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Reduced Winter-Time Clear Air Turbulence in the Trans-Atlantic Region Under Stratospheric Aerosol Injection

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Key Points:

- Winter-time severe North Atlantic Clear Air Turbulence under high-end global warming increases by 225% from now to the end of the century
- We simulate Stratospheric Aerosol Injection where temperature is reduced from high-end global warming to a moderate global warming
- SAI counteracts CAT enhancements due to global warming, resulting in CAT levels being closer to that from a moderate global warming scenario

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Abstract Clear air turbulence (CAT) is a safety threat within the aviation sector and is projected to worsen under global warming. Stratospheric aerosol injection (SAI) is a climate intervention strategy that aims to ameliorate climate change by artificially cooling Earth. Climate model simulations have found a side-effect of SAI would be a strengthening of the positive phase of the North Atlantic Oscillation (NAO). This links to a stronger North Atlantic jet stream and suggests enhanced CAT in the region. Here, we analyze simulations from the UKESM1 climate model to evaluate the impact of a realistic SAI application on winter-time trans-Atlantic CAT. We find a 23% decrease in severe CAT frequency under SAI when compared to a baseline high-end global warming scenario. Our results indicate that the amelioration of global warming under SAI has a more dominant impact on CAT over the North Atlantic than residual impacts to the NAO.

Plain Language Summary Stratospheric aerosol injection has been proposed to reduce climate change by cooling the planet in a similar way to volcanic eruptions. Previous research has shown that SAI may strengthen the North Atlantic jet stream, potentially enhancing Clear Air Turbulence (CAT) in this region, with impacts to the aviation sector. We use a climate model to simulate climate under global warming and SAI to evaluate impacts on CAT in the North Atlantic region in the northern hemisphere winter. We find a significant reduction in CAT events under SAI relative to high-end global warming, suggesting that the North Atlantic jet stream changes under SAI have a small impact on CAT compared to the impact of global cooling.

1. Introduction

Recent Intergovernmental Panel on Climate Change (IPCC) reports indicate that global warming since the pre-industrial period is likely to exceed 1.5°C within the next few decades (IPCC, 2023). This has prompted research into Climate Intervention (CI; alternatively denoted Geoengineering) strategies which propose to counteract climate change by deliberately intervening to influence Earth's energy budget on a wide scale (MacMartin et al., 2018). Solar radiation management (SRM) refers to a group of CI scenarios where a fraction of the incident sunlight is reflected back to space to increase the planetary albedo. Stratospheric Aerosol Injection (SAI) is the most prominent suggested SRM technique (Smith et al., 2018) as it is hypothesized to be effective, cheap and can be implemented quickly in comparison to other techniques (Shepherd, 2009).

In the atmosphere, aerosol interactions with clouds and radiation generally enhance the planetary albedo causing a net cooling of climate (Bellouin et al., 2020). Stratospheric aerosol injection proposes the deliberate injection of reflective aerosols into the stratosphere. This would increase back-scattered sunlight, cooling the planet analogously to that observed from explosive volcanic eruptions (Robock et al., 2013). The most commonly suggested material for SAI is gaseous sulfur dioxide (SO_2), which oxidizes to form sulfate (in the form of sulfuric acid, H_2SO_4) aerosols upon injection into the stratosphere (Visioni et al., 2017). The ready availability and natural occurrence of SO_2 combined with the volcanic analogue means that it is the most studied material for SAI (e.g., Haywood & Tilmes, 2022).

Clear-air turbulence (CAT) is a type of atmospheric turbulence that occurs without any visible sign of clouds or storm systems making it difficult to forecast or detect in advance (Dutton & Panofsky, 1970). It accounts for roughly 24% of all weather-related aircraft accidents (Kim & Chun, 2011) with most occurring above 10,000 ft cruising altitudes where passengers and crew are often unbuckled (Storer et al., 2017). Clear air turbulence is associated with strong wind shear in the jet stream inducing Kelvin-Helmholtz instability, and by other phenomena such as gravity waves, jet/frontal systems, and spontaneous emissions near the jet stream (Knox et al.,

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2008). Turbulent billows are created when their destabilising influence overcomes the stabilising influence of stratification, leading to strong variations in wind shear and direction in the upper troposphere and lower stratosphere (Williams & Joshi, 2013). The North Atlantic region is an area renowned for its heavy air traffic. It is susceptible to CAT due to the strong winds and high-altitude (∼9 km) jet streams occurring in the area.

