



Association between ice-supersaturated regions and clear-air turbulence: implications for safer contrail avoidance

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Abstract.

Contrail cirrus, formed in the wake of an aircraft, contributes significantly to aviation's climate impact. Diverting aircraft from ice-supersaturated regions (ISSRs) can mitigate this, as contrails can form and persist there. ISSRs can form when rising air cools to ice supersaturation; the same motion can cause clear air turbulence (CAT). This motivates characterising the turbulence risk associated with diversions to avoid ISSRs. Analysing the global log odds ratio distribution from ERA5 reanalysis data reveals a relationship between ISSRs and moderate-or-greater (MOG) CAT. However, the directionality of the relationship is highly sensitive to the three turbulence diagnostics used (i.e., Turbulence Index 1, NCSU1 and Brown 2). For contrail avoidance, a positive relationship presents an opportunity to mitigate both the climate impact and turbulence risk. Conversely, the opposite poses a potential trade-off between the two. Despite the sensitivity, there is agreement across the three turbulence diagnostics that: 1) when large-scale movements of air are encountered in the mid-latitudes, a pattern in the direction of the turbulence risk change emerges across the vertical velocity regimes; in particular, ISSRs in a strong updraft have on average a +19.0% increased risk of MOG CAT, and 2) in the mid-latitudes, the overall risk of MOG CAT in an ISSR is higher in winter (+33.3%, on average) and lower in summer (−42.6%). Collectively, these findings suggest that vertical velocity may differentiate two classes of ISSRs: those associated with an increased risk of MOG CAT and those that are not. This lays the groundwork to exploit this relationship to improve the operational efficiency of climate-optimised flight trajectories.

1 Introduction

Contrails are ice clouds which form in the wake of an aircraft which add to aviation's contribution to climate change (Kärcher, 2018; Lee et al., 2021; Bock and Burkhardt, 2019; Burkhardt and Kärcher, 2011). Long-lived (or persistent) contrails – which form in ice supersaturated regions (ISSRs) (Teoh et al., 2020b; Martin Frias et al., 2024) – have the greatest warming effect as they can spread, due to wind shear, and can last for several hours (Kärcher, 2018; Wolf et al., 2024). One approach to reducing the climate impact of persistent contrails is by adopting a contrail avoidance strategy whereby aircraft deviate from the planned route to avoid ISSRs (e.g., Smith et al., 2026). At cruise altitudes, ISSRs tend to be greater in horizontal extent than in vertical depth with a mean horizontal path length of 150 ± 250 km (Gierens and Spichtinger, 2000) and a vertical thickness



25 of 0.56 ± 0.61 km (Spichtinger et al., 2003). This has resulted in a range of strategies which include altitude modifications (e.g., Schumann et al., 2011; Teoh et al., 2020a), lateral deviations (e.g., Irvine et al., 2014), a combination of both (e.g., Yin et al., 2018), or modifications which are climate risk-aware (Borella et al., 2026).

ISSRs form when moist air rises through the atmosphere and cools adiabatically to become saturated with respect to ice (Gierens et al., 2012; Gierens and Brinkop, 2012). Thus, they are often thin and close to the tropopause (Spichtinger et al., 30 2003; Rädcl and Shine, 2007). In the mid-latitudes, they are often associated with storm tracks (Irvine et al., 2012, e.g.), specifically in relation to the fronts and the warm conveyor belt (e.g., Driver et al., 2025; Kästner et al., 1999; Spichtinger et al., 2005b), and to the jet stream (e.g., Lamquin et al., 2012; Irvine and Shine, 2015). In the tropics, ISSRs are associated with deep convection (Lamquin et al., 2012; Gettelman et al., 2006).

While not identical, the synoptic weather features associated with ISSRs share a number of similarities with those of clear 35 air turbulence (CAT). CAT is also generally associated with the tropopause (Dutton and Panofsky, 1970; Ellrod et al., 2015), jet streams and upper-level fronts (e.g., Keller, 1990; Sharman, 2016) as these regions are conducive for the instabilities to trigger turbulence (Wolff and Sharman, 2008). These instabilities are, and not limited to, the breaking of gravity waves and inertia-gravity waves, and Kelvin-Helmholtz instabilities (Sharman et al., 2012, and the references therein). At a more specific level, both ISSRs and CAT have been found to be associated with the warm conveyor belt (shown by Lee and Sprenger, 2025, 40 for CAT). Moreover, Spichtinger et al. (2005a) showed that both orographic gravity waves and inertial gravity waves from the jet stream led to the formation of ISSRs which are the same instabilities can lead to CAT (e.g., Fritts and Nastrom, 1992; Lane et al., 2004; Woiwode et al., 2023). Therefore, the commonalities between ISSRs and CAT provides reason to believe that a relationship exists between them. This study establishes whether moderate-or-greater (MOG) clear air turbulence (CAT) is related to ISSRs and what implications this could have for contrail avoidance.

45 According to NTSB (2021), from 2009 to 2018, turbulence was the leading cause of aviation accidents. Turbulence events can lead to injury of both crew and passengers. In severe cases, such as the Singapore Airlines flight SQ321 incident (TSIB, 2024; Gisinger et al., 2024; Wang, 2025), fatalities may result. For MOG turbulence encounters, the impacts are typically limited to injuries (NTSB, 2021), increased airframe fatigue from repeated encounters, and contribute to flight delays and financial costs to the airlines (Sharman et al., 2006; Sharman and Pearson, 2017; Wolff and Sharman, 2008; Kim et al., 2016). CAT is 50 of particular importance given it is not visible and cannot be detected by the onboard radar (Sharman, 2016). Consequently, to safely conduct contrail avoidance there is a need to understand how the two could be related.

Beyond this, anthropogenic climate change results in tropospheric warming and stratospheric cooling in the mid-latitudes (Goessling and Bathiany, 2016) thereby affecting the prevalence of both ISSRs and CAT. This entails an annual mean change of approximately 1% increase in ISSRs for the Northern Hemisphere by the end of the 21st century (Irvine and Shine, 2015) due 55 to an increase in relative humidity (Wright et al., 2010; Sherwood et al., 2010). For CAT, the increased temperature gradient drives stronger zonal winds (Simpson, 2016). This change has resulted in an increased in frequency and intensity of CAT (e.g., Jaeger and Sprenger, 2007; Wolff and Sharman, 2008; Williams, 2017), and is projected to increase further as the climate warms (Storer et al., 2017; Kim et al., 2023).



In this study, the statistical relationship between ISSRs and MOG CAT is explored through the odds ratio with an investi-
 60 gation into the potential implications on contrail avoidance. Section 2 introduces the methodology employed in this study: the
 meteorological data used (Sect. 2.1); the identification of MOG CAT regions (Sect. 2.2); and the quantification of the relation-
 ship between ISSRs and MOG CAT (Sect. 2.3). Sect. 3 presents the result of this study. To begin, the presence of a relationship
 between MOG CAT and ISSRs is established in Sect. 3.1 by examining the global distribution of the odds ratio for three tur-
 bulence diagnostics. Subsequently, we examine the impact of seasonal variations on the relationship between ISSRs and MOG
 65 CAT Sect. 3.2. Lastly, Sect. 3.3.1 presents a case study along a great circle flight route. This, alongside Sect. 3.3.2, supports the
 existence of two classes of ISSRs – those related to MOG CAT and those independent of it – by relating them through large
 scale atmospheric motions, i.e., vertical velocity. Sect. 4 addresses the applicability and implications of the presented results.

2 Methodology

The analysis presented here relies on `rojak` (Wong et al., 2025), a parallelised, peer reviewed Python package for the high-
 70 performance computing of CAT diagnostics. It implements 24 different turbulence diagnostics, including the three-dimensional
 frontogenesis equation (Bluestein, 1992) and the turbulence index 1 and 2 (Ellrod and Knapp, 1992). Using the verification
 strategy in Gill (2014); Ko et al. (2025); Sharman and Pearson (2017), the computed diagnostics were compared against
 turbulence observations from the AMDAR dataset (National Oceanic and Atmospheric Administration, 2025) in terms of the
 under the receiver operating curve (AUC). This AUC score was then benchmarked against those in Sharman and Pearson
 75 (2017) and were comparable.

This AUC score was then benchmarked against those in Sharman and Pearson (2017) and Gill and Buchanan (2014). For Gill
 and Buchanan (2014), the AUC for the common individual diagnostics was greater than or equal to their deterministic AUC.
 For Sharman and Pearson (2017), not all diagnostics were directly comparable due to the slight differences in the definition
 of diagnostics. Consequently, the AUCs were deemed comparable if they were greater than Sharman and Pearson (2017)
 80 $AUC_{\min} - 0.05$. Moreover, the package features unit and integration tests to check the validity of the implementation with a test
 suite coverage above 75%. For this study, only CAT diagnostics with an $AUC > 0.7$, following Sharman and Pearson (2017),
 and a Matthew’s correlation coefficient < 0.55 have been used.

The methodology is comprised of four main components, as illustrated in Fig. 1. The first of these, is the meteorological
 data used in the study which has been detailed in Sect. 2.1. From here, there are two main branches. The first branch involves
 85 the identification of the moderate-or-greater (MOG) turbulence regions described in Sect. 2.2 and the second branch involves
 the identification of ice super saturated regions as presented in Sect. 2.1. The final component, involves the computation of the
 odds ratio and its latitudinal stratified decomposition as described in Sect. 2.3.

