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ANALYSIS OF FLIGHT CONTRAIL FORMATION IN THE BRAZILIAN AIRSPACE

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To my parents, for teaching me, since I was little, the gift of determination and perseverance and for always encouraging me to reach ever greater heights.

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Last but not least, I would like to emphasize my gratitude to my work partner and great friend, Guilherme Ernando. You have no idea how much I have learned from you, and I continue to learn lessons of inestimable value for life with you.

Words cannot fully describe everything we have been through in these very intense and challenging five years. Thank you all for the memories and the unwavering companionship.

"For myself, losing is not coming second.
It's getting out of the water knowing you could have done better."
— IAN THORPE

Resumo

O impacto ambiental da aviação estende-se além das emissões de dióxido de carbono (CO_2) provenientes da combustão de combustíveis e inclui significativos efeitos não-CO_2. Entre estes, a formação de trilhas de condensação e nuvens *cirrus*, impulsionada pela condensação de vapor d'água na exaustão de aeronaves em grandes altitudes, destaca-se como um dos principais contribuintes para o forçamento radiativo total da aviação, resultando em um efeito líquido de aquecimento no clima da Terra. Este estudo investiga o fenômeno das trilhas de condensação no espaço aéreo brasileiro e discute potenciais estratégias e desafios para a mitigação de seus impactos ambientais. Utilizando um ano de dados de trajetórias de voo e meteorológicos, conduzimos uma análise espaço-temporal da ocorrência de trilhas de condensação ao longo das principais rotas domésticas, fornecendo novas perspectivas sobre o desempenho ambiental do tráfego aéreo brasileiro. Constatamos que trilhas de condensação persistentes provavelmente se formaram em 17,5% dos voos analisados, surgindo em vastas áreas e inclusive em regiões de baixa latitude. Os resultados também destacam a forte variabilidade sazonal e o comportamento não linear dos impactos das trilhas. Com base nesta avaliação fundamentada em dados, propomos novos indicadores de desempenho para o monitoramento de trilhas de condensação e avaliamos a contribuição potencial de estratégias de prevenção (*avoidance*) para a mitigação de seu impacto ambiental. Em última análise, este trabalho contribui para uma melhor compreensão das emissões não-CO_2 no espaço aéreo doméstico e apoia esforços para aprimorar o desempenho ambiental global da aviação brasileira.

Abstract

Aviation's environmental impact extends beyond carbon dioxide (CO_2) emissions from fuel combustion and includes significant non-CO_2 effects. Among these, the formation of contrails and cirrus clouds driven by the condensation of water vapor in aircraft exhaust at high altitudes stands out as a major contributor to aviation's overall radiative forcing, leading to a net warming effect on the Earth's climate. This study investigates the contrail phenomenon within the Brazilian airspace and discusses potential strategies and challenges for mitigating its environmental impacts. Using one year of flight trajectory and meteorological data, we conduct a spatiotemporal analysis of contrail occurrence along major domestic routes, providing novel insights into the environmental performance of Brazilian air traffic. We find that persistent contrails likely formed for 17.5% of the analyzed flights, appearing across wide areas and even in low-latitude regions. The results also highlight the strong seasonal variability and non-linear behavior of contrail impacts. Based on this data-driven assessment of contrail formation, we propose new performance indicators for contrail monitoring and evaluate the potential contribution of contrail-avoidance strategies for environmental impact mitigation. Ultimately, this work contributes to a better understanding of non-CO_2 emissions in the domestic airspace and supports efforts to improve the overall environmental performance of Brazilian aviation.

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List of Abbreviations and Acronyms

ANAC	*Agência Nacional de Aviação Civil* (National Civil Aviation Agency)
ATC	Air Traffic Control
ATM	Air Traffic Management
CNG	Carbon Neutral Growth
CoCiP	Contrail Cirrus Prediction Model
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	ECMWF Reanalysis v5
FIR	Flight Information Region
FL	Flight Level
GANP	Global Air Navigation Plan
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IGRA	Integrated Global Radiosonde Archive
Intl.	International
IPCC	Intergovernmental Panel on Climate Change
ISSR	Ice Super Saturated Region
KPI	Key Perfomance Indicator
LTAG	Long-Term Aspirational Goal
OCC	Operational Control Center
PFPCZ	Percentage of Flights in Persistent Contrail Zones
RDPCZ	Relative Distance in Persistent Contrail Zones
SAC	Schmidt-Appleman Criterion
TDPCZ	Total Distance in Persistent Contrail Zones
UTC	Universal Time Coordinated

Contents

1 Introduction

Aviation plays a significant role in modern transportation, but its continued development requires careful management of its environmental impacts, particularly in the context of climate change. Global aviation is responsible for approximately 5% of net anthropogenic radiative forcing, a figure expected to rise with increasing global air traffic (LEE *et al.*, 2021). While most attention is typically directed toward CO_2 emissions, recent research has demonstrated that condensation trails (contrails), and especially contrail cirrus, play a significant role in short-term climate warming, with immediate effects that can exceed the long-term radiative impact of CO_2 (ROOSENBRAND; SUN; HOEKSTRA, 2023).

Contrails are formed when hot, moist exhaust gases and soot released from aircraft engines mix with cold ambient air, nucleating small droplets around the soot that condenses and freezes into ice crystals, provided that atmospheric conditions are favorable like in humid areas at high altitude for example. This process is thermodynamically described by the Schmidt–Appleman Criterion (SAC), which determines the potential for trail formation based on parameters such as ambient temperature, pressure, relative humidity, and aircraft propulsion efficiency (SCHUMANN, 2005). Figure 1.1 provides a schematic representation of the contrail formation process.

However, the formation of contrails alone does not account for their climatic relevance, the biggest concern lies in the potential persistence of these trails. When formed within Ice Super Saturated Regions (ISSRs), contrails can remain for extended periods and evolve into contrail cirrus which consists of high-altitude ice clouds that influence Earth's radiative balance as presented in Roosenbrand, Sun and Hoekstra (2023). During daylight hours, these clouds reflect solar radiation (a cooling effect), but they are more effective at trapping terrestrial infrared radiation throughout the day and night (a warming effect). The net impact of these processes is a positive radiative forcing, contributing to a net warming of the climate system.

Stuber *et al.* (2006) show that, despite being a minority (about 25% of flights over southeast England and roughly 40% of global flight distance), night operations dominate contrail radiative forcing, contributing up to 80% of the annual mean. Figure 1.1 presents an illustrative diagram of this effect.