An important consequence of SAI to consider in the context of CAT is its effects on the North Atlantic Oscillation (NAO; Jones et al., 2021, 2022). The NAO is a climatic phenomenon characterised by an atmospheric pressure differential between the Icelandic low-pressure system and the Azores high pressure system. It is an important driver of climate variability in the North Atlantic affecting weather patterns and ocean circulations (Hurrell & Deser, 2010). Stratospheric aerosol injection increases the stratospheric tropical aerosol reservoir, warming the lower tropical stratosphere as radiation is absorbed by the aerosols (Huynh & McNeill, 2024). This increases the meridional temperature gradient between the equator and the poles especially in the boreal winter where the temperature difference is most extreme due to the polar night (Lorenz & DeWeaver, 2007; Scaife et al., 2008). By the thermal wind balance equation, an increased temperature differential increases vertical wind shear, linked with a stronger NAO positive phase (Jones et al., 2021). Persistent positive anomalies in the NAO were found in a multi-model analysis of SAI further confirming this relationship (Jones et al., 2022). The positive phase of the NAO is linked with a stronger jet stream over the North-Atlantic associated with a higher probability of encountering CAT (Kim et al., 2016). We therefore hypothesise that as SAI strengthens the positive phase of the NAO, it may also increase trans-Atlantic CAT occurrences.

Storer et al. (2017) predict a significant increase in CAT by 2080 under the high-emission Representative Concentration Pathway (RCP85) scenario (O'Neill et al., 2014). Other studies such as Smith et al. (2023) and Foudad et al. (2024) corroborate this result. The increasing meridional temperature gradient increases the vertical wind shear, resulting in increased Kevin-Helmholtz instabilities near the tropopause, an altitude frequently travelled by commercial airliners (Atrill et al., 2021). Clear air turbulence changes were found to be highest in the mid-latitudes of both hemispheres interfering with flight paths at multiple flight levels. Expanding upon the research of Williams (2017) and Storer et al. (2017), we investigate the effects of climate change and SAI on trans-Atlantic CAT frequency focusing on the boreal winter (December-February, DJF) when CAT is most active in the trans-Atlantic region (Jaeger & Sprenger, 2007). However, it is crucial we evaluate CAT trends under future scenarios including SAI to prepare for the anticipated impacts to the aviation industry and reduce future incidents.

2. Data and Methods

Following Williams et al. (2022), we use established CAT metrics applicable to climate models to evaluate the impact of global climate change and SAI on trans-Atlantic CAT in the Northern Hemisphere winter. For consistency, we define the trans-Atlantic basin as 50–75°N, 10–60°W; an area known to capture a large majority of regional air traffic. Stratospheric aerosol injection simulations were performed with the UK's Earth System Model version 1.0 (UKESM1-0-LL, hereafter UKESM1) which is a coupled atmosphere, land and ocean model with a resolution of 1.25° latitude and 1.875° longitude and 85 vertical levels up to an altitude of 85 km with a well-resolved stratosphere (Sellar et al., 2019). Over the North Atlantic, the 200 and 250 hPa pressure levels of interest equate to 11.8 and 10.1 km altitude respectively, with 4 vertical levels between them inclusive.

The target of the SAI simulations is to reduce global mean temperature from the high emissions SSP5-8.5 scenario to the medium-tier emissions SSP2-4.5 scenario following the Geoengineering Model Intercomparison Project (GeoMIP) G6sulfur protocol (Kravitz et al., 2015). This involves continuously injecting SO_2 into the lower stratosphere (18–20 km altitude) between 10°N and 10°S at the Greenwich meridian (Jones et al., 2021, 2022). SO_2 was injected at gradually increasing amounts so that when SAI is applied to the SSP5-8.5 scenario, the global 10-year mean near-surface temperature stays within ±0.2 K of the equivalent SSP2-4.5 model simulation.

As turbulent eddies are a sub-grid scale phenomenon, it is not computationally feasible to diagnose CAT explicitly in climate model simulations. Instead CAT diagnostics derived from larger-scale flow dynamics are applied to simulated meteorology (Williams & Joshi, 2013). Conceptually, this approach is similar to that of Jones et al. (2017) who used large-scale diagnostics to examine the impacts of SAI on the frequency of North Atlantic hurricanes. Williams and Joshi (2013) computed 21 established metrics currently used to diagnose clear air turbulence. Each CAT metric provides a unique way of diagnosing CAT based on different climatological parameters. 6 out of the 21 diagnostics are Graphical Turbulence Guidance 2 (GTG2) upper-level diagnostics used operationally by commercial airlines (Sharman et al., 2006). We choose to analyze this subset as they are the most reliable and supported by strong observational evidence. Sharman et al. (2006) provide a comprehensive overview of these metrics. The 6 metrics chosen are as follows.

1. The *negative Richardson number* captures regions of Kelvin-Helmholtz shear instability associated with turbulence.
2. The *Magnitude of the residual of the non-linear balance equation* (MRNBE) diagnoses regions of strong imbalance.
3. The *Colson Panofsky Index* (CPI) combines the Richardson index and vertical wind shear to diagnose turbulence.
4. The *Frontogenesis function* diagnoses turbulence through the breakdown of inertial gravity waves when the upper-level frontogenesis is unbalanced and gravity waves amplitude increase.
5. *Variant 1 of the Ellrod Index* combines wind shear with flow deformation and is most commonly used in operational CAT forecasting.
6. *Variant 1 of The North Carolina State University Index* builds on the Ellrod indices measures the separation between horizontal pressure gradients and total velocity to diagnose turbulence based on the ageostrophic frontogenesis function.