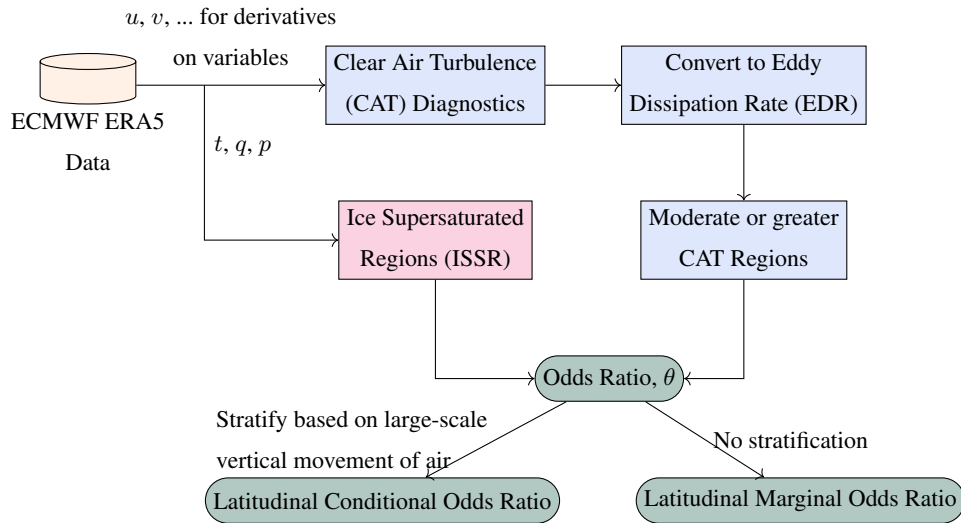


Figure 1. Flowchart summarising the methodology employed in this study.

2.1 Meteorological Data

To identify ISSRs and MOG turbulence, we have used the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis data (Hersbach et al., 2020) on pressure levels with a grid resolution of $0.25^\circ \times 0.25^\circ$ at six hour intervals from 2023 to 2025. The geographical region used covers all longitudes and latitudes from 70°N to 70°S .

The ERA5 dataset has previously been used to study the climatological distribution of turbulence (e.g., Lee et al., 2023; Foudad et al., 2024) and for establishing the relationship between CAT and synoptic weather features (Lee and Sprenger, 2025). For the turbulence diagnostics, the data on the following pressure levels were used: 200 hPa; 225 hPa; 250 hPa; 300 hPa. Using the ICAO standard atmosphere, these correspond to approximately 11 800 m, 11 000 m, 10 400 m and 9360 m in altitude. These pressure levels were selected as they cover the range of cruise altitudes of most airliners. This data was used for computing the turbulence diagnostics and the ISSRs using *rojak* (Wong et al., 2025).

The identification of ISSRs involves computing the relative humidity with respect to ice (RH_i) and applying a threshold on both the temperature and RH_i. The RH_i used is derived from the specific humidity, pressure and temperature using the formulae in Murphy and Koop (2005) instead of using the hybridised relative humidity from the ERA5 data. Previous studies (e.g., Schumann et al., 2021; Gierens et al., 2020; Reutter et al., 2020; Teoh et al., 2022) have shown the RH_i from ERA5 to be underestimated. As such, various models for correcting this have been used, such as matching the distribution of RH_i in ERA5 to in-situ measurements from the In-service Aircraft for a Global Observing System (IAGOS) (Teoh et al., 2022, 2024) or changing the critical RH_i threshold to a lower value (e.g., Schumann, 2012; Driver et al., 2025). For simplicity, the latter method in the literature was used with a threshold of 97.79% (Teoh et al., 2022) and 90% (Driver et al., 2025), as the corrections to the bias in the ERA5 data. Given that the application of a lowered critical RH_i threshold had a marginal impact, the strictest RH_i threshold of 100% has been adopted for this study.



Finally, based on Medeiros and Stevens (2011), meteorological regimes based on the large-scale vertical movement of air are diagnosed using the vertical velocity, w , on a single pressure level of 500 hPa from ERA5 data at the same spatial and temporal resolution. To stratify the data on vertical velocity, the distribution was discretised into categories based on the mean ($\mu_w \approx \pm 0.03 \text{ Pa s}^{-1}$, varying with latitude) and standard deviation ($\sigma_w = 0.22 \text{ Pa s}^{-1}$) computed over the study period. The resulting categories correspond to strong updraft/downdraft (beyond $\pm 1\sigma_w$ from the mean), weak updraft/downdraft (within approximately $\pm 1\sigma_w$), and still air (close to the mean).

2.2 Identifying moderate-or-greater turbulence region

The CAT diagnostics selected for this study are listed in Table 1. The first selected CAT diagnostic is Turbulence Index 1 (TI1) adopts a kinematic approach (Knox et al., 2016) to accurately forecast approximately 66 to 75 % of MOG turbulence (Ellrod and Knapp, 1992) and to be particularly effective at upper levels (Sharman and Pearson, 2017). The next CAT diagnostic is NCSU1, a semi-empirical diagnostic developed from investigating 44 severe turbulence cases (Kaplan et al., 2005b, a, 2006). Finally, the Brown 2 takes an energetics approach and targets regions of instability using the Richardson tendency equation and vertical wind shear to estimates the rate of turbulence energy dissipation (Roach, 1970).

Table 1. List of clear air turbulence diagnostics used in this study

Abbreviation	Description	Reference
TI1	Product of vertical wind shear and deformation	Ellrod and Knapp (1992)
NCSU1	"Responsive to inertial-advective forcing indicative of highly curved and accelerative jet stream flows" (Kaplan et al., 2006)	Sharman and Pearson (2017)
Brown2	Energy dissipation rate from the simplified Richardson tendency equation	Brown (1973)

These turbulence diagnostics have been selected on the basis that the $\text{AUC} > 0.7$ and the Matthew's correlation coefficient between the diagnostics is < 0.55 . The difference in the approach taken towards identifying CAT is reflected in the low correlation between the diagnostics. Since there is not a single CAT diagnostic that is effective at reliably identifying CAT (Knox et al., 2016), this selection criteria ensure that a broad range of generation mechanism and sources of CAT are represented. This maximises the generalisability of the conclusions, as it is not yet known whether the overall differences would still hold when examined with respect to ISSRs. CAT is generally associated with upper-level fronts, jet streams and the tropopause (Sharman et al., 2012, and the references therein), as such their ability to detect CAT in the tropics may be limited.

In order to identify MOG CAT regions with the diagnostics, they are first mapped to EDR. The ability to map to perform this mapping is based on the finding that the distribution of turbulence intensities – quantified in EDR – in both atmospheric models and measurements is approximately log-normal (e.g., Nastrom and Gage, 1985; Frehlich and Sharman, 2004). The log-normal fit for the distribution is,

$$F_{\epsilon} = \frac{1}{\sqrt{2\pi\sigma_{\epsilon}^2}} \exp\left(-\frac{[\epsilon - \mu_{\epsilon}]^2}{2\sigma_{\epsilon}^2}\right) \quad (1)$$



where ϵ is the natural logarithm of EDR (i.e. $\epsilon = \ln \varepsilon^{1/3}$), μ is the mean, and σ is the standard deviation.

By assuming a linear mapping between the CAT diagnostics and the climatological EDR (Sharman and Pearson, 2017),

$$\ln(I) = \alpha + \beta \ln \iota \implies I = \iota^\beta \exp(\alpha) \quad (2)$$

where ι is the raw diagnostic index value, I is the transformed diagnostic that is equivalent to EDR, α and β are transformation coefficients given by,

$$\beta = \frac{\hat{\sigma}_\epsilon}{\sigma_{\ln \iota}} \quad (3)$$

$$\alpha = \hat{\mu}_\epsilon - \beta \mu_{\ln \iota} \quad (4)$$

where $\hat{\mu}_\epsilon$ and $\hat{\sigma}_\epsilon$ are the climatological mean and standard deviation of $\ln \varepsilon^{1/3}$. These climatological values are computed from in-flight EDR observation. As Ko et al. (2025) showed improved performance by using the climatological distribution for their studies time period, the in-flight EDR observations from the National Oceanic and Atmospheric Administration (NOAA) AMDAR dataset (National Oceanic and Atmospheric Administration, 2025) was used to computed the EDR distribution to be $\hat{\mu}_\epsilon = -3.63$ and $\hat{\sigma}_\epsilon = 0.952$.

Table 2. Eddy dissipation rate thresholds for light, moderate and severe turbulence from (Sharman and Pearson, 2017)

Light	Moderate	Severe
$0.15 \text{ m}^{2/3} \text{ s}^{-1}$	$0.22 \text{ m}^{2/3} \text{ s}^{-1}$	$0.34 \text{ m}^{2/3} \text{ s}^{-1}$

With the transformed diagnostics as EDR values, the presence of the various severities of turbulence can be determined using a threshold. Table 2 summarises the thresholds used in (Sharman and Pearson, 2017). For forecasting MOG turbulence, the EDR must be greater than $0.22 \text{ m}^{2/3} \text{ s}^{-1}$.

2.3 Quantifying the relationship between ice supersaturated regions and turbulence

Table 3. A 2×2 contingency table of two variables X and Y . To ascertain the effect of ISSRs on MOG turbulence, X which is the explanation variable and corresponds to ISSRs and Y which is the response variable and corresponds to the presence of MOG turbulence.

