strongly dominated by a single regime and preventing the aircraft from crossing these areas. This threshold was chosen to find a balance: lower values would include areas where signals are weaker or mixed, while higher values would exclude wide regions where turbulence occurs frequently.

Flight simulations are performed separately for each weather regime, and for both westbound and eastbound directions. Two scenarios are considered: one where the optimisation aims to minimise fuel consumption only as in Wells *et al* (2023), and another where regions of high MOG-CAT probability are also avoided. Thus, the comparison between these two configurations is valuable to assess the trade-off between turbulence avoidance and fuel efficiency across weather regimes.

3. Results

3.1. Weather regimes and jet stream

NAO+ regime is associated with a strong meridional pressure gradient between a low pressure system over Greenland/Iceland and high pressure anomalies in the central Atlantic (figure 1(a)). The jet stream is strengthened across the North Atlantic and northern Europe (figure 2(a)). Wind anomalies exceeding $+8\,\mathrm{m\,s^{-1}}$ can be seen in the northeast of the Atlantic (figure 2(a)).

In contrast, NAO− regime (also known as Greenland blocking) is characterised by a high pressure system over Greenland/Iceland and low pressure anomalies in the central Atlantic, weakening and reversing the usual north–south SLP gradient (figure 1(b)). The zonal flow over the North Atlantic is reduced, and the jet stream shifts southward to about 30°–40° N, leading to negative wind speed anomalies in the northern part of the North Atlantic, and higher than normal speeds across the southern part (figure 2(b)).

AR regime is characterised by positive pressure anomalies in the North Atlantic (figure 1(c)). As a result, upper-level winds weaken over the North Atlantic, and high-wind speed anomalies are located at high latitudes, over Greenland (figure 2(c)).

BL regime is characterised by an anomalous high pressure system over Scandinavia (figure 1(d)). Wind speeds are lower than normal across the northeast Atlantic and Europe (figure 2(d)). Positive wind speed anomalies are found in two regions: the northwest Atlantic between 40°–50° N, and high latitudes—over the Norwegian and Barents Seas (figure 2(d)).

Figure 2 provides evidence of the link between the upper-level jet stream and North Atlantic weather regimes diagnosed with SLP. Our results are consistent with the findings of Madonna *et al* (2017), who used different atmospheric variables (geopotential height at 500 hPa for regime classification, lower tropospheric wind at 700–925 hPa for jet diagnostics), and ERA-Interim reanalysis (Dee *et al* 2011). NAO+ days are associated with a centrally located jet stream, with the climatological jet core around 50° N. NAO− corresponds to a southward shifted jet near 30°–40° N, while the AR regime is linked to a northern jet (55°–75° N). For the BL regime, two distinct jet branches are observed: one between 40°–50° N and another at high latitudes (60°–75° N), indicating a mixed or split jet configuration.

3.2. Spatial distribution of MOG-CAT under different regimes

To link the spatial distribution of CAT with the weather regimes, we calculate, at each grid point, the proportion of MOG-CAT days associated with each weather regime. The resulting maps (figure 3) reveal pronounced regime-dependent patterns, closely aligned with the structure and position of the upper-level jet (figure 2).

The NAO+ regime is the most conducive to MOG-CAT development in the North Atlantic sector (figure 3(a)). For example, more than 50% of all MOG-CAT occurrences in the northeast Atlantic and the United Kingdom are associated with NAO+ days. These regions coincide with areas where MOG-CAT is frequent. This reflects the intensification of the jet stream during the NAO+ regime over these regions (figure 2(a)), which strengthens VWS and deformation, both important ingredients for CAT generation (see supplementary figures S1 and S2). High MOG-CAT frequencies are also observed over Europe, the Alps, and North Africa, suggesting a dual enhancement of both polar and subtropical jet streams.

In contrast, the NAO− regime creates less favorable conditions for MOG-CAT development (figure 3(b)). High MOG-CAT occurrence is observed in a small domain west of France and the Iberian Peninsula, in regions influenced by the equatorward shifts of the jet stream. Regions of frequent MOG-CAT during NAO+, for example, west of the United Kingdom, experience a reduction in occurrence, reflecting the weakened, south-shifted jet (figure 2(b)).