Equations are provided in Williams and Storer (2022). Zonal and meridional wind and temperature fields were extracted from UKESM1 climate simulations for the 'Historical' simulations for the period (1985–2015), from SSP5-8.5 for the period (2070–2099), from SSP2-4.5 for the period (2070–2099) and from the G6sulfur simulations for the period (2070–2099) at 6-hr frequency for both 200 and 250 hPa pressure levels. Following the methodology of Williams (2017), 5 aviation-relevant severity thresholds are calculated per CAT metric using zonal and meridional wind and temperature field snapshots every 6 hr for 50 years of pre-industrial UKESM1 control simulations and 30 years of corresponding historical ERA-Interim data. Severity thresholds are determined by correlating each CAT metric with the vertical acceleration experienced by aircraft subjected to turbulence, with the latter metric having recognised severity thresholds (Williams, 2017). The top 0.1% (99.9%–100%) of the probability distribution for each diagnostic in the preindustrial simulation over the North Atlantic at 200 hPa is recognised as severe turbulence followed by moderate to severe (99.8%–99.9%), moderate (99.6%–99.8%), light-to-moderate (97%–99.6%) and finally light turbulence (91.1%–97%). All metrics are defined so that a positive change indicates an increase in CAT. A turbulent event is defined when simulation data exceeds the corresponding diagnostic's threshold for each severity category.

3. Results

The percentage change in mean-spatial CAT for climate scenarios SSP2-4.5, SSP5-8.5 and G6sulfur relative to historical conditions are shown in Figure 1. All future climate scenarios exhibit a mean increase in CAT compared to historical levels across all severity levels. The largest increase in CAT is expected for SSP5-8.5 ranging between 32% and 87%. SSP2-4.5 has a comparatively lower magnitude of 14%–56%, consistent with previous studies for CAT and climate change (Williams, 2017). G6sulfur exhibits a comparatively smaller increase between 17% and 44%. All diagnostics agree on an increase in CAT in relation to historical levels, confirming that future CAT levels are rising independent of the climate scenario.

Across all simulations, there is a visible correlation between the equally weighted mean and the severity level of CAT. Severe turbulence is predicted to increase the most for all future simulations but also exhibits the most disagreement between diagnostics, indicating higher uncertainty. Severe turbulence, associated with the strongest vertical wind shear, poses the greatest danger to aviation safety (Williams, 2017). The disproportionate increase in severe turbulence can be attributed to large changes in critical atmospheric fields surpassing critical thresholds, resulting in previously light CAT transitioning to more severe turbulence. The MRNBE metric forecasts the largest increase in CAT, especially for severe turbulence in SSP5-8.5 with levels predicted to increase by over 225%. In comparison, the CPI predicts an increase of only 111% further highlighting the inter-diagnostic variability.

Figure 2 compares the G6sulfur simulation with SSP2-4.5 and SSP5-8.5 climate scenarios. Clear air turbulence is strongly reduced in the G6sulfur simulation compared to SSP5-8.5. The only deviation to this trend is the CPI diagnostic, which indicates a marginal increase in severe turbulence. However, the probability of such patterns arising due to random variation is low, reinforcing the conclusion that SAI efficiently reduces CAT in the G6sulfur scenario. There is less consistency between diagnostics and considerably smaller magnitudes for the