	$Y = 1$	$Y = 0$	Total
$X = 1$	n_{11}	n_{10}	$n_{1\bullet}$
$X = 0$	n_{01}	n_{00}	$n_{0\bullet}$
Total	$n_{\bullet 1}$	$n_{\bullet 0}$	n

Contrail avoidance strategies require the aircraft to deviate from their planned trajectories (e.g., Teoh et al., 2020b), potentially routing them through regions of turbulence. To inform operational decisions, an interpretable quantitative measure of the



spatial relationship between ISSRs and MOG turbulence that captures the trade-off between contrail and turbulence avoidance is needed. The odds ratio has been selected as it captures how the risk of MOG turbulence changes given the presence or absence of an ISSR. In other words, it shows the effect of ISSRs on MOG turbulence. The odds ratio is defined as,

$$\theta_{XY} = \frac{\Omega_1}{\Omega_2} \quad (5)$$

155 where Ω_1 is the odds of encountering turbulence given that an ISSR is present and Ω_2 is the odds of encountering turbulence given that an ISSR is not present. This is estimated using the sample odds ratio,

$$\hat{\theta}_{XY} = \frac{n_{11}n_{00}}{n_{10}n_{01}} \quad (6)$$

n_{00} , n_{01} , n_{10} , and n_{11} are terms from the 2×2 contingency table in Table 3. An odds ratio of 1 corresponds to independence. A value greater than 1 indicates that $P(Y|X)$ is more likely than $P(Y|\neg X)$. For example, an odds ratio of 4 means that the
 160 former has four times the odds than the latter. While a value between 0 and 1 is the inverse, i.e. the latter has higher odds than the former. As the odds ratios is symmetrical about the value 1, the $\log \theta$ has been used such that the sign of $\log \theta$ would indicate the direction of the association and the magnitude the strength of the association (Agresti, 2002).

Table 4. Example $2 \times 2 \times K$ contingency table where Z has k categories.

Z	$X = \text{ISSR}$	$Y = \text{MOG Turbulence}$	
		$Y = 1$	$Y = 0$
Z_1	$X = 1$	n_{111}	n_{011}
	$X = 0$	n_{101}	n_{001}
$\vdots$	$\vdots$		$\vdots$
	$\vdots$		$\vdots$
Z_k	$X = 1$	n_{11k}	n_{01k}
	$X = 0$	n_{10k}	n_{00k}

The stratified contingency table in Table 4 allows for each ISSR and MOG turbulence occurrence to be classified into separate categories of the third covariate. For example, a $2 \times 2 \times 2$ contingency table can be created to classify based on the
 165 direction of the vertical velocity of air. With reference to Table 4, Z_1 would be for upwards moving air and Z_2 would be for downwards moving air. To examine whether the direction and magnitude of the vertical velocity of air is an effect modifier, a larger $2 \times 2 \times K$ contingency table can be created to account for the different velocity thresholds, e.g. Z_1 for $w \leq -0.5$, Z_2 for $-0.5 < w < 0$ and Z_3 for $w \geq 0$. For each of the k categories of Z , the conditional odds ratio is found using (Agresti, 2002),

$$\hat{\theta}_{XY(k)} = \frac{n_{11k}n_{00k}}{n_{10k}n_{01k}} \quad (7)$$



170 3 Results

3.1 Relationship between moderate or greater turbulence and ice supersaturated regions

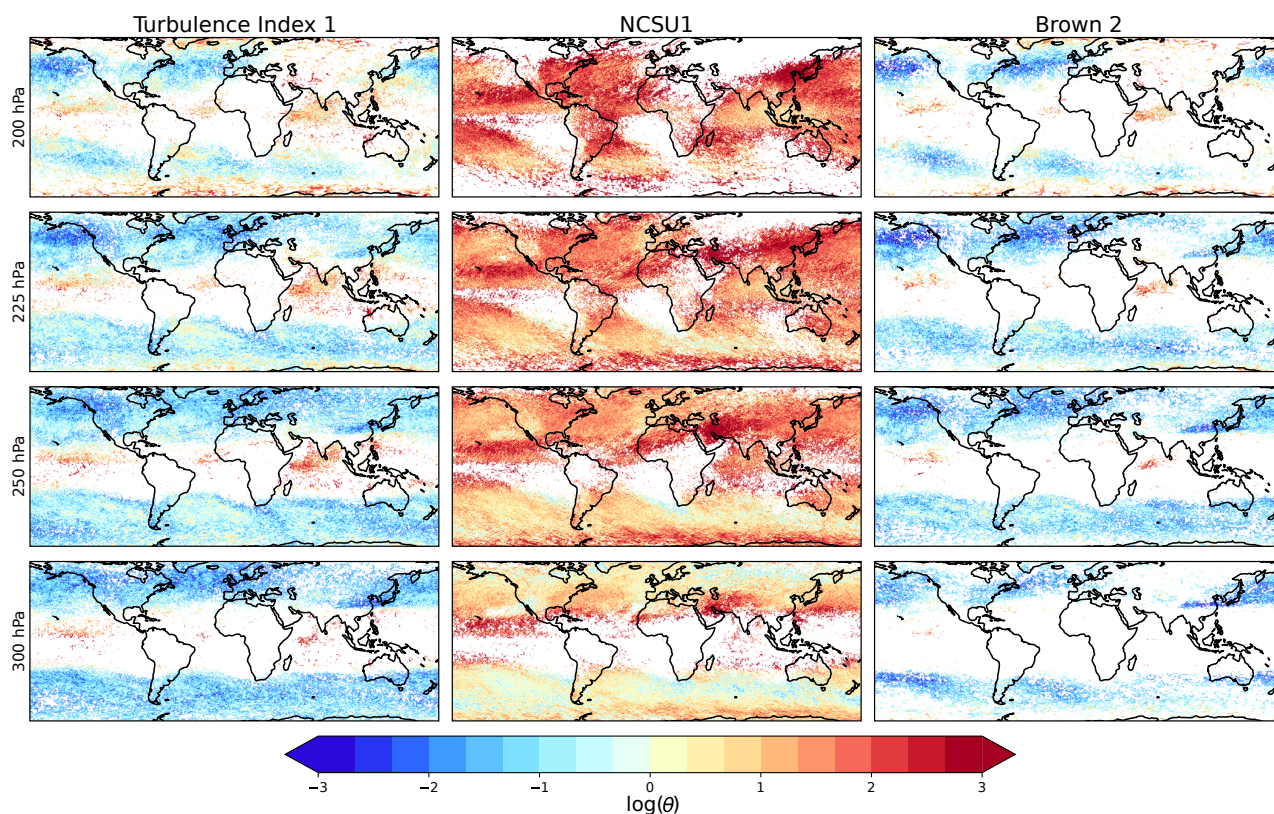


Figure 2. Global distribution of the odds ratio at 200 hPa, quantifying the relative likelihood of encountering MOG turbulence within an ISSR compared to outside an ISSR, for the Turbulence Index 1 (left), NCSU1 (middle), and Brown2 (right) turbulence diagnostics. The colour bar is symmetric in log space, spanning from 1/20 to 20 times the odds.

Figure 2 shows that the odds of encountering MOG turbulence given an ISSR is present is higher than when an ISSR is not present when $\log \theta > 0$. As a result, it would be operationally advantageous to avoid the ISSR, as the benefit would be twofold: improving safety and mitigating contrail formation. When $\log \theta < 0$, the opposite is true, i.e. the presence of an ISSR decreases the odds of encountering MOG turbulence thus potentially necessitating a trade-off between safety and potential contrail formation. Since the probability of encountering MOG turbulence is small, the odds ratio is a good approximation of the relative risk (Agresti, 2002). As such, the results can be interpreted as indicating the relative risk of encountering MOG turbulence when in an ISSR compared to when not in an ISSR, providing a ratio of the probabilities of encountering MOG turbulence under these two conditions. For example, a relative risk of four means that the probability of MOG turbulence when in an ISSR is four times that when not in an ISSR.



An overall comparison of the three diagnostics shows a stark difference in the directionality of the relationship with ISSRs. TI1 and Brown2 have a predominantly negative relationship while NCSU1 is largely positive. This difference is more marked than the mean prevalence of MOG CAT during the study period where all three diagnostics exhibit two distinct peaks in the mid-latitudes of both hemispheres.

185 In Fig. 2, the NCSU1 diagnostic results in a log odds ratio is almost uniformly positive at 200 hPa, indicating a that there is higher risk of encountering MOG turbulence when in an ISSR. As the altitude decreases to a 300 hPa, the mid-latitudes start exhibiting a mixture of positive and negative values. This suggests that there is a gradual weakening of the relationship – which is more evident in the Southern Hemisphere at the intermediate pressure levels – until the relationship reverses such that there are regions where there is a higher risk of encountering MOG turbulence when not in an ISSR.

190 The TI1 and Brown2 diagnostics in Fig. 2 present a more pronounced pattern in the tropics, with the log odds ratio being largely undefined in a significant portion it, regardless of the pressure level. This is a direct consequence of the definition of the sample odds ratio (Equation 6) which results in a value of 0 when there are no incidences of MOG turbulent ISSRs or regions free of both MOG turbulence and ISSRs. The tropical regions show consistently positive diagnostic values across pressure levels, implying that ISSR avoidance could give turbulence advantages. While the diagnostics' accuracy is limited in
 195 these regions, the rare instances where they predict turbulence are characterized by a strong and consistent positive relationship between ISSRs and MOG turbulence, which reinforces the potential benefits of ISSR avoidance for contrail mitigation.

Another commonality between the TI1 and Brown2 is that the mid-latitudes show a more strongly negative log odds ratio at 300 hPa and becomes less uniformly negative and slightly less negative as one moves upwards to 200 hPa. The main exception is over the North Atlantic for Brown2 where it remains strongly negative regardless of pressure level.

200 Overall, the results highlight the complex relationship between ISSRs and MOG turbulence. Most distinctively, the sensitivity to the choice of turbulence diagnostic in the relationship and the effect of altitude on the direction of the relationship.