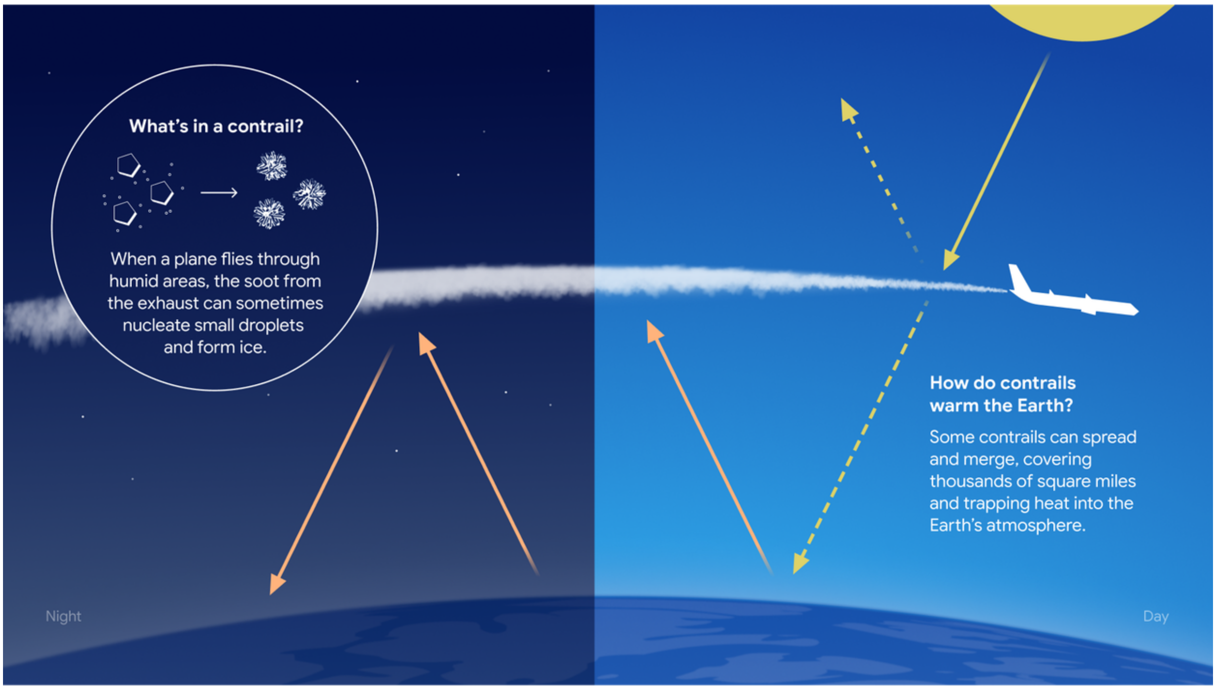


FIGURE 1.1 – Schematic representation of contrail formation and its impact on Earth's radiation balance (Source: Google (2025)).

For regulatory context, the International Civil Aviation Organization (ICAO) has articulated the ambition of Carbon Neutral Growth (CNG) from 2020 and, more recently, ICAO's Long-Term Aspirational Goal (LTAG) of net-zero CO_2 emissions by 2050. Together, these objectives define the sector's climate trajectory and provide the policy frame within which technical, operational, and fuel-switching measures are prioritized (International Civil Aviation Organization, 2022; International Council on Clean Transportation, 2023). In particular, ICAO emphasizes that the LTAG complements, rather than replaces, near and mid-term mechanisms designed to address net growth in emissions as air traffic expands.

The operationalization of CNG for international flights is primarily achieved through ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The architecture establishes a standardized monitoring, reporting, and verification (MRV) framework, coupled with the acquisition and cancellation of eligible units to offset emissions above the baseline. As detailed by the International Air Transport Association (2024), airlines remain responsible for robust MRV processes and for reconciling verified excess emissions via approved crediting programs during the scheme's compliance cycles.

In Brazil's context, the National Civil Aviation Agency (ANAC) transposed CORSIA's MRV and compliance obligations into the domestic legal framework via "*Resolução nº 743/2024*", aligning national implementation with ICAO guidance for international operations. The resolution specifies reporting thresholds, verification requirements, and administrative procedures applicable to operators on international segments, with entry into force synchronized to the initial years of the compliance phases. This ensures that carriers operating to and from Brazil meet consistent MRV standards and have clear accountability pathways throughout the CORSIA timeline (Agência Nacional de Aviação Civil, 2024).

CORSIA explicitly targets CO_2 emissions from international aviation and does not currently account for non-CO_2 climate effects (ÖKO-INSTITUT, 2022; Carbon Market Watch, 2024). This gap leaves room for complementary operational mitigation measures aimed at reducing the overall climate effects of flights. Significant prior research has examined the mechanisms behind persistent contrail formation such as Kärcher (2018) and Singh, Sanyal and Wuebbles (2024). More recent studies have leveraged the increasing availability of large-scale aircraft tracking data and meteorological data to quantify contrail formation potential while assessing the effectiveness of various mitigation strategies including Sun *et al.* (2024) and Roosenbrand, Sun and Hoekstra (2023). Among the most promising approaches are tactical altitude adjustments - small changes in flight level designed to avoid atmospheric layers conducive to persistent contrail formation, however, most existing studies focus primarily on the Northern Hemisphere. (SUN *et al.*, 2024).

This study aims to quantify and analyze the formation of condensation trails in the Brazilian airspace. We use historical flight trajectory data and meteorological information to perform a spatiotemporal analysis of condensation trail occurrence along major domestic flight routes, providing novel insights about the environmental impact of Brazilian air traffic. Beyond the characterization of historical contrail formation, this study also explores operational strategies for contrail avoidance, analyzing their potential contribution towards improving the environmental performance of air traffic. Finally, we suggest the creation of new Key Performance Indicators (KPIs) for contrail monitoring. Ultimately, the work aims to contribute to complement the CNG/CORSIA framework with evidence-based operational guidance regarding non-CO_2 aviation environmental impacts.

2 Literature Review

The scientific understanding of contrails and their consequent climatic impact has seen great progress over the past eight decades. Early investigations, prompted by observations during the era of piston-engine aviation, focused primarily on the thermodynamic mechanisms underlying the formation of these visible trails. The pioneering work of Schmidt (1941) laid the conceptual foundation by demonstrating that the mixing of hot, moist exhaust gases with cold ambient air could result in water vapor saturation, followed by condensation and freezing, ultimately producing contrails, generating an initial empirical understanding that emphasized the threshold atmospheric conditions necessary for the phenomenon to occur.

With the transition to jet propulsion in the post-war period, the need to refine and adapt these formation criteria to the specific characteristics of modern aircraft arose. In this context, Appleman (1953) developed a more robust graphical and quantitative methodology, explicitly incorporating variables such as ambient temperature, pressure, and relative humidity, as well as critical engine and aircraft parameters, including the heat-to-water vapor emission ratio and propulsive efficiency. These developments culminated in the cornerstone of the prediction of initial contrail formations, the Schmidt–Appleman Criterion (SAC), a fundamental diagnostic tool that establishes the critical atmospheric temperature below which contrail formation is thermodynamically possible for a given flight condition.

Figure 2.1 presents a schema for the process of microphysical formation and evolution of contrails: from exhaust aerosol emission and plume mixing/cooling to activation into droplets, wake vortex formation and freezing into ice crystals, culminating in crystal growth in the upper wake and sublimation in the lower wake.

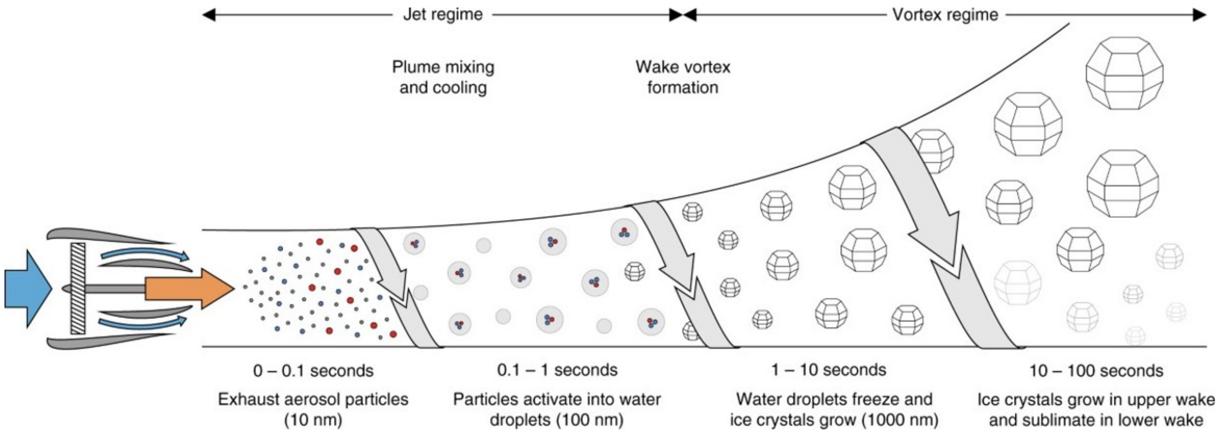


FIGURE 2.1 – Schematic representation of the specific processes and durations for each stage in the contrail formation cycle for jet aircraft (Source: Kärcher (2018)).