The AR regime is associated with a high probability of MOG-CAT over Greenland, Northeast Canada, and the Labrador Sea, where more than 70% of events in these regions occur under the AR regime (figure 3(c)). These areas lie outside the MOG-CAT climatology, except in southern Greenland and the Labrador Sea. The AR regime is associated with a northward shift of the jet (figure 2(c)), which creates favorable environmental conditions for large VWS and deformation (supplementary figures S1(c) and S2(c)), thus CAT may occur even in the absence of a strong jet.

The BL regime is associated with increased MOG-CAT frequencies over the Norwegian and Barents Seas, although it is not a region of high MOG-CAT occurrence (figure 3(d)). This pattern is consistent with the presence of a persistent anticyclone over Scandinavia (figure 1(d)), and stronger than normal upper-level winds in this region (figure 2(d)), which maintain environmental conditions conducive to CAT development.

These regime-dependent patterns of MOG-CAT reflect changes in the position and intensity of the upper-level jet stream (figure 2). In summary, the results show that the probability of encountering MOG-CAT varies significantly with the weather regime, suggesting that regime-based flight planning could support turbulence avoidance.

3.3. Optimised flight trajectories

3.3.1. Westbound routes (LHR to JFK)

In the AR and BL regimes, the two optimised routes with and without MOG-CAT constraints are very similar (figures 4(c) and (d)). For BL, the trajectories are exactly aligned, indicating that turbulence does not influence the optimal route during this regime. Despite the minimal impact of MOG-CAT, both AR and BL routes deviate from the GC path: the AR route shifts slightly southward, while the BL route detours northward to avoid headwinds associated with the jet stream, in order to save fuel and reduce emissions.

During NAO− days, the algorithm simulates a northward trajectory in both scenarios to reduce fuel burn (figure 4(b)), following a route that closely resembles the route of BL regime. The CAT-constrained route is slightly shifted north compared to the fuel-only route, avoiding regions with higher probabilities of encountering MOG-CAT.

In contrast, NAO+ days lead to the most pronounced divergence between the two scenarios (figure 4(a)). The fuel-only route takes a high-latitude trajectory to minimise headwinds. However, this region coincides with frequent MOG-CAT, especially on the northern flank of the jet. Consequently, the CAT-constrained route is shifted south of the GC path to avoid turbulence regions.

3.3.2. Eastbound routes (JFK to LHR)

For eastbound flights, fuel-efficient trajectories generally follow a route slightly shifted south of the GC path (figure 4), to benefit from strong tailwinds provided by the jet stream. The southward shift is most pronounced during NAO− days, reflecting the equatorward displacement of the jet.

For both AR and BL regimes, the simulated trajectories—with and without MOG-CAT constraints—are nearly identical and remain close to the GC path (figures 4(c) and (d)). This is due