3.2 Seasonal Variations

3.2.1 Effect of seasons on the odds ratio

The relationship between ISSRs and MOG CAT is also affected by seasonality. The increased prevalence of ISSRs in the
 205 mid-latitudes during winter is largely driven by storm tracks (Gierens and Brinkop, 2012). Similarly, the climatologies of MOG CAT from observations through automated reports (Sharman et al., 2014; Kim and Chun, 2016) and PIREPs (Wolff and Sharman, 2008; Kim and Chun, 2011), and model derived climatologies (Jaeger and Sprenger, 2007; Lee et al., 2023; Williams and Storer, 2022) has shown a peak in turbulence frequency and intensity in the mid-latitudes during winter. Since both ISSRs and MOG CAT experience a mid-latitude peak in winter, we would expect the relationship to exhibit a seasonal dependence.

210 The formation of ISSRs can either occur when air rises in the atmosphere (Gierens et al., 2012) or slowly through radiative cooling (Fusina et al., 2007; Fusina and Spichtinger, 2010), thereby becoming saturated with respect to ice. Similarly, vertical air motions is a key factor in turbulence generation (Sharman, 2016), and aircraft are particularly susceptible to turbulence in the vertical direction (Houbolt, 1973). Thus, large-scale vertical motions are associated with both ISSRs and MOG turbulence.

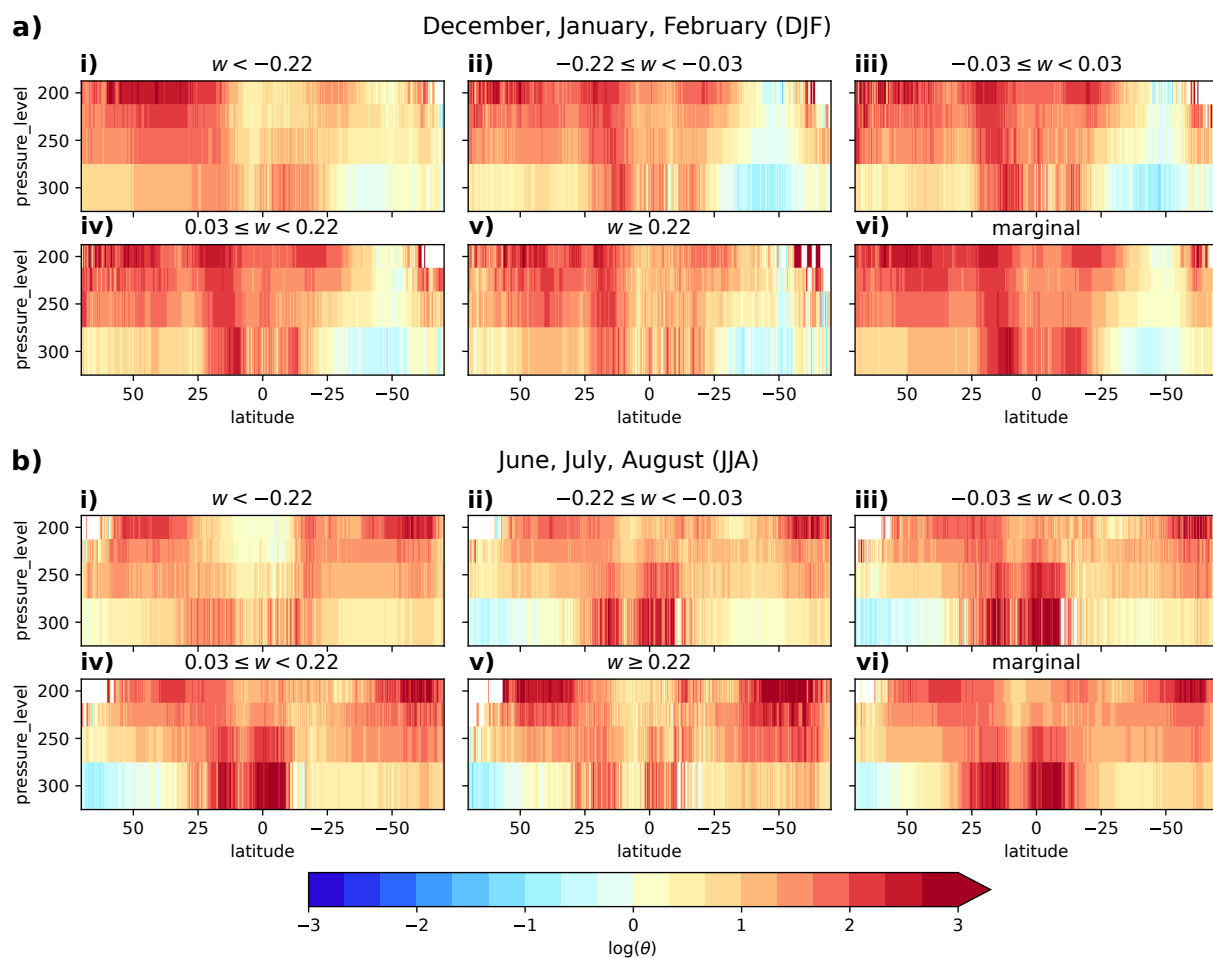


Figure 3. Latitudinal conditional odds ratio for the 5 strata of vertical velocity in panels (i-v) and the latitudinal marginal odds ratio in panel (vi) for the effect of ISSRs on MOG turbulence for the NCSU1 turbulence diagnostic during the seasonal months of December, January and February (in block (a)), and June, July and August (in block (b)) of 2023 to 2025



Therefore, to ascertain if these two classes of ISSRs relate to MOG CAT in the same way, panels (i-v) of Fig. 3(a-b) contain the
 215 log latitudinal conditional odds ratio. This has been computed by stratifying the data based on the mean and standard deviation
 of the vertical velocity (introduced in Sect. 2.1) to create a $2 \times 2 \times 5$ contingency table similar to Table 4. This resulted in the
 conditional odds ratio for the 5 categories: strong updraft ($w < -0.22 \text{ Pa s}^{-1}$); weak updraft ($-0.22 \leq w < -0.03 \text{ Pa s}^{-1}$); still
 air ($-0.03 \leq w < 0.03 \text{ Pa s}^{-1}$); weak downdraft ($0.03 \leq w < 0.22 \text{ Pa s}^{-1}$); and strong downdraft ($w \geq 0.22 \text{ Pa s}^{-1}$). Panel
 (vi) of Fig. 3(a-b) is known as the marginal case and the latitudinal equivalent of the global distribution in Fig. 2. For brevity,
 220 the log latitudinal odds ratio, is referred to as the odds ratio with the distinction between the marginal and conditional preserved.

Figure 3(a-b)(vi) shows the seasonal dependence of the log latitudinal odds ratio for NCSU1 for the months of June, July,
 August (JJA) and December, January, February (DJF). This is particularly evident in the mid-latitudes at the 300 hPa pressure
 level where odds ratio is largely negative in the summer hemisphere and positive in the winter hemisphere. As this hemispher-
 ical difference predominantly occurs at 300 hPa, the analysis is restricted to this pressure level. Similarly, the hemispherical
 225 difference can also be seen in the conditional odds ratio for all the cases (Fig. 3(a-b)(ii-v)) except for the strong updraft case
 during JJA (Fig. 3(b)(i)). Thus, the relationship between ISSRs and MOG CAT consistently displays a seasonal dependence.

This difference in the sign of the odds ratio results in a statistical artefact – the Simpson’s paradox – when the climatological
 latitudinal odds ratio is examined in Sect. 3.3.2. The Simpson’s paradox occurs when the sign of the conditional odds ratio is
 opposite to the marginal odds ratio (Agresti, 2002). Typically, this indicates that the relationship seen in the marginal odds ratio
 230 is an artefact of aggregating across the vertical velocity strata rather than a reflection of the underlying relationship between
 ISSRs and MOG turbulence. However, in this case, it is due to an aggregation over time which masks the seasonal dependence
 of the relationship.

3.2.2 Seasonality of MOG turbulence risk of ISSRs

The difference in the log odds ratio ($\log(\theta/\theta_{clim})$) has been used to ascertain the impact of season on the MOG turbulence risk
 235 of ISSRs. Figure 4 shows how the latitudinal log odds ratio changes relative to a climatological latitudinal odds ratio for the
 mid-latitudes (i.e., 25°N to 70°N and 25°S to 70°S) where a positive value indicates an increased odds of MOG turbulence
 relative to the climatological latitudinal marginal odds ratio, while a negative value indicates a decreased odds. When the
 climatological odds ratio is positive, it indicates that the odds of encountering MOG CAT is higher in an ISSR than not in
 an ISSR. Thus, when the difference in the log odds ratio with the climatological ratio is positive, it indicates that there is a
 240 strengthening in the relationship and a higher odds of MOG CAT relative to the climatological prevalence. Table 5 details all
 possible permutations for determining how the risk of MOG CAT changes based on a comparison of the odds ratios.

Figure 4 shows that overall, for all three diagnostics and vertical velocity cases, the winter hemisphere has an increased risk
 of MOG turbulence while the summer hemisphere has a decreased risk of MOG turbulence. In addition, the marginal case for
 all three diagnostics shows that in the absence of any stratification, an increased risk of turbulence is present during winter.
 245 When aggregated across all three diagnostics, there is a +33.3% mean percentage increase in the marginal odds of encountering
 MOG CAT when in an ISSR, where Brown2 has the largest increase of +39.9% and NCSU1 with smallest increase of +26.5%.
 For ease of comparison, Table 6 summarises the mean percentage changes.