Subsequent research expanded beyond the initial formation stage, delving into the persistence and microphysical evolution of contrails, as well as their radiative impacts. Key contributions by Schumann (2005) established that the persistence of contrails, transforming them into aviation-induced cirrus clouds (contrail cirrus) with potential long-term climatic implications, depends fundamentally on the presence of Ice Super Saturated Regions (ISSRs) in the upper troposphere. Microphysical investigations revealed the critical role of soot particles emitted by engines as nucleation sites for condensation and freezing, affecting the initial size and number of ice crystals (KäRCHER, 2018). At the same time, the scientific community began to quantify the climatic effects of contrails, recognizing their influence on Earth's radiative balance—an aspect highlighted in global climate assessments such as the IPCC's special report on aviation and the global atmosphere by Intergovernmental Panel on Climate Change (1999) and subsequent reviews by Lee *et al.* (2021). These assessments confirm that the effective radiative forcing of contrail cirrus is the single largest non-CO_2 contribution from aviation to anthropogenic climate change, with potential for significant growth in the coming decades due to projected increases in air traffic (SINGH; SANYAL; WUEBBLES, 2024).

Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W/m^2) at the tropopause or top of atmosphere due to a change in an external driver of climate change such as a change in the concentration of greenhouse gases (e.g., carbon dioxide). Radiative forcing from human activity is commonly defined as the change relative to the reference year 1750 and, unless otherwise noted, refers to a global and annual average value and consists of a metric, and not something that is actually determined by direct measurements of the atmosphere. It is often used in simple climate models as a parameterization of the processes described in more detailed mechanistic models (ENTING, 2018).

However, accurate quantification of this radiative forcing and the evaluation of mitigation strategies are challenged by uncertainties in modeling contrail cirrus evolution, their interactions with natural clouds, and observational limitations in distinguishing them. To address these issues, recent research has increasingly relied on large-scale empirical analyses that combine detailed meteorological datasets with flight trajectory data, often from open-access sources.

Illustrating this approach, the studies by Sun *et al.* (2024) and Sun and Roosenbrand (2023) extensively use aircraft surveillance data from platforms such as the OpenSky Network, alongside meteorological inputs from radiosondes (Integrated Global Radiosonde Archive - IGRA) and reanalysis models (ECMWF Reanalysis v5 - ERA5), to investigate contrail occurrence and the viability of mitigation strategies—particularly vertical flight level adjustments. Sun and Roosenbrand (2023) focused on identifying persistent contrail formation by matching global OpenSky flights with high-vertical-resolution IGRA radiosonde stations. By analyzing flights intersecting conditions favorable to persistent contrail formation (satisfying both SAC and ISSR as shown in Figure 2.2), they evaluated the potential for mitigation via small altitude changes (around a 2,000 feet margin, corresponding to standard flight levels). Their findings suggest that such adjustments could prevent approximately half of persistent contrail-forming segments. Importantly, the study also initiated an assessment of trade-offs, estimating marginal increases in CO_2 emissions due to diversions and evaluating air traffic conflict risks, ultimately concluding that while promising, mitigation requires a careful cost-benefit analysis.

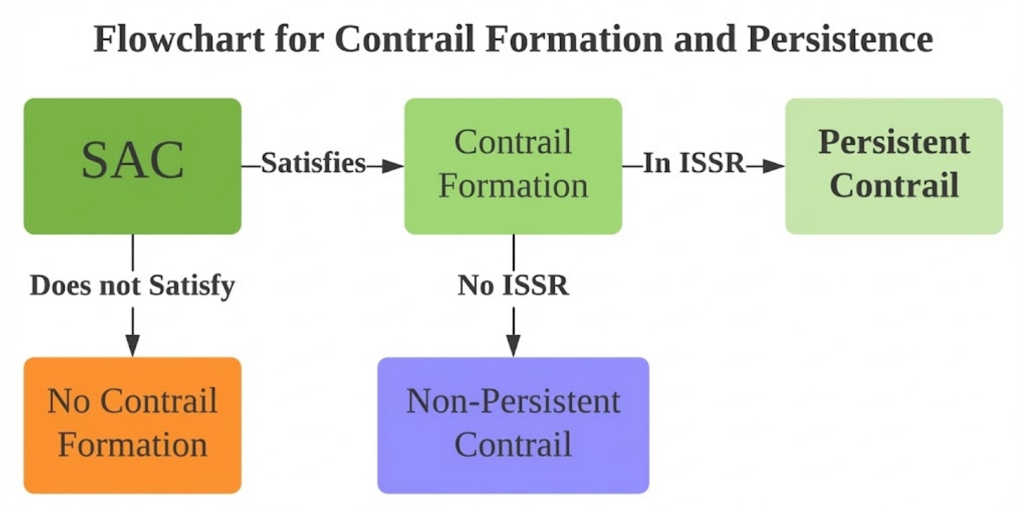


FIGURE 2.2 – An illustrative flowchart of the persistent contrail formation process (Source: Roosenbrand, Sun and Hoekstra (2022)).

Expanding both geographical scope and meteorological sources, Sun *et al.* (2024) conducted a global analysis using OpenSky flight data (including satellite-tracked routes over the Atlantic) for the year of 2022, combined with ERA5 reanalysis data. This study estimated that 5% to 9% of total monthly flight distance occurred under conditions favorable for persistent contrails (SAC + ISSR). Applying a basic altitude deviation algorithm to identify the minimum vertical shift required to exit these conditions, they estimated that approximately 70% of such contrails could be avoided. These results reinforce the global potential of altitude-based mitigation, even when using lower-vertical-resolution reanalysis data instead of radiosonde observations.

These recent empirical studies, based on open data and efficient computational tools, complement more complex modeling approaches by providing quantitative estimates of contrail formation prevalence and the practical potential of mitigation strategies such as altitude deviation. Nevertheless, they inherit limitations from their data sources (e.g., coverage, resolution, humidity uncertainty in reanalysis models) and from methodological simplifications (e.g., persistence thresholds, deviation algorithms), reinforcing the need for continued validation and region-specific research that integrates climatic and operational impact assessments. Overcoming these limitations and pursuing more accurate quantification of the contrail life cycle and their radiative forcing has motivated the development and application of more advanced modeling tools.

In this context, the combined use of satellite observations, airborne measurements, and radiative transfer models has, over recent decades, enabled major advances in quantifying contrail coverage and climate effects. The development of models like the Contrail Cirrus Prediction Model (CoCiP) discussed by Engberg *et al.* (2024) and previously introduced by Schumann (2012) marked a qualitative leap from empirical frameworks. These models allow for detailed simulation of contrail formation, dispersion, and radiative effects by coupling meteorological reanalysis data (e.g., ERA5) with high-resolution aircraft trajectory information. Such tools provide the foundation for the design of climate-conscious air traffic management strategies.

Despite these advances, most contrail-related research has remained focused on the Northern Hemisphere, particularly over North America and Europe, where air traffic density and observational infrastructure are more robust. Consequently, there remains a significant knowledge gap regarding contrail dynamics and climate impacts over less observed regions such as South America.

This study seeks to contribute toward filling this gap by applying SAC and ISSR identification frameworks, along with CoCiP-style modeling approaches, to Brazilian airspace. It further aims to evaluate the feasibility and potential of altitude-based mitigation strategies, previously tested in American and European contexts, within the distinct meteorological and operational landscape of Brazil. The analysis will center on contrail formation and persistence, the evaluation of modeling tools and datasets used for forecasting and simulation, and the status of operational mitigation strategies, with the goal of identifying critical research gaps and enabling the extension of these methods to new geographic contexts.