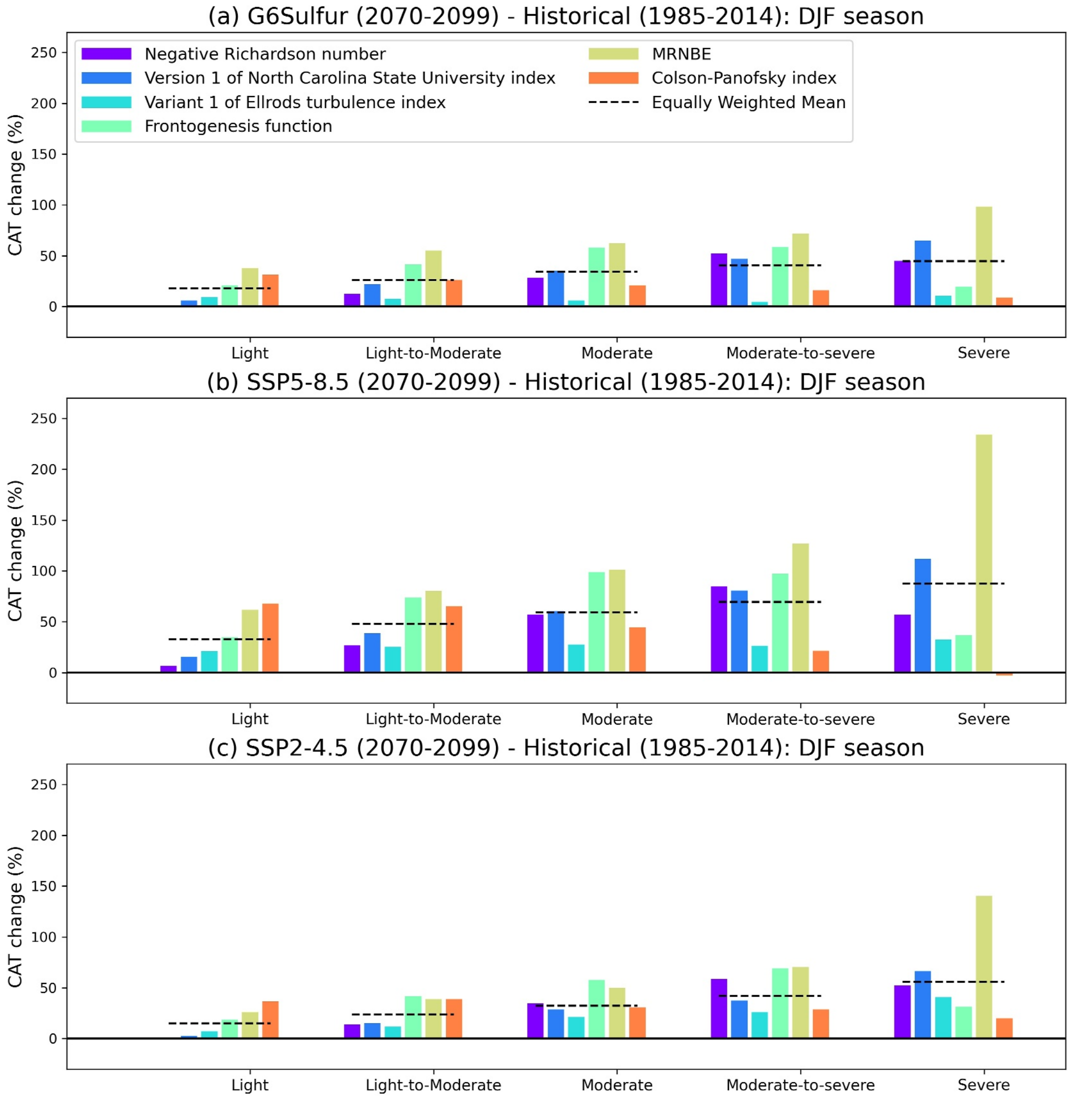

Figure 1. Spatial mean percentage change in CAT relative to historical conditions at 200 hPa level. The spatial mean covers 50–75°N, 10–60°W, a region which captures most trans-Atlantic flights. Each color bar represents turbulence diagnosed by a different diagnostic ordered in relation to SSP2-4.5—historical simulations for continuity. Dashed lines indicate the equally weighted mean of all 6 diagnostics. Comparisons shown include (a) G6Sulfur—Historical (b) SSP5-8.5 - Historical and (c) SSP2-4.5—Historical.

SSP2-4.5 comparison. SSP2-4.5 predicts a smaller increase in CAT compared to historical simulations therefore the effects of SAI in reducing CAT levels are correspondingly lower, especially for less severe CAT. The same relationship between the severity of turbulence and the equally weighted mean is also observed in Figure 2. We therefore conclude global warming has a dominant effect on CAT in comparison to the impacts of SAI on differential heating within the stratosphere.

Vertical wind shear and vorticity play a key role in the mechanisms leading to the occurrence of CAT. Figure 3 shows UKESM1 model output of wind dynamics for each simulation relative to a historical climate. The increase in wind shear is most prominent in the SSP5-8.5 simulation, specifically in lower latitudes of our defined region. This follows for all simulations but with lower magnitudes, implying that wind shear is enhanced under the high global mean temperatures of SSP5-8.5. A statistically significant decrease in wind shear can be seen north of the projected increases in the lower latitudes only for G6sulfur as a result of the change in strength and location of the jet streams due to SAI (Jones et al., 2021). Stronger spatial variations are evident in the vorticity plots. A consistent decrease in vorticity is observed in-between two regions of statistically significant increase for all