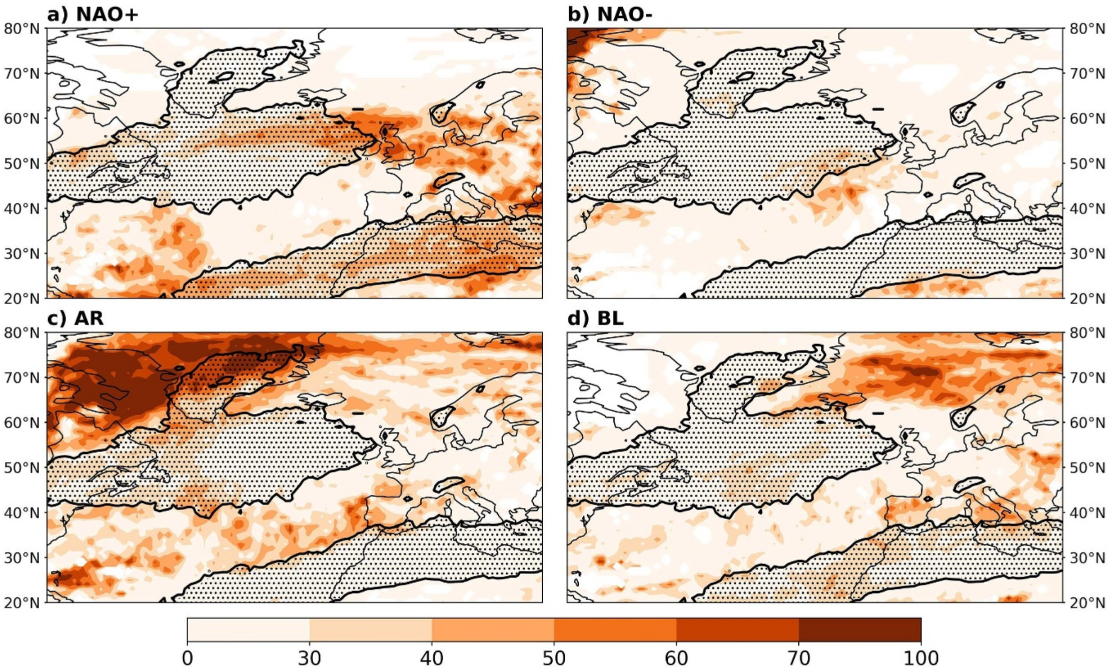

Figure 3. Percentage of MOG-CAT occurrences associated with each weather regime (shading; %) over the North Atlantic for (a) NAO+, (b) NAO−, (c) AR, and (d) BL. Regions where MOG-CAT occurs more frequently (frequency ⩾ 1%) are highlighted by black contours with overlaid black dots. The figure is based on ERA5 reanalysis and Turbulence Index 1 (TI1) at the 250 hPa level for the winter season from 1979 to 2020.