3 Methodology

The methodological approach for flight contrail estimation in the Brazilian airspace is based on the integration of flight tracking data, meteorological data and physical models of contrail formation. Initially, historical datasets of flight tracks and meteorological reanalysis are acquired and preprocessed. This includes filtering cruise-level flight segments and interpolating meteorological variables onto four-dimensional trajectory points. The subsequent modeling phase applies the Schmidt-Appleman Criterion (SAC) and Ice Super Saturated Region (ISSR) detection to identify flight segments conducive to the formation and persistence of contrails. Key Performance Indicators (KPIs) are proposed and applied to quantify the extent of the persistent contrail formation. The results are then aggregated to support a space-time analysis of persistent contrail occurrence, followed by geospatial visualization and physical consistency evaluation through comparisons with both meteorological expectations and findings from the literature. Finally, the spatiotemporal characterization of contrail formation is leveraged to evaluate operational strategies for contrail avoidance and environmental impact mitigation. The data sources, models and tools used in each of these methodological steps are detailed in the following sections.

3.1 Data Sources

3.1.1 Flight Tracking Data

Historical flight tracking data is sourced from Flightradar24, providing four-dimensional flight positions (latitude, longitude, altitude, and timestamp). The data cover one year of flight operations during 2023. Table 3.1 shows the main variables present in the dataset.

TABLE 3.1 – Description of the variables present in the flight tracking dataset.

Variable (abbreviation)	Description
indicat	Unique indicator of each trajectory
time	UTC time of observation
lat	Latitude
long	Longitude
alt	Altitude (ft)
speed	Speed (kt)
equip	Aircraft type
reg	Aircraft registration
plan_dep	Origin airport (planned)
plan_arr	Destination airport (planned)
real_arr	Destination airport (real)
id_icao	Callsign (ICAO format)
id_iata	Callsign (IATA format)

3.1.2 Meteorological Data

The meteorological data is sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF). We use the ERA5 reanalysis data as the atmospheric backbone for diagnosing contrail formation. ERA5 provides hourly global fields on a 0.25° × 0.25° latitude–longitude grid and pressure levels spanning the troposphere and lower stratosphere (e.g., 1000–100 hPa) as the example shown in Figure 3.1.

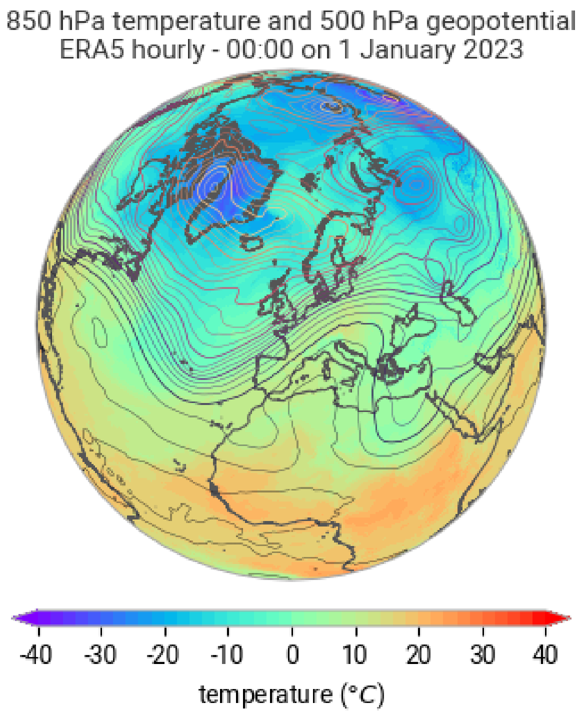


FIGURE 3.1 – Visualization of the spatial distribution of air temperature and geopotential height for an example date/hour based on data derived from the ECMWF ERA5 hourly reanalysis on pressure levels.

The ERA5 subset is extracted over Brazil's Flight Information Regions (FIRs), restricted to months in 2023. The variables ingested in this study are temperature (T), pressure (p) (or pressure level), and relative humidity (RH). These variables are sufficient to evaluate the thermodynamic conditions for contrail formation and persistence based on the physical models applied in this study.

Because contrails form near typical jet cruise altitudes, we focus on the 300–200 hPa layer ($\approx$ 8–13 km), while allowing the interpolation to use the bracketing pressure levels that encompass each trajectory point's pressure/altitude. Each flight trajectory sample is matched to ERA5 in four dimensions for 4D collocation and interpolation:

- **Horizontal (lon–lat):** bilinear interpolation among the four surrounding grid nodes;
- **Vertical (pressure):** linear interpolation between the two adjacent pressure levels;
- **Temporal (hourly):** linear interpolation between bracketing hourly analyses.

This produces collocated $T(\lambda,\phi,p,t)$ and $RH(\lambda,\phi,p,t)$ estimates at the aircraft point. From T and RH we compute relative humidity with respect to ice, RH_{ice}, via standard saturation formulations, and then evaluate ISSR whenever $RH_{ice} > 100\%$.

While ERA5 is state-of-the-art for global reanalysis, there are considerations to be made about uncertainties relative to the data. Contrail diagnostics are sensitive to vertical humidity structure. The spacing of pressure levels and the smoothing inherent to data assimilation can blur thin ISSR layers, introducing biases in RH_{ice} and layer thickness. Temporal sampling at 1 h also means rapidly evolving features may be under-resolved.

3.2 Data Preprocessing

The preprocessing stage involves filtering trajectories to isolate cruise-phase segments (typically above 20,000 ft), and interpolating meteorological fields (T, p, RH) to each trajectory point. One intrinsic challenge to these large-scale assessments is the computational intensity required to integrate massive flight trajectory datasets with four-dimensional meteorological fields. Sun and Roosenbrand (2023) addressed this bottleneck by developing FastMeteo, a Python library optimized to efficiently extract cloud-based ERA5 data in Zarr format. This tool implements a fast interpolation architecture, applied in this work as a client-server with local caching, to extract temperature, humidity, and wind profiles along flight paths. Figure 3.2 illustrates the architecture of the FastMeteo library.

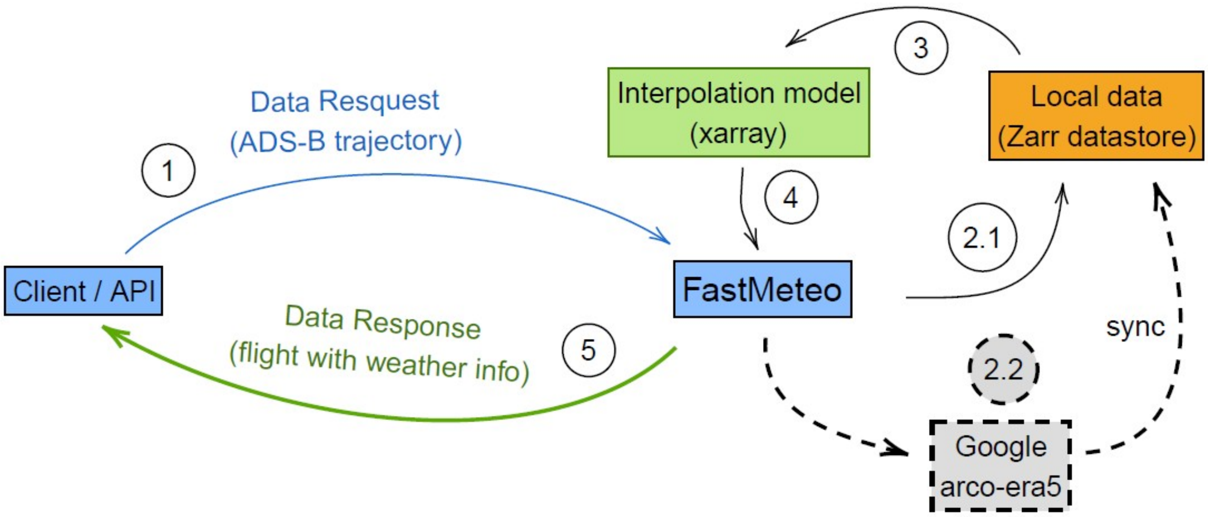


FIGURE 3.2 – Illustrative schema of the architecture of the FastMeteo library (Source: Sun and Roosenbrand (2023)).