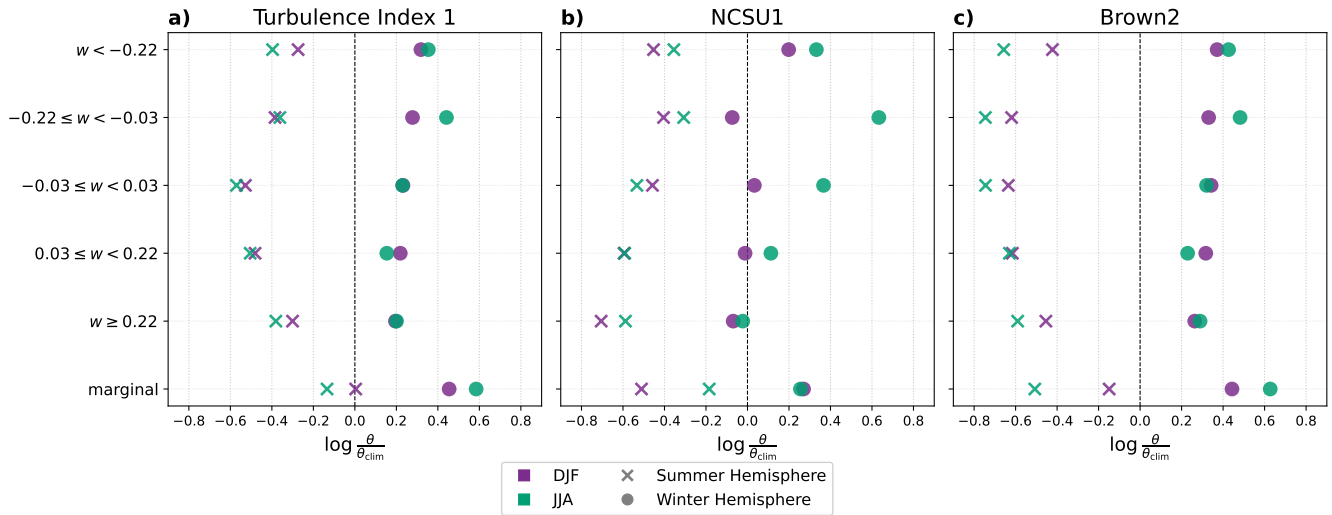


Figure 4. Mean of the latitudinal signed change in the log odds ratio (ϑ) for December, January, February (DJF) and June, July, August (JJA) over 2023 to 2025 in the mid-latitudes (i.e., $\pm 25^\circ$ to 70°) for Turbulence Index 1 (panel a), NCSU1 (panel b) and Brown2 (panel c). It is relative to the log latitudinal marginal odds ratio of the full study period of 2023 to 2025. A positive value indicates a strengthening of the association between ISSRs and MOG turbulence relative to the overall latitudinal marginal odds ratio, while a negative value indicates a weakening.

Table 5. Framework for comparing the log conditional odds ratio with the log marginal odds ratio. This framework is used to compare the log latitudinal odds ratio against the climatological log latitudinal odds ratio where θ_{ref} is the climatological log latitudinal odds. The log latitudinal conditional odds ratio, $\theta_{XY(k)}$, is compared against the log latitudinal marginal odds ratio θ_{XY} (i.e., θ_{ref}), when the framework is used to understand the effect of vertical velocity on the relationship between ISSRs and MOG turbulence, and to determine the impact of the condition on the odds of encountering MOG turbulence relative to the marginal case.

Sign of reference odds ratio	Odds ratio vs. reference	Effect on relationship	Relative odds of MOG turbulence to the reference case
Negative	$\theta > \theta_{\text{ref}}$	Weakens	Higher
	$\theta < \theta_{\text{ref}}$	Strengthens	Lower
Positive	$\theta < \theta_{\text{ref}}$	Weakens	Lower
	$\theta > \theta_{\text{ref}}$	Strengthens	Higher



With reference to Table 5, an increased risk of MOG turbulence is present when $\log(\theta/\theta_{\text{clim}}) > 0$. Thus, for Fig. 4 an increased risk of MOG turbulence in winter is present when the round markers lie in the positive portion of the x -axis. This can be seen for all cases for TI1 and Brown2 (Fig. 4(a,c)). For NCSU1 (Fig. 4(b)) in JJA, the risk of MOG turbulence is increased across all cases, with the strong updraft case being the exception, showing a near-zero change. During DJF, the change in MOG CAT risk shows a near-zero change for all cases except the marginal and strong updraft cases.

Table 6. Summary of the mean percentage change in the marginal odds of encountering MOG CAT in an ISSR the the Turbulence Index 1, NCSU1, Brown2 turbulence diagnostics, and the mean across the diagnostics.

Season	TI1	NCSU1	Brown2	Diagnostics Mean
Winter	33.6%	26.5%	39.9%	33.3%
Summer	−33.5%	−40.4%	−54.0%	−42.6%

Similarly, Fig. 4 shows a decreased risk of MOG turbulence in summer when all cross markers lie in the positive portion of the x -axis. This can be seen for all turbulence diagnostics and cases except the marginal case of TI1 (Fig. 4(a)) where the change is very close to zero. Overall, for the marginal case, there is a mean $−42.6\%$ in the odds of encountering MOG CAT when in an ISSR across the three diagnostics, where Brown2 has the largest decrease of $−54.0\%$ and TI1 with the smallest decrease of $−33.5\%$.

The seasonal patterns presented here are consistent with seasonal dependence of both ISSRs and MOG CAT (e.g., Gierens and Brinkop, 2012; Sharman et al., 2014). In particular, the aforementioned mid-latitudinal peak in MOG CAT during winter and a reduction in summer.

3.3 Identifying ice supersaturated regions related to turbulence

3.3.1 A case study along a flight route

The aggregation over time in Fig. 2 enables us to understand the climatological distribution of the relationship between ISSRs and MOG turbulence. However, aggregating diagnostics in this way risks obscuring the underlying drivers, as the relationship with ISSRs can greatly differ between individual diagnostics. By examining individual cases along a flight route, it becomes possible to identify the shapes and patterns of occurrence of these two regions, and what implications they could have for contrail avoidance. For this case study, we have selected the great circle route from John F. Kennedy International Airport (JFK) to London Heathrow Airport (LHR). Figure 5 shows the instantaneous vertical and horizontal cross-section along the route at the start of the six-hourly interval.

On average at cruise altitudes, ISSRs tend to be greater in horizontal extent than in vertical depth with a mean horizontal path length of 150 ± 250 km (Gierens and Spichtinger, 2000) and a vertical thickness of 0.56 ± 0.61 km (Spichtinger et al., 2003) with most being shallow (Kärcher, 2018; Rädcl and Shine, 2007). In the context of contrail avoidance, it allows vertical diversion strategies to be employed (Schumann et al., 2011; Teoh et al., 2020a, b; Mannstein et al., 2005; Avila et al., 2019).

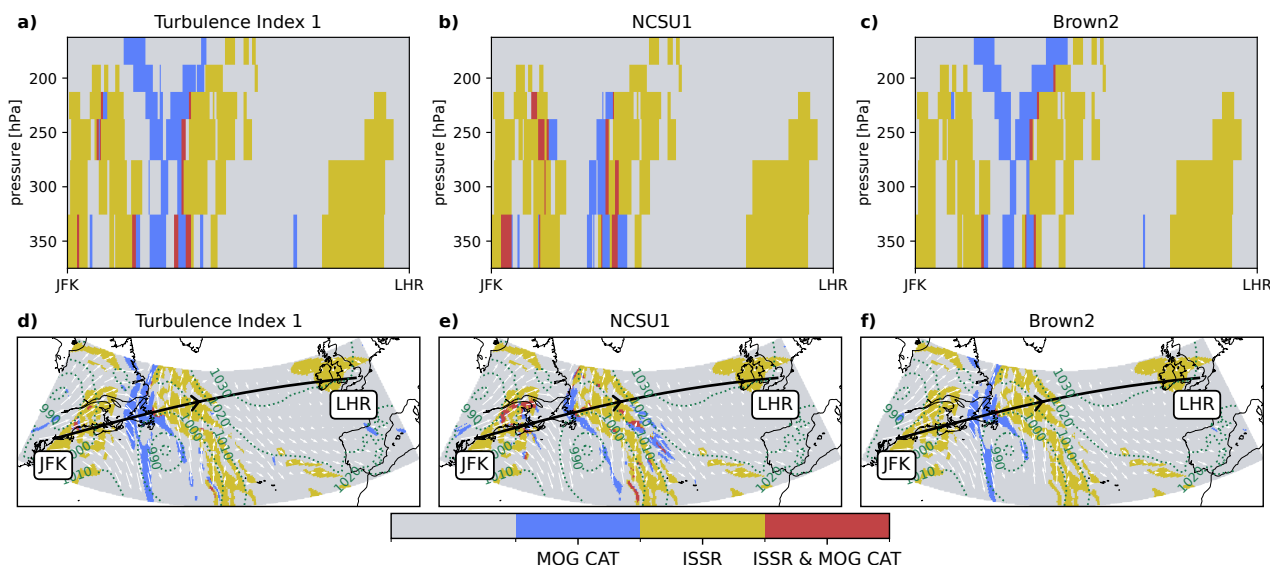


Figure 5. Cross-sectional views of moderate-or-greater turbulence, ISSRs and turbulent ISSRs for the CAT diagnostics, Turbulence Index 1, NCSU1, and Brown 2, along the great circle route from John F. Kennedy International Airport (JFK) to London Heathrow Airport (LHR) on the 29th December 2025 at 18:00. Panels (a-c) show the vertical cross-section of cruise altitudes along the route. Panels (d-f) show the horizontal cross-section at 250 hPa around the route. The solid black line indicates the great circle route between JFK and LHR, the vertical cross-section of which is shown in panels (a-c). The dotted green contours indicate the mean sea level pressure in hPa and the ERA5 wind direction and speed at 250 hPa are indicated by white arrows.