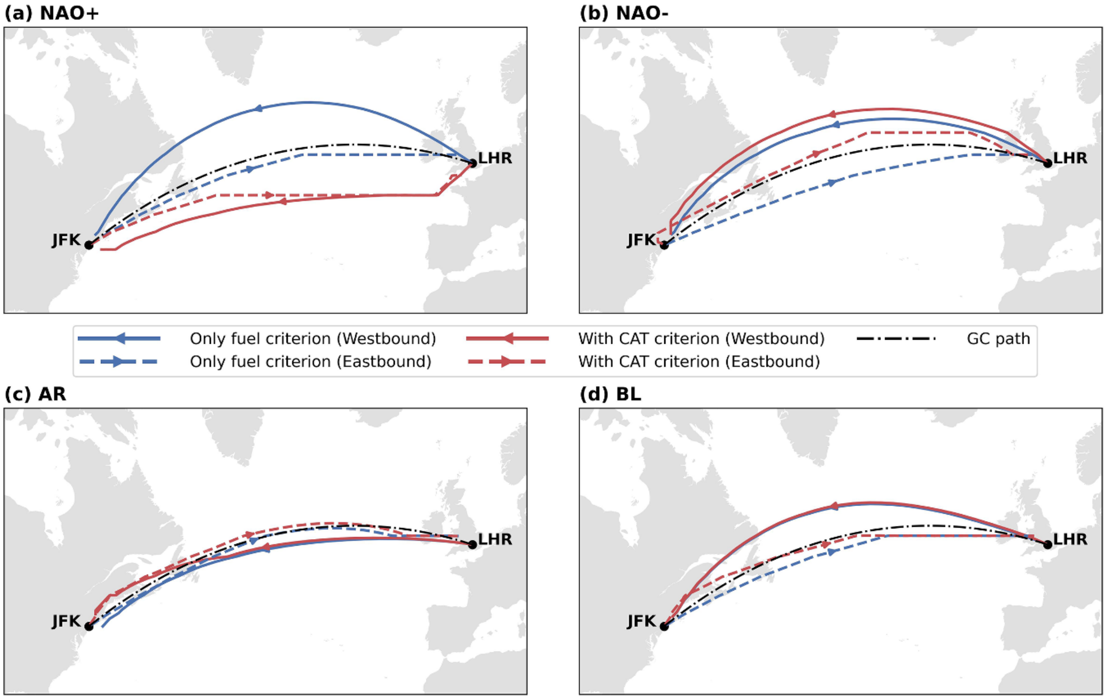

Figure 4. Optimised flight routes between JFK and LHR airports under different weather regimes: (a) NAO+, (b) NAO−, (c) AR, and (d) BL. Solid and dashed lines represent westbound and eastbound flights, respectively, with arrows indicating the direction of travel. Blue lines indicate fuel-optimised routes without considering CAT, while red lines represent optimised routes when considering CAT information. The black dash-dotted line represents the great-circle (GC) path. These trajectories are derived from the climatology of atmospheric conditions at the 250 hPa level over the North Atlantic for each regime, based on ERA5 reanalysis data for the winter season from 1979 to 2020.

to relatively weak upper-level winds and low MOG-CAT probabilities under these regimes, resulting in a minimal deviation from the GC path.

In contrast, during NAO− days, the CAT-constrained route shifts northward compared to the GC path and the fuel-only route (figure 4(b)). This detour is to avoid MOG-CAT areas located in the northern flank of the jet. In the NAO+ regime, the fuel-only route remains very close to the GC path to benefit from tailwinds (figure 4(a)). However, due to the high probability of MOG-CAT north of 40° N (figure 3(a)), the CAT-constrained route is shifted further south.

3.4. Impact on fuel consumption and flight duration

Figure 5 shows the fuel consumption and flight time for the optimised routes with and without MOG-CAT constraints under each weather regime. As expected, eastbound flights are faster and use less fuel due to strong tailwinds, while westbound flights encounter headwinds and require more fuel. For fuel-optimal trajectories only, the time difference between eastbound and westbound flights increases approximately to 81 minutes under the BL regime and 104 minutes under the NAO+ regime. Westbound fuel consumption is on average 30%–40% higher than eastbound.

NAO+ regime leads to the highest westbound fuel consumption due to strong headwinds, while the NAO− regime provides the most fuel-efficient routes. For eastbound flights, fuel consumption is lowest under NAO+ and highest under the AR regime (figure 5).

MOG-CAT avoidance has very small penalties under the AR and BL regimes, where the constrained and unconstrained routes are nearly identical. In contrast, NAO+ shows the largest penalty: including MOG-CAT constraints increases both fuel consumption and flight time, especially westbound. In NAO− eastbound flights, fuel consumption also increases significantly when avoiding high probability MOG-CAT regions (figure 5).

These results suggest that considering turbulence avoidance in flight route optimisation leads to minimal fuel and time penalties, except under specific regimes such as NAO+, which are the most conducive to MOG-CAT (section 3.2) and where avoiding areas of high turbulence can increase fuel use and flight duration. However, from a flight safety perspective, prioritising turbulence avoidance may outweigh the associated environmental and operational costs. This highlights the complex balance between minimising emissions and ensuring passenger safety. Weather-regime-informed route optimisation thus offers a robust framework to navigate this trade-off and support more adaptive decision-making in future flight planning.

4. Discussion

North Atlantic weather regimes have significant influence on the spatial distribution of MOG-CAT, and on fuel efficiency of transatlantic flights. By including weather regimes in the flight trajectory optimisation algorithm, we quantify how they affect both turbulence and operational trade-offs related to fuel consumption and flight time.

The NAO+ regime is the most conducive to MOG-CAT development, leading to more occurrences in the northeast Atlantic (figure 3). This is driven by the poleward intensification of the jet stream (figure 2), increasing upper-level wind shear. In contrast, NAO− shifts the regions of high MOG-CAT probability equatorward, while the AR and BL regimes displace MOG-CAT occurrence to higher latitudes, especially over Greenland and the Norwegian Sea (figure 3). These regime-dependent patterns align well with the jet stream configurations identified in this study and are consistent with previous work (Woollings *et al* 2010, Hannachi *et al* 2012, Madonna *et al* 2017): NAO+ is linked to a central jet, NAO− a southern jet, AR a northern jet, and BL a mixed jet (figure 2).