3.3 Physical Modeling of Contrail Formation

To detect potential contrail formation, the Schmidt–Appleman Criterion (SAC) is applied. This criterion determines whether ambient thermodynamic conditions support contrail formation by comparing the actual atmospheric temperature T to a threshold critical temperature T_{LC}. This threshold is derived from engine and exhaust properties and atmospheric pressure p, as defined by:

$$G = \frac{EI_{H_2O} \cdot c_p \cdot p}{\varepsilon \cdot Q \cdot (1-\eta)} \tag{3.1}$$

Where:

- EI_{H_2O}: water vapor emission index
- c_p: specific heat at constant pressure
- p: atmospheric pressure
- ε: ratio of molar masses (water/air)
- Q: heating value of the fuel
- η: propulsion efficiency (assumed 0.4)

The critical temperature T_{LC} is derived through:

$$T_{LC} = -46.46 + 9.43 \ln(G - 0.053) + 0.720[\ln(G - 0.053)]^2 \tag{3.2}$$

If $T < T_{LC}$, the conditions are suitable for contrail initiation.

To assess persistence, the Ice Super Saturated Region (ISSR) condition is checked, requiring that the relative humidity with respect to ice (RH_i) exceed 100%:

$$RH_i = RH_w \cdot \frac{e_w(T)}{e_{ice}(T)} \tag{3.3}$$

Where RH_w is the relative humidity with respect to liquid water.

Condensation conditions are evaluated using vapor pressure over liquid (e_{liq}) and over ice (e_{ice}), respectively:

$$\begin{aligned} \ln(e_{liq}) = 54.842763 - \frac{6763.22}{T} - 4.210 \ln(T) + 0.000367T \\ + \tanh(0.0415(T - 218.8)) \cdot \\ \left(53.878 - \frac{1331.22}{T} - 9.44523 \ln(T) + 0.014025T\right) \end{aligned} \tag{3.4}$$

$$\log_{10}(e_{ice}) = 9.550426 - \frac{5723.265}{T} + 3.53068 \ln(T) - 0.00728332T \tag{3.5}$$

Flight segments satisfying both $T < T_{LC}$ and $RH_i > 1$ are classified as candidates for persistent contrail formation, as shown in Figure 3.3.

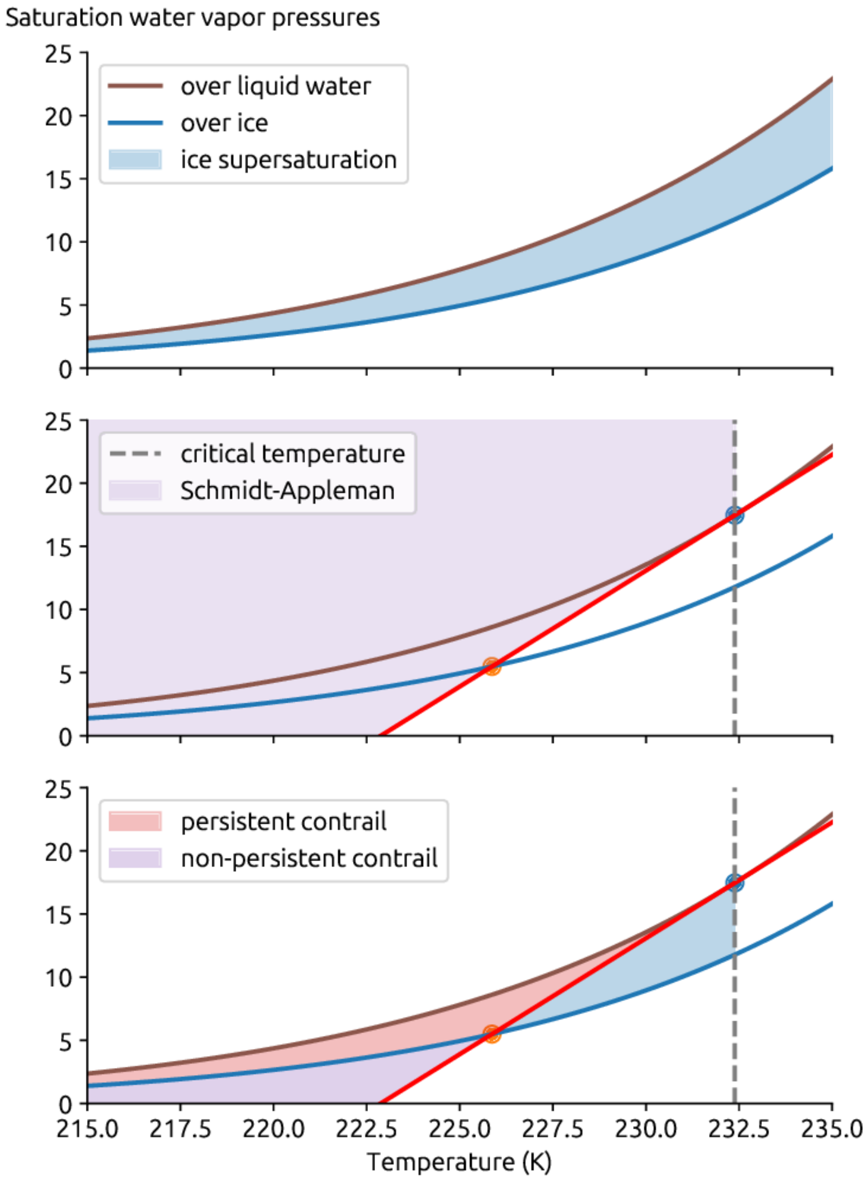


FIGURE 3.3 – Contrail forming criteria including the determination of SAC thresholds and ISSR conditions at an example given pressure condition (Source: Sun *et al.* (2024)).

3.4 Contrail Impact Quantification

Effective management of aviation's climate impact requires objective, quantifiable metrics. Inspired by the Key Performance Indicator (KPI) framework used in global monitoring platforms such as ICAO's Global Air Navigation (GANP) Portal, this work proposes three primary indicators to quantify the exposure of flight operations to conditions conducive to persistent contrail formation.

3.4.1 Relative Distance in Persistent Contrail Zones (RDPCZ)

$$\text{RDCPZ} = \frac{d_{\text{persist. contrail}}}{d_{\text{total}}} \times 100 \tag{3.6}$$

Definition: The fraction of flight distance traversed under persistent contrail conditions (i.e., satisfying both SAC and ISSR criteria) with continuous windows longer than 2 minutes.
Unit: Dimensionless (%).
Measurement: Sum of trajectory arcs labeled as persistent, divided by the total flight distance.
Scope: Per flight or aggregated by route or airspace volume on a daily, monthly or annual basis.
Remarks: This metric is specifically designed to quantify the operationally and climatically relevant phenomenon. The application of the two-minute temporal filter is a methodologically sound approach to isolate segments with a high probability of evolving into persistent contrail cirrus, thereby filtering out isolated or short-lived events whose radiative forcing is likely marginal.

3.4.2 Total Distance in Persistent Contrail Zones (TDPCZ)

$$\text{TDPCZ} = \sum_{\text{flights } f} \sum_{\text{segments } s \in f} d_s \quad \text{with} \quad s \in \{\text{SAC} \cap \text{ISSR}, \text{ window} > 2 \text{ min}\}. \tag{3.7}$$

Definition: Total distance flown under persistent contrail conditions.

Unit: Nautical miles (NM).

Measurement: Sum the lengths of all trajectory arcs labeled as persistent (same SAC+ISSR mask with the ≥ 2 min filter)

Scope: Per flight or aggregated by route or airspace volume on a daily, monthly or annual basis.

Remarks: TDPCZ expresses the absolute scale of persistent contrail generation and helps identify routes/hubs with the largest total contribution. It complements RDPCZ (relative exposure) by providing an aggregate volume metric useful for annual/monthly rankings and prioritization.

3.4.3 Percentage of Flights in Persistent Contrail Zones (PFPCZ)

$$\text{PFPCZ} = \frac{\#[\text{flights with persistent contrails}]}{\#[\text{total flights}]} \tag{3.8}$$

Definition: Share of flights that experienced at least one operationally relevant persistent-contrail event. A flight is marked as persistent if any of its segments simultaneously satisfies SAC and ISSR for a continuous window longer than 2 minutes.