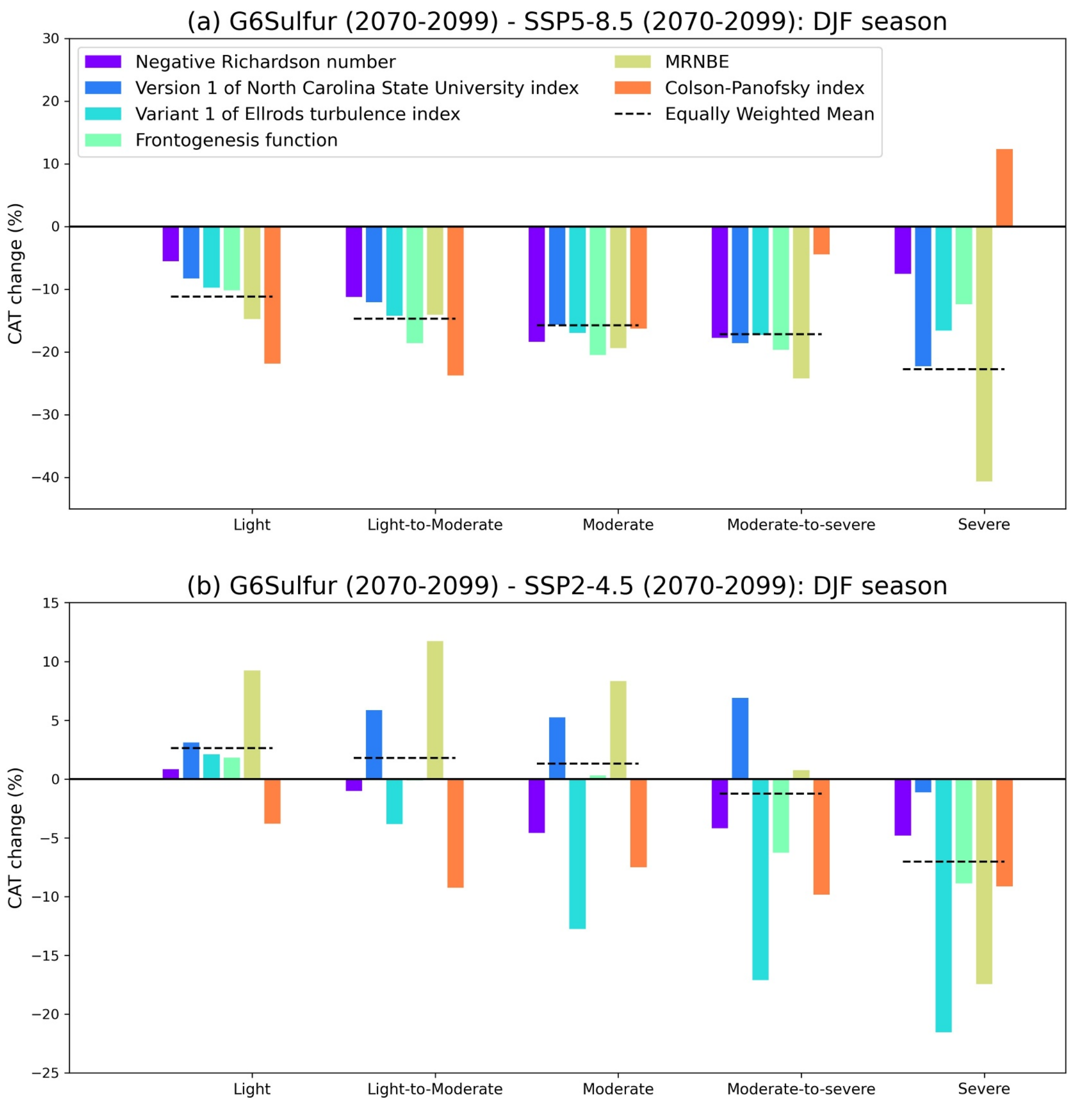

Figure 2. Spatial mean percentage change in CAT between model future simulations at 200 hPa in the trans-Atlantic basin which we define as 50–75°N, 10–60°W. Each color bar represents turbulence diagnosed by a different diagnostic. Dashed lines indicate the equally weighted mean of all 6 diagnostics. Comparisons shown include (a) G6Sulfur—SSP5-8.5 (b) G6Sulfur—SSP2-4.5.

simulations, most apparent in G6sulfur. All future scenarios suggest a northward shift in the subtropical jet due to global warming, which is reflected in the geographical changes in vorticity for all simulations.

Geographic maps of the percentage change in CAT over the trans-Atlantic region are shown in Figure 4. Figure 4a shows turbulence is most active in the lower latitudes (20–45°N) in historical simulations as a result of the strength of the subtropical jet. Figure 4b finds major spatial discrepancies in CAT changes for G6sulfur compared to historical conditions. A clear latitudinally stratified shift from an increase to a decrease in CAT is apparent across more than half of the diagnostics and the mean plot near 45°N latitude. This region aligns with the changes seen in wind shear and vorticity plots in Figure 3. Figures 4c and 4d compare SSP5-8.5 and SSP2-4.5 with G6sulfur, showing a consistent spatial decrease in total CAT except for a small region off the USA coast around 50°N latitude. This is an area of particular importance as air traffic is high and frequently unavoidable in the region due to its proximity to multiple international airports. Again, the increasing intensity and northward shift of the jet stream in the G6sulfur simulation may be responsible for the localized increase in this region.