From a trajectory planning perspective, our findings show that including regime-based turbulence avoidance in flight trajectory optimisation can reduce the occurrence of MOG-CAT with limited operational cost—particularly under the AR and BL regimes—which together account for half of winter days. For these regimes, fuel and time penalties associated with MOG-CAT avoidance are minimal, with round-trip fuel increases of only 0.6% for AR and 1.4% for BL (table 1).

In contrast, NAO+ represents a more challenging scenario. Reducing turbulence hazard under this regime requires substantial rerouting, leading to fuel and time increases of around 8% for a round-trip. NAO− regime shows more moderate impacts, with round-trip fuel penalties of approximately 4%. Flight durations follow similar patterns across regimes. Similar results and conclusions are obtained when the analysis is repeated using a different aircraft type, the Boeing 777.

However, it is worth noting that the percentage increases in fuel consumption and flight time reported in table 1 are calculated relative to fuel efficient routes, rather than actual operational routes. Wells *et al* (2023) showed that these simulated fuel-minimal routes can already reduce fuel use by an average of 4.2% relative to observed flights. In addition, while daily CAT occurrences are more localised than the regime-based probability fields used here, the strategic avoidance of these broader high-probability envelopes likely results in more conservative (i.e. larger) detours than those required for tactical avoidance on individual days. Furthermore, the percentage changes do not account for the dynamic

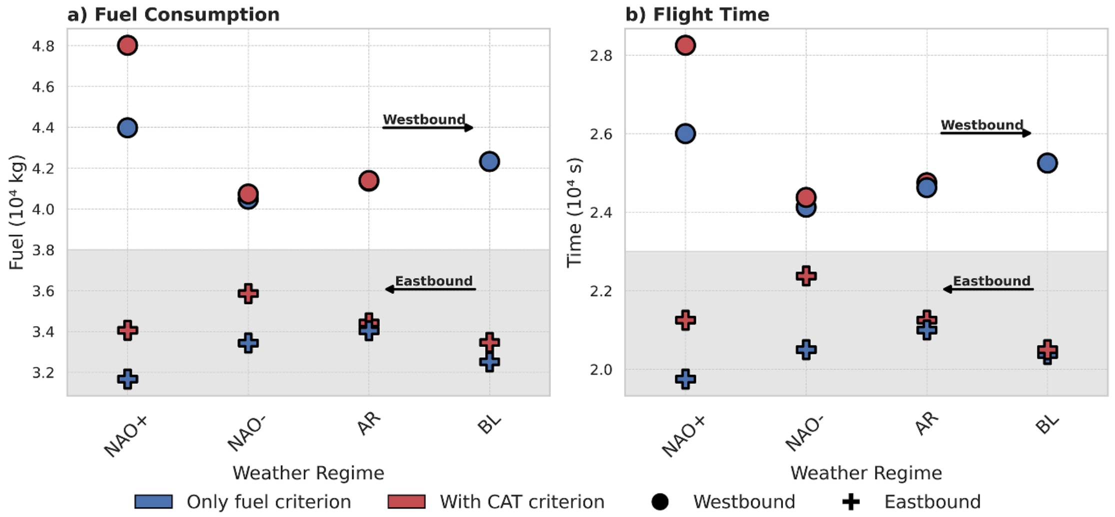

Figure 5. Impact of weather regimes on (a) fuel consumption and (b) flight time for transatlantic flights between JFK and LHR. Results are shown for westbound (circles) and eastbound (crosses) flights under different weather regimes: NAO+, NAO−, AR, and BL. Blue colour indicates optimised routes without considering CAT, while red colour indicates optimised routes when considering CAT information. For visualisation purpose, when values are very close, only the color corresponding to the higher value is visible, as it overlays the other marker. Shaded grey areas visually separate the lower values associated with eastbound flights from the higher westbound values. The analysis is based on flight trajectories derived from ERA5 reanalysis data for the winter season from 1979 to 2020.

Table 1. Percentage changes in fuel consumption and flight time due to MOG-CAT under different weather regimes for transatlantic flights between JFK and LHR. Results are shown separately for westbound, eastbound, and round-trip flights. The analysis is based on flight trajectories derived from ERA5 reanalysis data for the winter season from 1979 to 2020.