Unit: Percentage (%).

Measurement: For each flight, assign a binary flag (1 if any qualifying event is present; 0 otherwise).

Scope: Aggregated by route or airspace volume on a daily, monthly or annual basis.

Remarks: PFPCZ complements RDPCZ (relative distance) and TDPCZ (total distance) by quantifying incidence per flight, being robust to few extreme events.

3.5 Analysis Approach

The analysis of contrail formation and mitigation potential was structured along two distinct fronts, a necessary approach to balance the need for robust climatological insight with the computational feasibility of simulating counterfactual mitigation scenarios:

1. The first analysis front comprises a spatiotemporal evaluation of contrail formation for the five busiest domestic routes in 2023. This phase focuses on identifying and quantifying the occurrence of persistent contrail-favorable conditions, defined through the combined SAC and ISSR threshold, as well as characterizing seasonal trends and computing proposed quantitative indicators;

2. The second part is dedicated to assessing the potential impact of contrail mitigation strategies. This component is applied exclusively to selected flights from isolated case-study days, prioritizing trajectories with high values of the contrail impact indicator (i.e., those with substantial fractions of flight distance within persistent-contrail-prone airspace).

This methodological design is primarily dictated by computational limitations: the volume of reanalysis meteorological data (ERA5) required for full four-dimensional interpolation is exceptionally large: one month of data, retrieved via the *FastMeteo* library, typically amounts to approximately 170 GB. Extending counterfactual mitigation simulations to cover a full year would require the download and storage of roughly 2 TB of data, in addition to processing times that exceed the feasible scope of this project.

Accordingly, the adopted strategy involves selecting candidate routes from the isolated-day samples that exhibit elevated contrail formation potential, thereby enabling a targeted proof-of-concept for mitigation without compromising project execution.

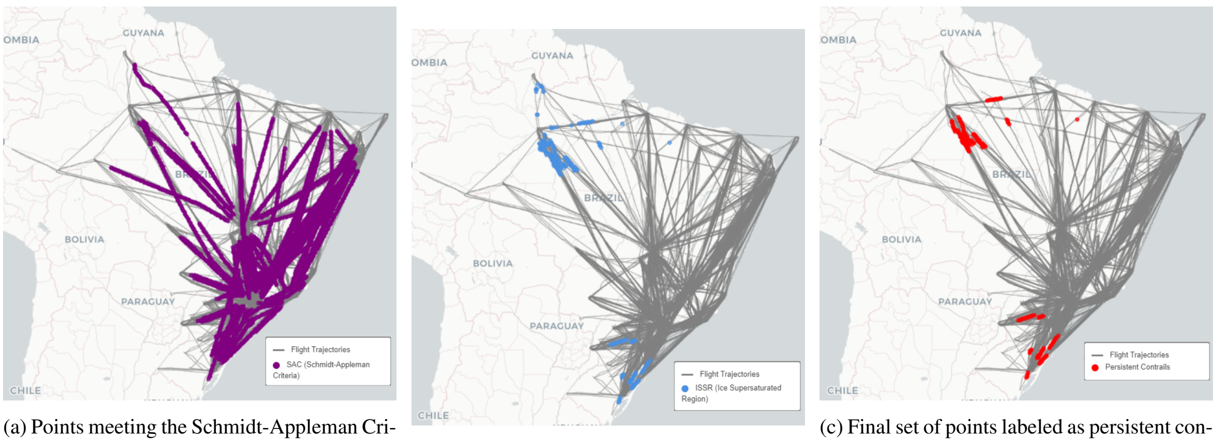
Additionally, to mitigate noise arising from potential trajectory data inaccuracies and to focus solely on events of operational and climatic relevance, a temporal filter was applied to the analysis results. Only flight segments that simultaneously satisfy SAC and ISSR conditions for a continuous period exceeding two minutes were classified as zones with a non-negligible probability of persistent-contrail formation. This threshold ensures that the analysis concentrates on trails with potential to evolve into persistent cirrus, while disregarding isolated or short-lived events whose radiative forcing is likely marginal.

4 Results and Discussion

This chapter presents the results of the spatiotemporal analysis of contrail formation in the Brazilian airspace and discusses the potential impacts and implementation challenges of operational mitigation strategies.

4.1 National-Scale Visualization of Flight Contrails in Brazil

First, we selected two days from our dataset to provide a visualization of the contrail estimation results for the entire domestic airspace. Figures 4.1 and Figure 4.2 show the actual trajectories flown by commercial flights in the Brazilian airspace on August 1st, 2023 and February 1st, 2023, respectively. Trajectory segments that likely formed persistent contrails according to the physical criteria applied in this work are highlighted in red. The results challenge the assumption that contrail formation is an issue confined to traditionally colder, temperate regions, such as the South and Southeast of Brazil. On the contrary, favorable conditions (SAC + ISSR) arise at multiple altitudes and latitudes, spanning the national airspace more widely than might be initially assumed.

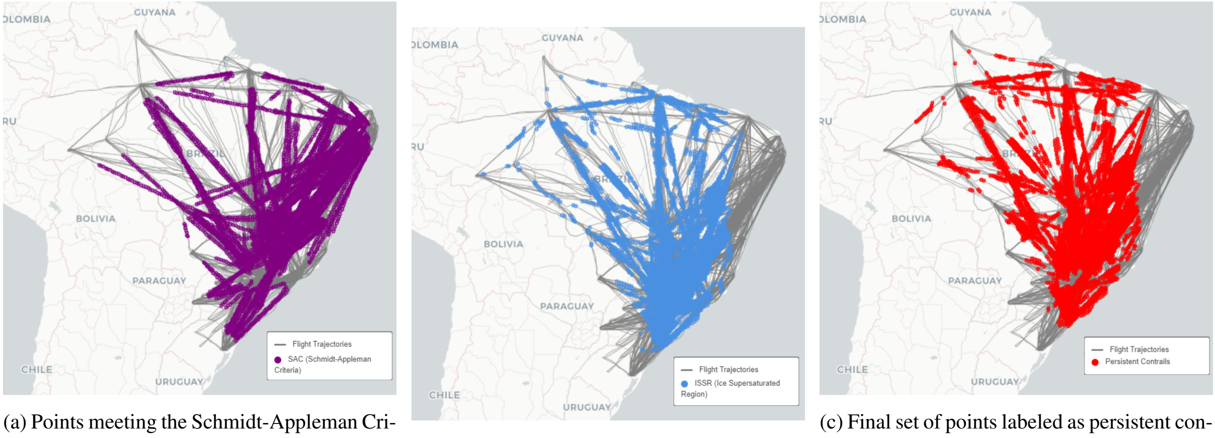


(a) Points meeting the Schmidt-Appleman Criterion.

(b) Points in Ice Super Saturated Regions.

(c) Final set of points labeled as persistent contrails.

FIGURE 4.1 – Spatial distribution of flight contrail formation and persistence in the Brazilian airspace on August 1st, 2023.



(a) Points meeting the Schmidt-Appleman Criterion. (b) Points in Ice Super Saturated Regions. (c) Final set of points labeled as persistent contrails.

FIGURE 4.2 – Spatial distribution of flight contrail formation and persistence in the Brazilian airspace on February 1st, 2023.

Figures 4.1a and 4.2a confirm that SAC is met almost ubiquitously across the Brazilian territory at typical cruise altitudes. This is physically expected, as the 8-13 km altitude band where jet aircraft operate is consistently cold enough (typically below -40°C or 233 K) to meet the thermodynamic threshold for contrail formation.

The more critical and limiting factor is the presence of ISSRs, shown in Figures 4.1b and 4.2b. The distribution of ISSRs is far more heterogeneous and sporadic, appearing as transient patches and layers in the upper troposphere. These regions are the key determinants for contrail persistence.