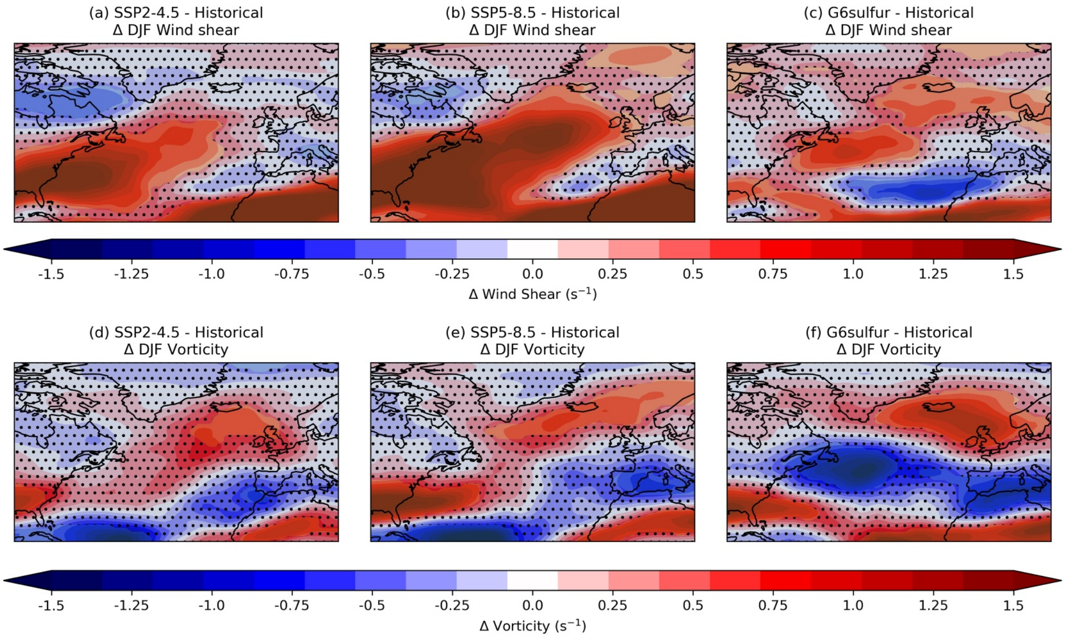

Figure 3. Changes in 200–250 hPa Vertical Wind shear and 200 hPa Vorticity is plotted over the trans-Atlantic regions relative to historical simulations for (a), (d) SSP2-4.5 (b), (e) SSP5-8.5 and (c), (f) G6Sulfur. Stippling indicates regions with no statistically significant change between simulations based on a two tailed pooled *t*-test at the 90% significance level.

The biggest difference in spatial means between G6sulfur and both SSP2-4.5 and SSP5-8.5 are seen for the negative Richardson number, followed by the CPI. However, the changes manifest themselves in different geographic locations. The decrease is concentrated in the lower latitudes for the negative Richardson number but are more evenly distributed for the CPI. The spatial discrepancies between the metrics underscore the different mechanisms turbulence may arise from, and how variations in a warming climate may affect CAT diagnostics differently.

4. Discussion

Greenhouse gases preferentially warm the upper troposphere near the tropics and cool the lower stratosphere near the poles. This increases the latitudinal temperature gradient just below the tropopause, increasing the speed of the jet stream and its northward displacement at typical commercial cruise altitudes (Lee et al., 2019). A faster jet stream is associated with enhanced CAT due to increased vertical wind shear, and may particularly impact eastbound trans-Atlantic flights which utilize the high speeds of the jet stream to reduce fuel consumption. Increases in CAT are therefore most apparent in the high global warming SSP5-8.5 simulation. The complexity of atmospheric dynamics means multiple dynamical processes work against each other, adding a layer of complexity to forecasting CAT as we must consider the underlying mechanisms driving the increase in CAT.

It was hypothesized that SAI would increase CAT because of its effects on the strength of the jet as evident in the increased positive phase of the NAO (Jones et al., 2021, 2022). In G6sulfur, sulfate aerosols are injected into the stratosphere which absorb solar and terrestrial radiation at wavelengths exceeding 1.4 microns (Dykema et al., 2016). This increases heating in the lower stratosphere which increases meridional temperature gradients thus increasing vertical wind shear by the thermal wind balance equations contributing to the intensification of the positive phase of the NAO and the strengthening of the polar vortices. Together, these are projected to increase the speed and northward displacement of the subtropical jet stream associated with an increased magnitude and change in location of trans-Atlantic CAT.