	Westbound		Eastbound		Round-trip	
Weather regime	Fuel	Time	Fuel	Time	Fuel	Time
NAO+	9.19	8.65	7.54	7.59	8.37	8.12
NAO−	0.64	1.04	7.25	9.15	3.95	5.10
AR	0.07	0.51	1.13	1.19	0.60	0.85
BL	0.00	0.00	2.92	0.61	1.46	0.31

impacts of turbulence—such as the loss of altitude or airspeed—which can lead to additional fuel burn and delays (Sharman and Lane 2016). These effects were not included in the optimisation framework due to their complexity and the lack of relevant data. This suggests that the penalties associated with avoiding MOG-CAT, as reported in table 1, are likely overestimated. Therefore, we hypothesise that including regime-dependent turbulence avoidance in flight trajectory planning may reduce both turbulence hazard and fuel consumption, and thus lower aviation-related CO_2 emissions.

A limitation of the present approach is the assumption of a fixed cruise altitude of 250 hPa (approximately 34 000 feet; FL340), which corresponds to the average flight level used for North Atlantic crossings and the flight level at which the organised track system is currently calculated (Mangini *et al* 2018). This simplification is generally acceptable, as aircraft on these routes typically maintain a constant altitude (Irvine *et al* 2013, Williams 2016, Mangini *et al* 2018, Kim *et al* 2020, Wells *et al* 2021, 2023). However, enabling altitude changes in future simulations could lead to more efficient and turbulence-aware routing.

Another limitation of this study lies in the use of regime-averaged composites constructed over the 1979–2020 period. While this approach provides robust statistical representations of the atmospheric circulation associated with each regime, it does not capture the day-to-day variability. It is important to note, however, that the MOG–CAT probabilities shown in figure 3 are derived from daily ERA5 data, where each grid point represents the frequency of days exceeding the turbulence threshold within a given regime. Hence, the turbulence fields reflect daily variability, even though the large-scale circulation patterns are represented by composites. This day-to-day variability reflects the intra-regime uncertainty in both jet-stream structure and MOG–CAT occurrence, which can be substantial within a given regime. Quantifying this variability would provide valuable insight into how jet-stream structure and turbulence occurrence vary within each regime. However, such an analysis lies beyond the scope of the present study and would require a dedicated investigation using daily data to assess the implications of intra-regime variability for operational flight routing. The use of regime composites is well established in many fields, such as energy meteorology, where they are applied to link atmospheric circulation patterns to energy production and demand (e.g. Thornton *et al* 2017, van der Wiel *et al* 2019, Bloomfield *et al* 2020). In our study, composites provide a practical compromise that enables a proof-of-concept study, given the high computational cost of running the dynamical programming optimisation algorithm on daily fields for 42 winters. Future work using daily ERA5 fields—focusing on specific winters—could allow for a more detailed evaluation of the methodology and its sensitivity to synoptic-scale variability.

The choice of resolution appropriate for this type of analysis may be debatable. Sensitivity tests (see supplementary figures S3 and S4) have demonstrated that the spatial patterns of the TI1 index, calculated from ERA5 data on the native $0.25^\circ \times 0.25^\circ$ grid and on the interpolated $1^\circ \times 1^\circ$ grid are very similar, suggesting that the main conclusions of this study are not sensitive to horizontal resolution, consistent with previous findings (e.g. Williams and Storer 2022, Foudad *et al* 2024). Further details on the influence of horizontal resolution on MOG-CAT diagnostics are discussed in detail in Foudad (2024). In addition, our analysis is based on a single turbulence diagnostic (TI1), which mainly represents shear and deformation-induced turbulence in the upper troposphere and lower stratosphere. TI1 has been shown to be among the most skillful individual diagnostics for upper-level turbulence (Gill 2014, Sharman and Pearson 2017) and is widely used operationally. However, a single diagnostic cannot capture all mechanisms that generate CAT—for example, turbulence arising from inertial instability—and future studies should extend this framework by using a multi-diagnostic approach.