Figures 4.1c and 4.2c depict the final set of points labeled as persistent contrails, representing the intersection of actual flight trajectories with regions satisfying both SAC and ISSR conditions. The distribution exhibits higher-frequency peaks over denser traffic corridors (e.g., the Rio–São Paulo axis, and routes converging on Brasília), which is an expected consequence of greater flight volume in these areas. However, the phenomenon is demonstrably evident in trajectories across the North and Northeast, including over tropical regions. The presence of persistent contrail segments near major hubs like Manaus and Recife confirms that high humidity and very low temperatures at cruise altitudes can create an environment favorable to contrail-cirrus formation, regardless of latitude. This distribution suggests that contrail formation is a national challenge, not merely a regional one, and any potential mitigation policy must account for the entire national airspace.

4.2 Case Study: Top-5 Busiest Domestic Routes

We conducted a detailed spatiotemporal analysis of persistent contrail formation for the top-5 domestic routes (one way) in 2023 using the KPIs proposed in section 3.4. The selected routes are listed in Table 4.1.

TABLE 4.1 – Selected routes.

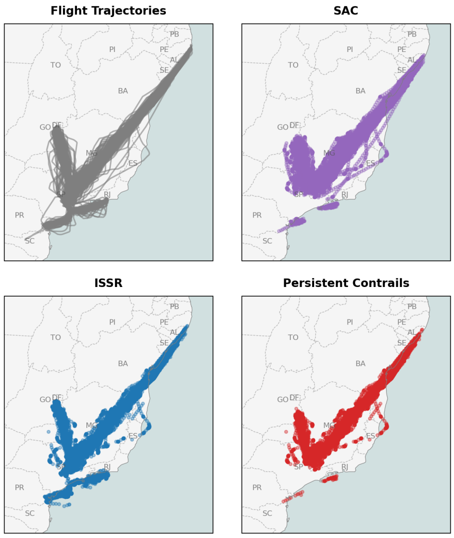
Origin Airport	**Destination Airport**
Sao Paulo/Congonhas Airport (SBSP)	Rio de Janeiro/Santos Dumont Airport (SBRJ)
Brasilia/Presidente Juscelino Kubitschek Intl. Airport (SBBR)	Sao Paulo/Congonhas Airport (SBSP)
Belo Horizonte/Confins Intl. Airport (SBCF)	Sao Paulo/Congonhas Airport (SBSP)
Curitiba/Afonso Pena Intl. Airport (SBCT)	Sao Paulo/Congonhas Airport (SBSP)
Recife/Guararapes Intl. Airport (SBRF)	Sao Paulo/Guarulhos Intl. Airport (SBGR)

The calculated contrail KPIs for each month of 2023 are presented in a series of detailed visualizations: a general visualization panel (Figure 4.3), a density map (Figure 4.4), and monthly indicator tables (Tables A.1-A.12). For a synthesis of the global performance of these routes, the aggregated values of the KPIs for the year 2023 are presented in Table 4.2.

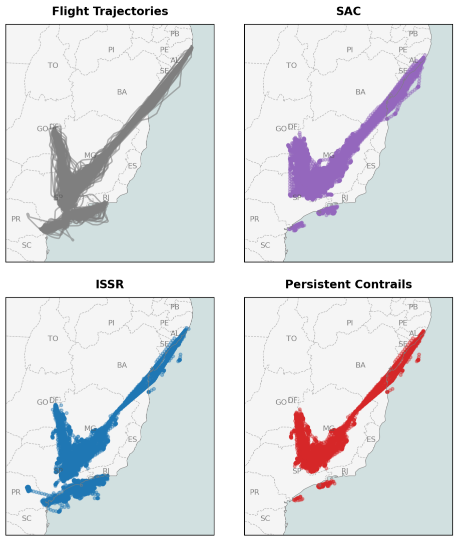
TABLE 4.2 – Calculated contrail KPIs by route for 2023.

Route	**RDPCZ (%)**	**TDPCZ (NM)**	**PFPCZ (%)**	**Min. Monthly RDPCZ (%)**	**Max. Monthly RDPCZ (%)**
SBBR–SBSP	20.4	352,075.9	50.0	13.6 (Sep)	23.8 (Jan/Aug)
SBCF–SBSP	17.1	104,844.4	37.8	11.0 (Dec)	22.5 (Jul)
SBCT–SBSP	16.4	2,320.0	22.3	0.0 (Feb/Nov)	24.0 (May)
SBRF–SBGR	14.2	478,050.3	0.9	7.8 (Sep)	18.2 (Feb)
SBRJ–SBSP	15.1	5,668.6	0.8	0.0 (Dec)	22.9 (Oct)
Global	16.4	942,959.3	17.5	-	-

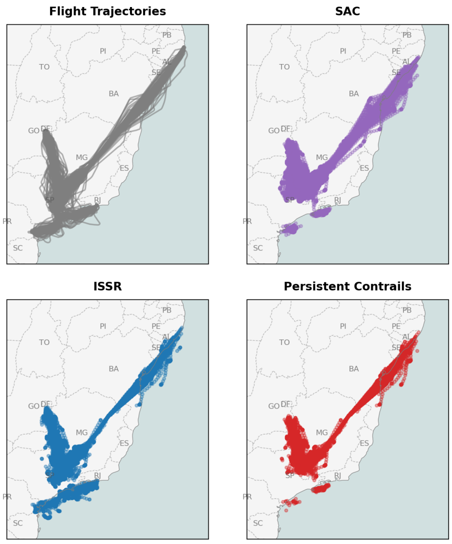
The results shown in Table 4.2 reveal several critical findings. First, routes terminating in Brazil's busiest airports (SBSP/SBGR) are relevant contrail generators. The SBBR-SBSP route, in particular, stands out, with more than 20% of its entire annual distance flown in persistent contrail conditions. Both SBBR-SBSP and SBCF-SBSP recorded significant contrail formation in every single month of the year. Second, we observe the occurrence of 0.0% RDCPZ values for the two shortest routes, SBCT-SBSP (in February and November) and SBRJ-SBSP (in December). This observation sparked a specific investigation, as detailed in the following subsection.



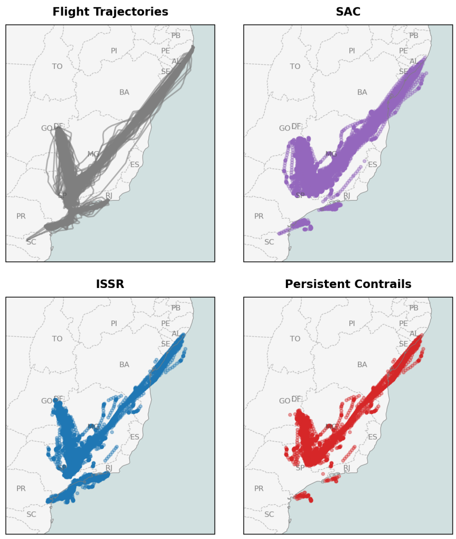
(a) January/2023.



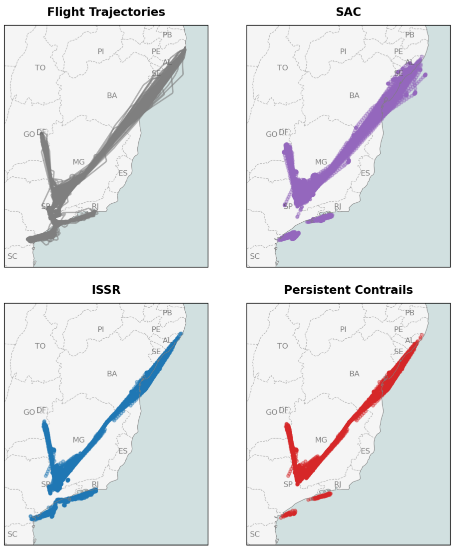
(b) February/2023.



(c) March/2023.



(d) April/2023.