Thus, the vertical cross-section in Fig. 5(a-c) provides a first approximation of the potential trade-off between contrails and turbulence for climate optimised flight trajectories, and whether they present any identifiable structures. The horizontal cross-section at 250 hPa in Fig. 5(d-f) complements this by providing the mesoscale context for the vertical cross-section, showing the mean sea level pressure contours alongside the ERA5 wind speed and direction at 250 hPa.

An analysis of a broader set of cases consistently reveals that there appear to be two classes of ISSRs – those related to MOG turbulence, and those which are not. Figure 5 presents a representative example which shows both classes. Towards the end of the flight route, close to LHR, there is a large contiguous ISSR. TI1 and Brown2 (in Fig. 5(a) and (c) respectively) diagnose a small MOG turbulent region ahead of it at 350 hPa. Given how distant the ISSRs is from the MOG turbulence and the independence of the two regions, it suggests that this falls into the latter category of an ISSRs that is not related to MOG turbulence.

On the other hand, the ISSR approximately midway between JFK and LHR is related to MOG turbulence. All three diagnostics in Fig. 5(a-c) diagnose MOG turbulence ahead of the ISSR and intersects with the ISSR on all four of the pressure levels. The agreement on the presence of MOG turbulence across all three diagnostics is noteworthy, as they are not strongly correlated. TI1 and Brown2 have the greatest agreement with a Matthew's correlation coefficient of 0.51. This is reflected in the similarities in the MOG turbulence regions seen in both the horizontal and vertical cross-sections. On the other hand,



NCSU1 has a correlation coefficient of 0.16 and 0.11 with TI1 and Brown2 respectively. This is reflected in the difference
 290 in the morphology of the MOG turbulence region, where the TI1 and Brown2 have a v-shape between the two ISSRs while
 NCSU1 tends to be closer to and intersect with the ISSRs.

The agreement between the diagnostics is driven by the cold front from the low-pressure system (seen in the surface pressure
 contours of Fig. 5(d-f)) near to and south of the flight route, which is consistent with both the literature and their intended
 design. TI1's ability to identify the cold front is due to its definition as being the product of deformation and vertical wind
 295 shear (Ellrod and Knapp, 1992). Moreover, its effectiveness to forecast CAT at upper levels (Sharman and Pearson, 2017) has
 been attributed to its ability to capture turbulence generated by both fronts and jet streams (Knox et al., 2016). NCSU1 was
 designed to identify CAT due to the curved and accelerated flow of the jet stream (Kaplan et al., 2006). The wind velocity
 field in Fig. 5(e) shows that the low-pressure system has caused the air to curve and accelerate relative to the surrounding air.
 This is reflected in the diagnostic's identification of these regions as having MOG CAT. In addition, the sensitivity these flow
 300 characteristics can be seen in the other MOG turbulence regions in Fig. 5(e). Finally, Brown2 by Brown (1973) diagnoses CAT
 using a simplification of the Richardson tendency equation proposed by Roach (1970) to identify regions of instability, such as
 fronts.

The locality of the ISSR to the same low-pressure system suggests that it is due to the warm conveyor belt (Driver et al.,
 2025; Spichtinger et al., 2005b). Given that Lee and Sprenger (2025) has shown through automated in-flight observations that
 305 CAT tends to occur in the vicinity of the warm conveyor belt ascent, it lends further support to the notion that this ISSR is
 related to MOG turbulence and the potential for the existence of two classes of ISSRs.

3.3.2 Relating ice supersaturated regions and turbulence through vertical velocity

Whilst the case study in Sect. 3.3.1 suggests the potential existence of two classes of ISSRs, the extent to which this holds more
 generally remains to be established. In order to characterise this quantitatively, the conditional odds ratio has been presented in
 310 Fig. 6(a-c)(i-v) for each of the vertical velocity regimes (detailed in Sect. 3.2.1). In addition, Fig. 6(vi) in panels (a-c) contains
 the latitudinal marginal odds ratio (i.e. the odds ratios for the unstratified case which has been presented in Fig. 2) such that it
 can be compared against the conditional odds ratio. Since the analysis is comparative in nature, the discussion that follows is
 organised around each of the six cases rather than by panel. This comparison sheds light two aspects: i) the effect of vertical
 velocity on the relationship between ISSRs and MOG turbulence, and ii) how the odds of encountering MOG turbulence
 315 changes relative marginal case. Both of which are outlined in the framework presented in Table 5 and are discussed in the
 remainder of this section.

Overall, the latitudinal marginal odds ratio across all three turbulence diagnostics in Fig. 6 is broadly consistent with the
 patterns identified in the global distribution plots in Fig. 2. For TI1 in Fig. 6(a)(iv), the latitudinal marginal odds ratio shows a
 similar latitudinal pattern in Fig. 6 to the global distribution plots of Fig. 2, where the tropics exhibit a positive log odds ratio
 320 that weakens as pressure decreases from 300 hPa to 200 hPa. In the extratropics, the log odds ratio is negative, also becoming
 weaker and closer to zero at higher altitudes. At approximately $\pm 55^\circ$ latitude in both hemispheres at 200 hPa, the log odds ratio
 transitions from negative to positive. Similarly, the Brown2 diagnostic in Fig. 6(c)(iv) is consistent with the global distribution

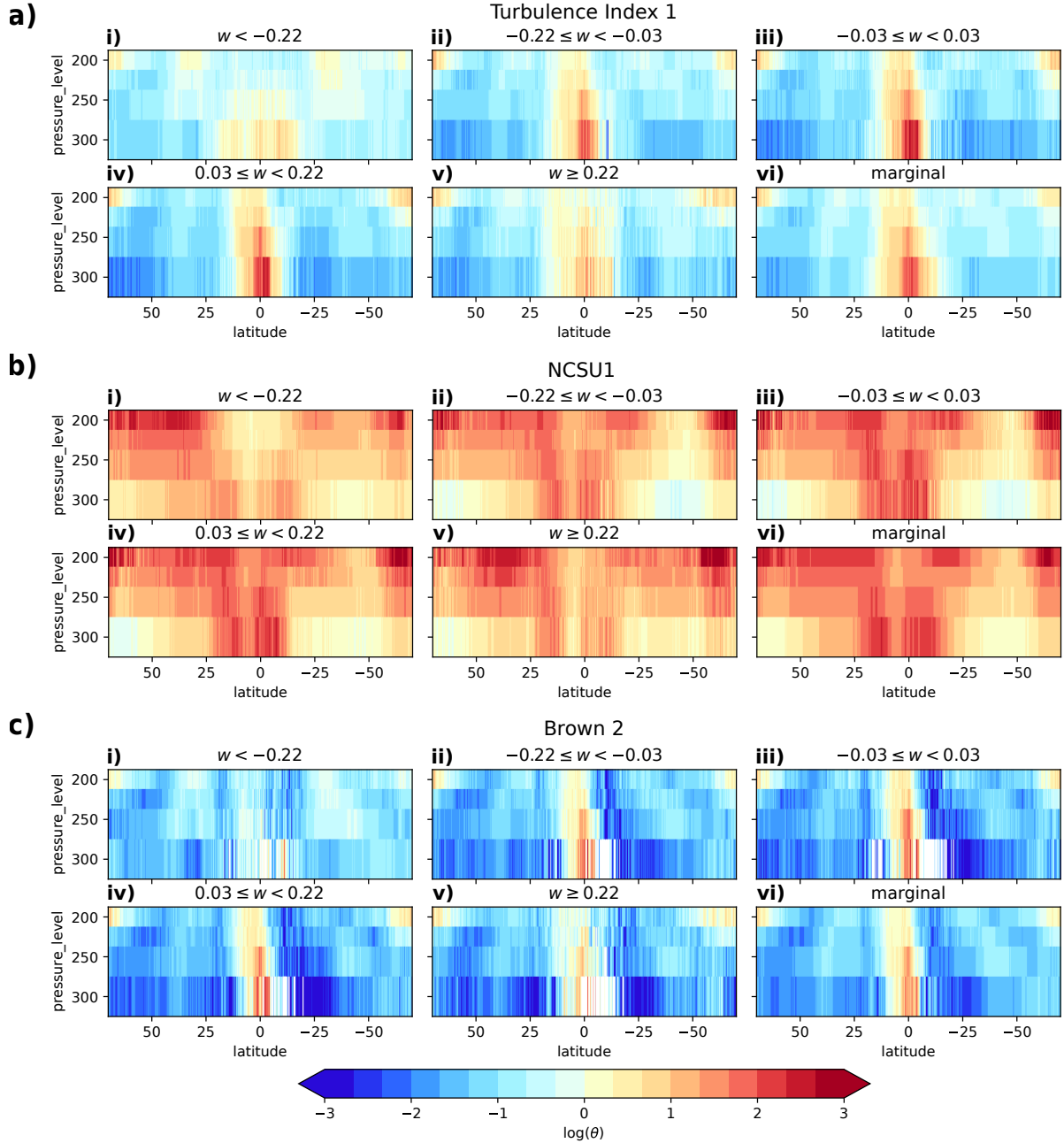


Figure 6. Logarithm of the latitudinal marginal odds ratio in panels (vi) and logarithm of the latitudinal conditional odds ratio for five categories of vertical velocity in panels (i-v): strong updraft ($w < -0.22 \text{ Pas}^{-1}$); weak updraft ($-0.22 \leq w < -0.03 \text{ Pas}^{-1}$); still air ($-0.03 \leq w < 0.03 \text{ Pas}^{-1}$); weak downdraft ($0.03 \leq w < 0.22 \text{ Pas}^{-1}$); and strong downdraft ($w \geq 0.22 \text{ Pas}^{-1}$). Each block of panels (i-vi) corresponds to a turbulence diagnostics (i.e., Turbulence Index 1, NCSU1, and Brown2 in blocks (a), (b), and (c) respectively) from 2023 to 2025.



in Fig. 2 and exhibits a largely similar pattern to TI1, with some notable differences in the tropics. Close to the equator, the marginal odds ratio is more weakly positive, and slightly further from the equator the values become largely negative. This is likely a consequence of the greater frequency of null turbulence forecasts in the tropics for Brown2 relative to TI1, where a zero marginal odds ratio arising when no turbulence is forecast at a given location and time. The transition from positive to negative associations moving from the tropics to the extratropics is still evident, though the positive association near the equator is considerably weaker than for TI1. At higher latitudes and pressure levels, Brown2 is consistent with TI1, with the exception that the majority of values exhibit a negative association rather than being weakly positive. Therefore, on average, for TI1 and Brown2, it is advantageous to avoid ISSRs close to the equator. However, as one moves away from the equator, this benefit diminishes with the potential for a trade-off between climate and safety benefits.