Despite its limitations, the present study demonstrates the relationship between large-scale atmospheric circulation (weather regimes), MOG-CAT, and fuel efficiency. This study does not aim to provide an operational tool, but rather introduces a proof-of-concept study showing how regime-dependent information on turbulence occurrence can be included in flight trajectory optimisation. This framework may support medium-range planning, complementing operational daily forecasts. Recent advances in S2S forecasting of North Atlantic weather regimes (e.g. Scaife *et al* 2014, Ferranti *et al* 2015, Dunstone *et al* 2016, 2023) may support the use of regime-based trajectory optimisation weeks to months in advance. For example, the ECMWF currently provides probabilistic forecasts of weather regime occurrence up to six weeks ahead, based on a 101-member ensemble (ECMWF 2025). The use of probabilistic regime forecasts in flight planning could complement daily forecasts by identifying periods when circulation patterns—and their associated turbulence occurrence—are more likely, thus supporting aviation sustainability goals and improve operational safety.

The operational use of these results depends on the persistence of weather regimes and the accuracy of their prediction. North Atlantic regimes have a mean persistence of about one week (e.g. Madonna *et al* 2017), though this duration varies considerably, with some blocking events persisting for several weeks (e.g. Hannachi *et al* 2017). Differences in persistence reflect inherent predictability limits that directly influence the usable forecast lead time. Regimes also tend to follow preferred transition pathways, such as the transition from NAO+ to BL, and then to NAO− (e.g. Ferranti *et al* 2018). These transitions are linked to physical precursors such as the Madden–Julian Oscillation (Cassou 2008), Rossby wave breaking (Michel and Rivière 2011), or stratospheric conditions (Charlton-Perez *et al* 2018). Although models may exhibit biases in the timing of certain transitions, S2S systems show useful skill beyond 10 days in predicting the NAO and blocking (e.g. Ferranti *et al* 2018). For example, the representation of the ECMWF model for transitions into NAO+ is accurate, and preferred paths such as the transition from blocking to NAO− are well-reproduced at extended ranges (Ferranti *et al* 2018). Persistent regimes therefore provide extended ‘windows of opportunity’ for strategic, regime-based flight optimisation in the subseasonal range.

Finally, this MOG-CAT–weather regime framework could be applied to other regions and major flight corridors using regime classifications over the Pacific (Michelangeli *et al* 1995, Fabiano *et al* 2021), North America (e.g. Lee *et al* 2023b), and East Asia (Yang *et al* 2022)—where the largest increase in CAT is projected (Foudad *et al* 2024), to investigate its broader relevance for turbulence-aware and fuel-efficient flight planning.

5. Conclusions

This study demonstrates that the spatial distribution of MOG-CAT and weather regimes over the North Atlantic are strongly linked. By using ERA5 reanalysis and a classification derived from SLP, we show that the NAO+ regime is the most conducive to MOG-CAT development, leading to increased occurrence in the northeast Atlantic due to a poleward shifted jet. In contrast, the NAO− regime shifts the regions of high MOG-CAT probability equatorward. The AR and BL regimes displace MOG-CAT occurrence to higher latitudes, especially over Greenland and the Norwegian Sea.

These regime-dependent patterns are included in a dynamic programming framework, which minimises the fuel consumption in transatlantic flight routes. Results show that MOG-CAT occurrence could be reduced without significant fuel penalties, especially under AR and BL regimes, which together account for about half of winter days. In contrast, the NAO+ regime leads to substantial rerouting to avoid regions where turbulence is frequent, with fuel and time increases up to 8% for a round-trip route. As discussed in section 4, these values are likely overestimated, as they are calculated relative to fuel-efficient routes and do not account for in-flight responses due to turbulence, such as speed loss or altitude changes. Future work should take these aspects into account.

This work introduces a weather-regime-aware framework that supports turbulence avoidance while maintaining fuel efficiency. It may be of use in addition to short-term turbulence forecasting and contribute to broader efforts toward more sustainable aviation. Future work should extend the methodology to account for the day-to-day atmospheric variability and altitude changes, and apply it to other flight routes, such as transpacific, transpolar, as well as domestic flights over Europe, North America, and East Asia. These extensions may support the broader adoption of turbulence-aware and fuel-efficient flight planning on a global scale.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=overview.

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