Applying the G6sulfur strategy to SSP5-8.5 effectively ensures that the simulated global mean temperatures are in line with those from SSP2-4.5 simulations. Therefore, any differences in the diagnosed CAT between G6sulfur and SSP2-4.5 are due to the increased AOD as a result of the additional sulfate aerosols in the stratosphere and also increased concentrations of greenhouse gas levels. The resulting reduction in CAT when SAI is applied to the

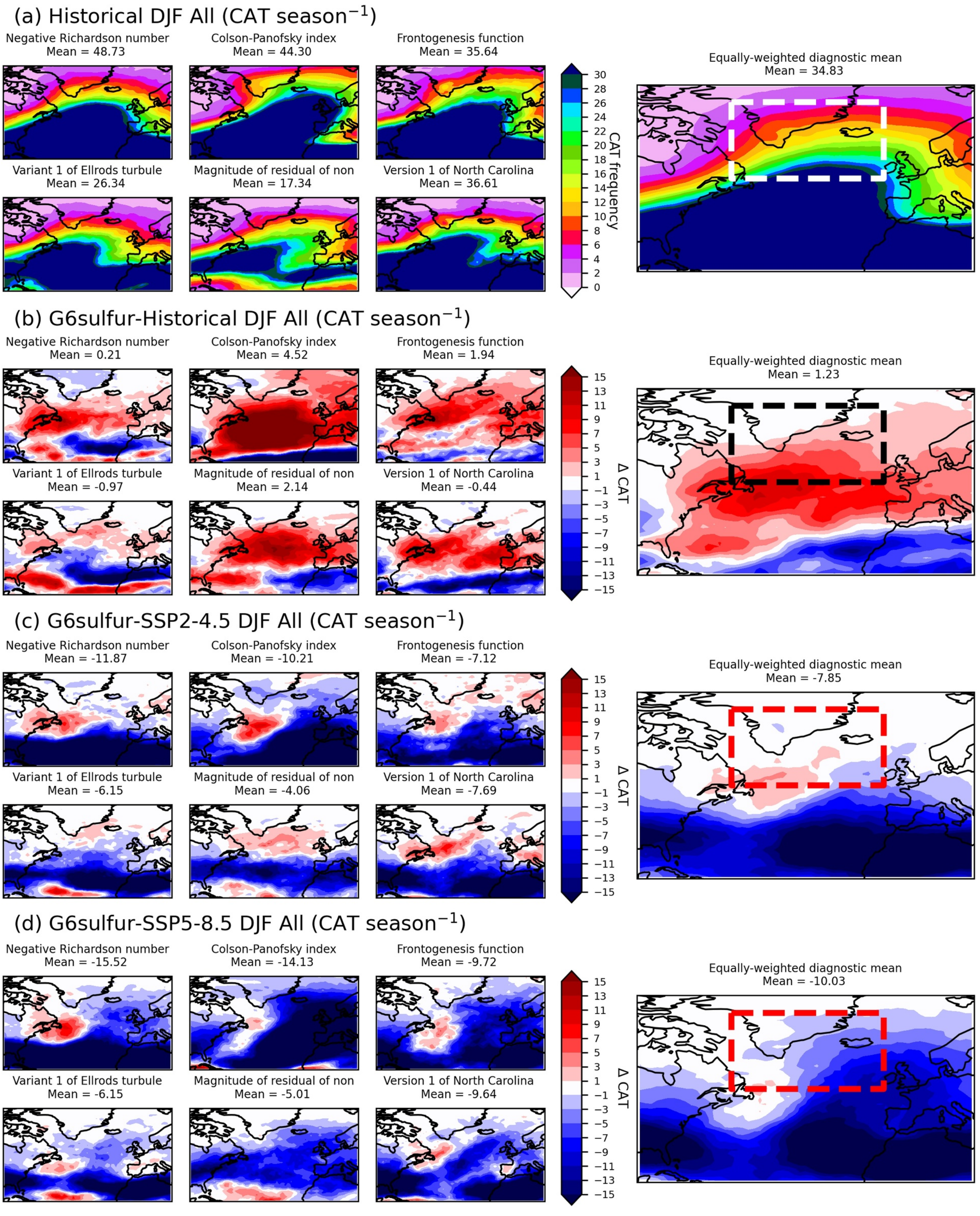

Figure 4. Spatial maps of transatlantic CAT diagnosed by 6 CAT diagnostics at 200 hPa. Large graphs on the right depict the equally weighted mean of the 6 diagnostics. Scaling factors are used to down-weight the smaller high-latitude grid boxes compared to larger high-latitude grid-boxes using the cosine of the latitude for the geographic averages. The bounding box captures the area 50–75°N, 10–60°W where stats are applied to calculate spatial means in Figures 1 and 2. The mean refers to the area average of the larger spatial region for each diagnostic. Simulation comparisons include (a) Historical CAT (b) G6sulfur-Historic Simulation (c) G6sulfur-SSP5-8.5 simulation and (d) G6sulfur-SSP2-4.5 simulation.