In the case of NCSU1 in Fig. 6(b)(iv), it is advantageous to avoid ISSRs across all latitudes as established by Fig. 2. Figure 6(b)(iv) shows that the tropical region has a more strongly negative log odds ratio at 300 hPa, which weakens as pressure decreases towards 200 hPa. At mid-latitudes, the inverse behaviour is observed, with a weaker relationship at lower pressure levels increases at higher pressure levels.

The first case to examine is the still air strata ($-0.03 \leq w < 0.03 \text{ Pas}^{-1}$). This case most closely approximates the conditional effect of ISSRs on MOG turbulence in the absence of large-scale air movements. In the tropics Fig. 6(a)(iii), TI1 has a conditional odds ratio that is more positive than the marginal case across all pressure levels. With reference to Table 5, this indicates a strengthening of the relationship and a higher risk of encountering MOG turbulence than the marginal case. In the extratropics from 300 hPa to 225 hPa, the conditional odds ratio becomes more negative. Thus, there is a similar strengthening of the relationship leading a lower risk of encountering MOG turbulence. At 200 hPa above approximately $\pm 60^\circ$, the odds ratio is positive. When compared with the marginal case, it is consistent with the rest of the extratropics showing a strengthening of the relationship. The Brown2 diagnostic in Fig. 6(c)(iii) exhibits a similar behaviour with an overall strengthening of the relationship between ISSRs and MOG turbulence. Close to the equator, both the conditional and marginal odds ratio are positive with the conditional odds ratio being more positive. Away from the equator the marginal odds ratio is mostly negative and the conditional odds ratio is largely more negative. Thus, for both TI1 and Brown2 in still air have an overall higher risk of encountering MOG turbulence close to the equator and a lower risk (-16.6% and -9.70% respectively) in the mid-latitudes.

For the same case, NCSU1 in Fig. 6(b)(iii) at the equatorial region has a conditional odds ratio that is more positive than the marginal odds ratio across all pressure levels. Therefore, there is a strengthening of the relationship and a higher risk than the marginal case of encountering MOG turbulence. In the mid-latitudes at 300 hPa, the weakly positive marginal odds ratio is contrasted against the weakly negative conditional odds ratio. This sign reversal is consistent with Simpson's Paradox (Agresti, 2002) which statistically suggests that the positive relationship seen in the marginal odds ratio is artefact of aggregating across the vertical velocity strata rather than a reflection of the underlying relationship between ISSRs and MOG turbulence. As discussed in Sect. 3.2.1, this is a statistical artefact due to the aggregating over time that obscures the seasonal variations and not due to the aggregating over the vertical velocity strata. Despite this, the mid-latitudinal conditional odds ratio shows a -28.2% risk of MOG turbulence in an ISSR.

Collectively, the three diagnostics agree that in still air, the risk of encountering MOG turbulence to the marginal case is higher in the tropics and lower in the extratropics. For reference, Table 7 provides a consolidated summary of the percentage change in the mid-latitudinal conditional odds ratio (i.e., above 25° and below 25°) and the mid-latitudinal marginal odds ratio. This shows how the relative risk of encountering MOG turbulence changes when ISSRs are stratified based on the vertical velocity, with respect to the marginal case.

Table 7. Summary of the percentage change in the mid-latitudinal conditional odds ratio relative to the mid-latitudinal marginal odds ratio, for each vertical velocity strata and turbulence diagnostic. In addition, the mean percentage change of the TI1, NCSU1 and Brown2 turbulence diagnostics has been included to provide a summary statistic. Here, the mid-latitudes has been defined as the region above 25°N and below 25°S . A positive value indicates a higher relative odds of encountering MOG turbulence within an ISSR compared to the marginal case, while a negative value indicates a lower relative odds.

Case	Name	TI1	NCSU1	Brown2	Mean of Diagnostics
$w \leq -0.22$	Strong updraft	23.4%	17.0%	16.7%	19.0%
$-0.22 \leq w < -0.03$	Weak updraft	-8.96%	-31.6%	-6.71%	-15.7%
$-0.03 \leq w < 0.03$	Still air	-16.6%	-28.2%	-9.70%	-18.2%
$0.03 \leq w < 0.22$	Weak downdraft	-19.0%	-15.3%	-12.3%	-15.6%
$w \geq 0.22$	Strong downdraft	-0.204%	6.51%	-5.55%	0.25%

The second and third cases – weak updraft ($-0.22 \leq w < -0.03 \text{ Pas}^{-1}$ in Fig. 6(a-c)(ii)) and weak downdraft ($0.03 \leq w < 0.22 \text{ Pas}^{-1}$ in Fig. 6(a-c)(iv)) – follow a similar pattern to the first (i.e. still air) case across all three turbulence diagnostics. On average, the diagnostics show that there is a -15.7% and -15.6% decreased risk of MOG CAT in the weak updraft and weak downdraft cases, respectively (Table 7). The sole exception to the identified pattern is in the equatorial region of the weak updraft case where TI1 and NCSU1 diverge from the still air case (in Fig. 6(a,c)(ii)). In this region, the conditional odds ratio for TI1 and NCSU1 (in Fig. 6(a)(ii) and Fig. 6(c)(ii) respectively) show a slight weakening of the relationship. Consequently, in the equatorial region, a weak updraft in the presence of an ISSR would decrease the risk of encountering MOG turbulence for the TI1 and NCSU1 diagnostics.

The fourth case is when there is a strong downdraft ($w \geq 0.22 \text{ Pas}^{-1}$ in Fig. 6(a-c)(v)). Here, the trends across the turbulence diagnostics becomes less consistent. Both TI1 and Brown2 (in Fig. 6(a)(v) and Fig. 6(c)(v) respectively) broadly show a weakening of the association in the tropics and a strengthening in the extratropics. Accordingly, there is a lower risk of encountering MOG turbulence relative to the marginal case in the mid-latitudes in a large downdraft for these two diagnostics, with a -0.204% decrease for TI1 and -5.55% decrease for Brown2 (Table 7).

For NCSU1 in Fig. 6(b)(v), there is consistent weakening of the relationship in the tropics between 25°N – 25°S . Thus, there is a lower risk of MOG turbulence in this region. Outside of this region, there is hemispherical difference. In the Southern Hemisphere from 25°S onwards, there is an overall strengthening of the relationship resulting in high relative risk of encounter-



ing MOG turbulence to the marginal case. In the Northern Hemisphere from 50°N onwards, there is agreement across pressure levels that the relationship weakens resulting in a lower relative risk of encountering MOG turbulence. Between 25°N-50°N, this applies equally at 300 hPa, whereas the opposite is true above 300 hPa. This hemispherical difference arises due to the seasonal dependence of the relationship between MOG CAT and ISSRs (established in Sect. 3.2). Consequently, NCSU1 shows an overall increased risk of +6.51% MOG CAT at the mid-latitudes as opposed to the decreased risk seen in TI1 and Brown2 (Table 7).

The final case to examine is the strong updraft strata (i.e. $w < -0.22 \text{ Pas}^{-1}$ in Fig. 6(a-c)(i)). For this strata, all three turbulence diagnostics agree on how the risk of encountering MOG turbulence changes relative to the marginal case. In the tropics, there is an overall lower risk while the mid-latitudes has an overall higher risk. When comparing the percentage change in mid-latitudinal odds ratios, TI1 had the largest increase (+23.5%), with NCSU1 and Brown2 showing similar increase of +17.0% and +16.7%. Given that ISSRs can either form from rising air (Gierens et al., 2012) or form through radiative cooling (Fusina et al., 2007; Fusina and Spichtinger, 2010), this result lends support to the notion that ISSRs fall into two classes: those with large updrafts, which are associated with an overall mean increase of +19.0% in turbulence risk, and all other cases (summarised in Table 7) are associated with a decrease.

For the strong updraft case, the tropics of TI1 in Fig. 6(a)(i) exhibits a conditional odds ratio is lower than the marginal case at 300 hPa and 250 hPa, indicating a weakening of the association between ISSRs and MOG turbulence under strong updrafts. This weakening intensifies with decreasing pressure, and at 225 hPa and 200 hPa the association reverses in sign. Similarly for Brown2 in Fig. 6(c)(i), the sign reversal is present close to the equator in the tropics. The conditional odds ratio of strong updraft case is largely negative while the marginal odds ratio is positive close to the equator and becomes negative as one moves away from it. Thus, this region for TI1 and Brown2 shows a Simpson's Paradox-like artefact, due to the opposing seasonal signals. For NCSU1 in Fig. 6(c)(i), a strong weakening of the association is observed across all pressure levels in the tropics, indicating a comparatively lower odds of encountering MOG turbulence within a large upward moving ISSR near the equator, but without the directional reversal seen in TI1 and Brown2.

At extratropical latitudes of the strong updraft case, both TI1 and Brown2 (in Fig. 6(a,c)(i) respectively) have a conditional odds ratio that is closer to zero than the marginal odds ratio across all pressure levels, indicating a weakening of the relationship. As a result, there is an increased relative risk of encountering MOG turbulence compared to the marginal case. For NCSU1 in Fig. 6(b)(i), the extratropical show a strengthening of the relationship, with the conditional odds ratio becoming more positive than the marginal case, further supporting an increased risk of encountering MOG turbulence in strong updrafts.

For each of the cases shown in Fig. 6, we have compared the conditional odds ratio against the marginal odds ratio to establish what the effect vertical velocity has on the relationship between ISSRs and MOG turbulence, and how the risk of encountering MOG turbulence changes relative marginal case. As shown in Table 7, agreement is observed across all cases and turbulence diagnostics in the mid-latitudes where the turbulence diagnostics are the most reliable. The sole exception arises in the strong downdraft case, where NCSU1 fails to display a consistent overall pattern, while the remaining diagnostics continue to show agreement.



4 Discussion

This analysis has mainly focussed on analysing the relationship between ISSRs and MOG turbulence in the mid-latitudes. The rationale for this is twofold. Firstly, this regions accounts for the majority of the flight traffic with 30°N and 60°N accounting
 415 for 69% of global emissions in 2006 (Wilkerson et al., 2010). Moreover, it covers the North Atlantic – one of the busiest flight corridors in the world – and in 2019 it accounted for 4.9% of the global distance travelled which had a contribution of 11% to the global annual energy forcing due to contrails (Teoh et al., 2024). In addition, this region has seen an increase in frequency and intensity of CAT due to climate change (Williams and Joshi, 2013; Tenenbaum et al., 2022; Smith et al., 2023).

Secondly, the diagnostics used in this study are primarily designed to detect CAT which is generally associated with upper
 420 level fronts and the jet stream where there is increased wind shear and instabilities (Sharman et al., 2012). For instance, the Brown2 diagnostics adopts an energetics approach towards identifying regions conducive for Kelvin-Helmholtz instabilities to identify CAT (Knox et al., 2016). Given that the Brown2 diagnostic is derived using the thermal wind relation and includes an absolute vorticity term (Brown, 1973), its performance is compromised in the tropics, where these underlying assumptions are less valid. This is particularly evident in the global odds ratio distribution Fig. 2 where parts of plots are white indicating that
 425 there is insufficient data to indicate whether a relationship exists. Similarly, the TI1 diagnostic adopts a kinematic approach towards forecasting CAT (Knox et al., 2016) and is derived from the Petterssen's frontogenesis function (Ellrod and Knapp, 1992). It has been found to be particularly effective at cruise altitudes and to capturing CAT generated due to the jet stream and fronts (Sharman and Pearson, 2017). Consequently, it is unsurprising that in Fig. 2 both TI1 and Brown2 rarely identify MOG CAT in the tropics leading to the log odds ratio to be undefined. This, therefore, suggests that their general applicability
 430 in regions with significant convective, such as the tropics, may be limited. In order to accurately characterise the relationship in this region, the analysis would need to be extended to convection induced turbulence in addition to CAT.

The case study presented in Sect. 3.3.1, while primarily motivating the investigation into the presence of two classes of ISSRs, also brought to light the adjacent nature of the ISSR and MOG CAT regions, and the relationship of both regions to the warm conveyor belt. The adjacency relevant to contrail avoidance decision making is not fully captured by the odds ratio,
 435 which is limited to point-to-point comparisons and cannot account for the surrounding spatial context. For the latter, Driver et al. (2025); Spichtinger et al. (2005b) established the relationship between ISSRs and the warm conveyor belt, whilst Lee and Sprenger (2025) independently identified a similar relationship between MOG turbulence and the warm conveyor belt. The fact that both relationships converged on the warm conveyor belt suggests that it may have represented a more appropriate choice. Nonetheless, the finding that mid-latitude ISSRs with a strong updraft are associated with an increased risk of MOG
 440 turbulence (Table 7) is consistent with the warm conveyor belt link between ISSRs and MOG CAT, lending further support to this relationship despite the use of vertical velocity as the stratifying variable. As such, the selection of vertical velocity has been a suitable starting point for establishing and unpicking the relationship between ISSRs and MOG turbulence.

In the context of contrail avoidance, this relationship between ISSRs and MOG turbulence highlights both the complexity of operationalising contrail avoidance and the potential to simultaneously reduce turbulence exposure, bringing widespread
 445 adoption a step closer. The sensitivity of the relationship's directionality to the CAT diagnostics is evident in Fig. 2. In it,



positive values indicate that avoiding ISSR are operationally advantageous as it would improve safety and mitigate contrail formation, while a negative value indicates a potential trade-off between safety and potential contrail formation. This highlights the importance of an accurate diagnosis of CAT – which remains a challenge due to its highly localised and transient nature (Sharman and Pearson, 2017) and the lack of a universally effective diagnostic (Knox et al., 2016) – and its comparison against observations. Relatedly, Fig. 3 and Fig. 4 also showed same directional sensitivity to seasons. This suggest that contrail avoidance strategies may require tailoring based on the season and may not be straightforward during inter-seasonal months.

Nevertheless, there is the potential to use the two classes of ISSRs and the aforementioned sensitivities to assists with the implementation of contrail avoidance. For example, forecasts of ISSRs with strong updrafts and turbulence are more likely to increase the risk MOG turbulence and contrail forming regions. By combining the information, it may reduce the uncertainty and aid with the climate-optimized flight trajectory optimisation.

The identification of these two classes of ISSRs has implications for understanding how each may respond to anthropogenic climate change. In the mid-latitudes, both ISSRs (Irvine and Shine, 2015) and MOG turbulence (e.g., Jaeger and Sprenger, 2007; Lee et al., 2023; Foudad et al., 2024; Kim et al., 2023) are expected to increase in frequency.

A key implication of the present study concerns how each of the two identified classes of ISSRs may respond to anthropogenic climate change. Although both ISSRs (Irvine and Shine, 2015) and MOG turbulence (e.g., Jaeger and Sprenger, 2007; Lee et al., 2023; Foudad et al., 2024; Kim et al., 2023) are expected to increase in frequency in the mid-latitudes, it remains unclear whether the two classes respond similarly or divergently, and whether the processes driving each are equally sensitive to a changing climate. Should the two classes respond differently, this would have important consequences for the future distribution and frequency of ISSRs and, by extension, for the viability of contrail avoidance strategies. This therefore represents an important avenue for future research, particularly in the context of long-term contrail avoidance planning under a changing climate.

5 Conclusions

The statistical relationship between ISSRs and MOG CAT has been characterised through the odds ratio to quantify the turbulence risk of ISSRs. When examining this relationship, two classes of ISSRs were identified – those linked to MOG CAT and those unrelated to it. Understanding this relationship and the classes of ISSRs is key to turbulence-aware contrail avoidance, which can balance climate benefits and turbulence risk.

The presence of a relationship between ISSRs and MOG turbulence was established using the TI1, NCSU1 and Brown2 CAT diagnostics in the global distribution of the odds ratio. Figure 2 demonstrated the sensitivity of the direction in the relationship to the CAT diagnostic, i.e. the CAT diagnostic affected whether the odds of MOG turbulence given an ISSR was greater than the odds of MOG turbulence given there is no ISSR.

In the context of contrail avoidance flight planning, instantaneous vertical and horizontal cross-sections along a flight route from JFK to LHR (Fig. 5) were examined to explore the implications of the established relationship, leading to the proposal



that there exists two classes of ISSRs. By stratifying the odds ratio based on the vertical velocity, we identified that in the mid-latitudes ISSRs with a strong updraft lead to a +19.0% risk of MOG CAT (Fig. 6 and Table 7).

480 The seasonal variations which are present in ISSRs and MOG turbulence is also observed in the relationship between them. In the mid-latitudes during DJF and JJA, Fig. 4 and Table 6 showed that, consistently across both the marginal and conditional odds ratios, the risk of MOG turbulence is higher in the winter hemisphere and lower in the summer hemisphere relative to climatological risk. Taking the marginal odds ratio, averaged across diagnostics, the mean percentage change is +33.3% in winter and -42.6% in summer. This is consistent with the increased prevalence of CAT during the winter months (e.g., Lee
485 et al., 2023; Sharman et al., 2014).

Ultimately, the findings of the present study lay the groundwork towards turbulence-aware contrail avoidance and understanding how the corresponding relationship between ISSRs and MOG CAT would respond under climate change. Moreover, it highlights the complexity of the relationship and the need for further investigation in how the two could be combined to help improve decision-making around contrail avoidance.

490 Realising the operational potential of this work will first require validation against a dataset which contains both in-situ turbulence measurements and reliable relative humidity measurements. This is a combination that is not yet available. This limits verification to MOG turbulence or ISSRs independently, rather than to the effect of ISSRs on MOG turbulence. The development of such a dataset, whether through dedicated research flights or the expansion of relative humidity reporting from commercial flights to include EDR measurements, represents the most critical next step toward operationalising turbulence-
495 aware contrail avoidance.

Code and data availability. This uses the Python library `rojak` v1.0.1. The scripts and steps required to reproduce the results in this paper can be found in this GitHub repository: <https://github.com/wong-hl/towards-safer-contrail-avoidance>. It is also available at <https://doi.org/10.5281/zenodo.22896976>. The ERA5 pressure level reanalysis was obtained from the Climate Data Store (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels>, last access: 5 January 2026)

500 *Author contributions.* All the authors contributed to designing the study. HLW performed the analysis and wrote the article. RP and EG provided comments and suggestions.

Competing interests. The authors declare that they have no conflict of interest.

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