SSP5-8.5 scenario highlights SAI's effect on CAT are secondary to its primary effect in counteracting global warming. Stratospheric aerosol injection therefore ameliorates some of the effects of climate change known to strengthen the jet stream such as the increased temperature difference between the upper troposphere and the lower stratosphere. This reverses the northward shift of the jet stream we see under climate change, opposing the northward shift from the increased positive phase of the NAO.

The CPI stands out amongst the 6 metrics, opposing the trend of larger increases in more severe turbulence in addition to predicting more CAT for G6sulfur than SSP5-8.5 for severe turbulence. When climate models are compared with reanalysis data, diagnostics including a thermodynamic process have the worst agreement. Colson Panofsky Index incorporates wind shear and temperature gradients and was found to have the least agreement of all diagnostics with reanalysis data (Williams & Joshi, 2013). This could explain its conflict with the other 5 diagnostics. Similarly, in Figure 4b, both Version 1 of the North Carolina University State Index and Version 1 of Ellrod's Turbulence directly oppose the 4 other diagnostics that predict an increase in CAT for G6sulfur relative to historical simulations. This highlights the importance of forecasting turbulence through the equally weighted mean of all diagnostics, while analyzing each metric separately can give insight to how specific climate dynamics impact future CAT. Each metric by itself does not provide a complete and reliable tool as to how total CAT will evolve.

While CAT is diagnosed from the large-scale flows produced by UKESM1, diagnostics themselves may be biased in the mechanisms CAT is produced through. The majority of CAT is produced through wind changes in the upper atmosphere as a result of changes in large scale atmospheric dynamics. The limited spatial resolution and complexity in representing atmospheric processes accurately may result in simulations misdiagnosing turbulence or missing turbulence arising from smaller scale mechanisms such as atmospheric blocking, convective instabilities or mountain waves caused by strong winds deflecting off mountains (Venkatesh & Mathew, 2013). Williams and Storer (2022) found greater increases in reanalysis CAT compared to model predictions suggesting climate model simulations may underestimate future CAT increases, so some caution is needed when interpreting our results. Additionally, the ability of aerosols to effect both large atmospheric dynamics and microphysical interactions increases the complexity of the G6sulfur simulation, resulting in further uncertainty in forecasting CAT.

In this study, a single climate model is used to investigate CAT. This choice is justified, because most of the uncertainty in the response of CAT to climate change has been shown to come from the CAT diagnostics rather than the climate model (Williams & Storer, 2022). Smith et al. (2023) have shown that the CAT tendencies found here appear robust across other CMIP6-era climate models including higher resolution models for future global warming scenarios. A similar NAO response to SAI is found in other climate models (e.g., Jones et al., 2021) indicating that a multi-model analysis would likely find qualitatively similar CAT responses, but this should be investigated to confirm our conclusions.

Furthermore, our simulations forecast the percentage change over the trans-Atlantic region for the current levels of trans-Atlantic flights under the assumption we cannot detect and avoid CAT in advance. If air traffic increases, by default, so will the frequency of aircraft coming into contact with CAT. Flight trajectories also impact the exposure of aircraft to CAT. Eastbound flights utilizing the jet stream for speed and fuel-efficiency generally experience more turbulence than westbound flights. Further research should investigate optimal flight paths to avoid regions of increased severe CAT to provide safer passage for passengers and crew. While the focus of this study is on CAT, there are other aspects of SAI that would have implications for the aviation industry. In particular, the direct corrosive effect of enhanced concentrations of H_2SO_4 in the upper troposphere and lower stratosphere could have particular impacts as evidenced by increased corrosion of the aircraft fleet subsequent to the eruption of Mount Pinatubo in 1991 (e.g., Guseva et al., 2002).

The impacts of climate change and SAI on winter-time trans-Atlantic CAT have been explored in this paper. Strong increases in CAT for the high-emission SSP5-8.5 global warming scenario are found, with largest increases found for severe CAT. When SAI is applied to the SSP5-8.5 scenario, its ability to counteract the effects of global warming results in a decrease in CAT for all severities. Despite the initial hypothesis predicting an increase in CAT under SAI, we find the primary effects of SAI in offsetting global warming overpower secondary effects strengthening the positive phase of the NAO. Smaller differences between SSP2-4.5 and G6sulfur are found showing the same effects but are much less conclusive. It therefore appears that global mean temperature is a reasonable predictor of CAT. The aviation industry should prepare for the forecasted CAT enhancements in a changing climate to reduce damage to aircraft and unnecessary injuries to passengers and crew.

Data Availability Statement

UKESM1 model data for the SSP5-8.5, SSP2-4.5, and G6sulfur experiments are available from the Earth System Grid Federation (https://esgf-node.llnl.gov/projects/cmip6). The 6 hourly data sets (wind, temperature) used to generate the figures in this study are available online at A. C. Jones (2024).

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