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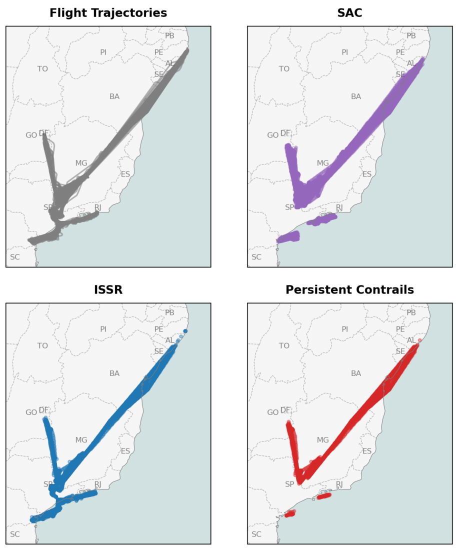
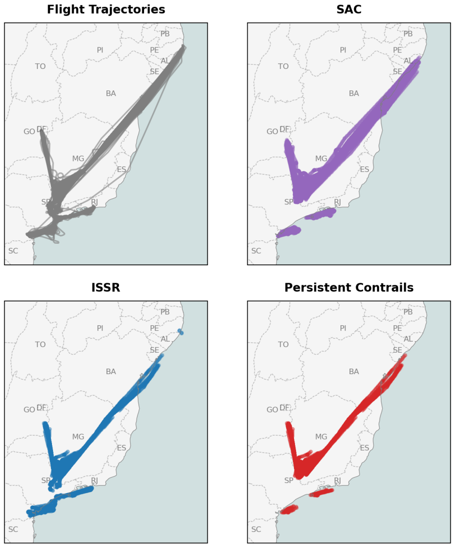
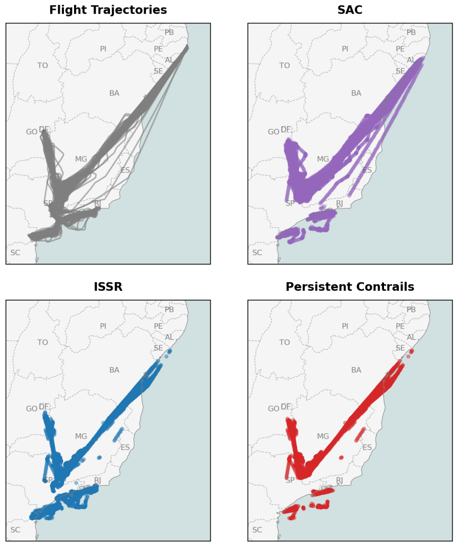


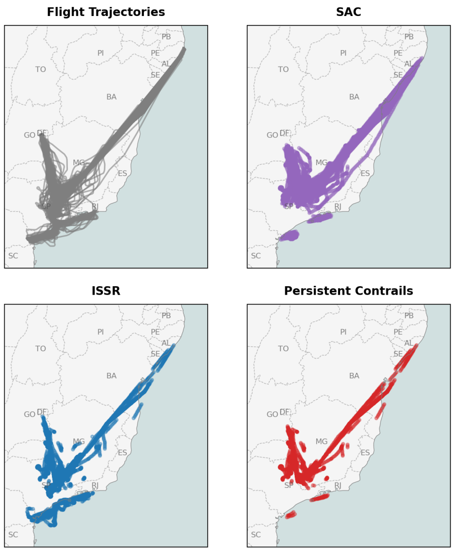
(f) June/2023.



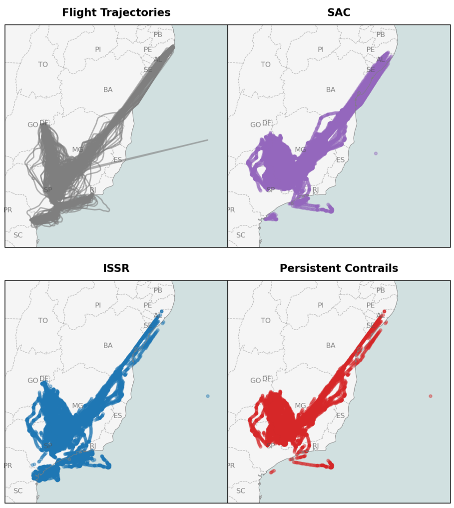
(g) July/2023.



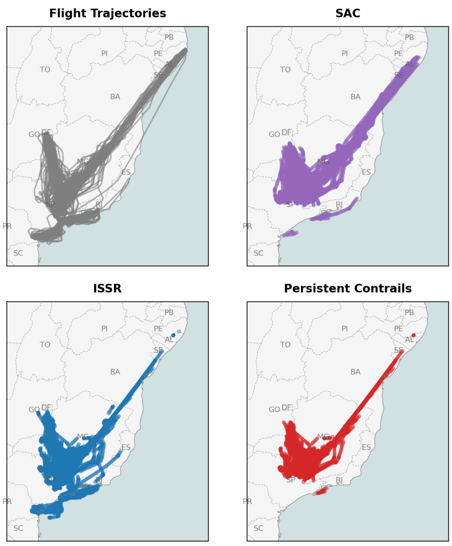
(h) August/2023.



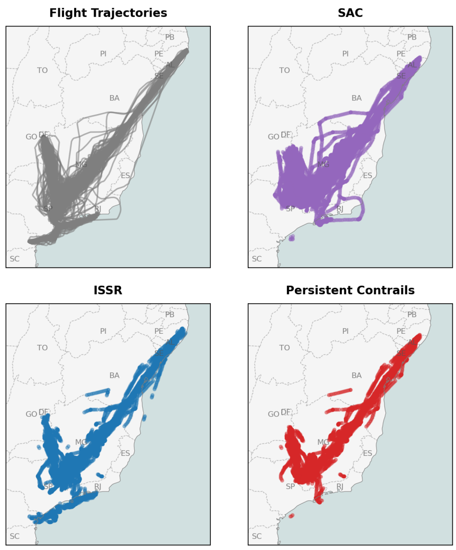
(i) September/2023.



(j) October/2023.

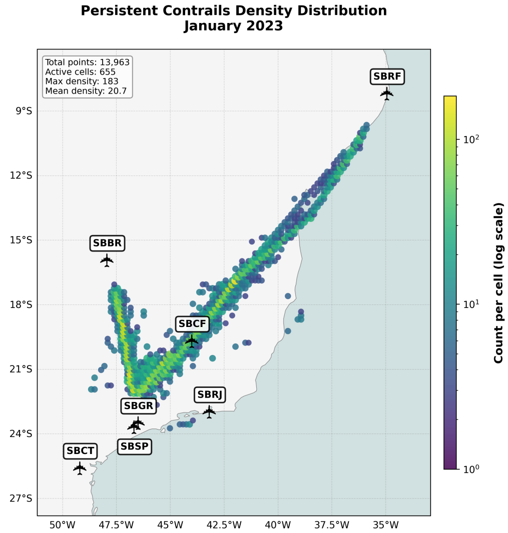


(k) November/2023.

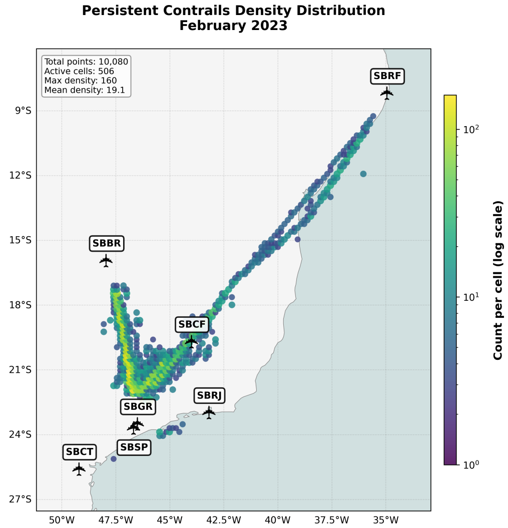


(l) December/2023.

FIGURE 4.3 – Spatial distribution of flight contrail formation and persistence for the five busiest domestic routes for each month of 2023.



(a) January/2023.



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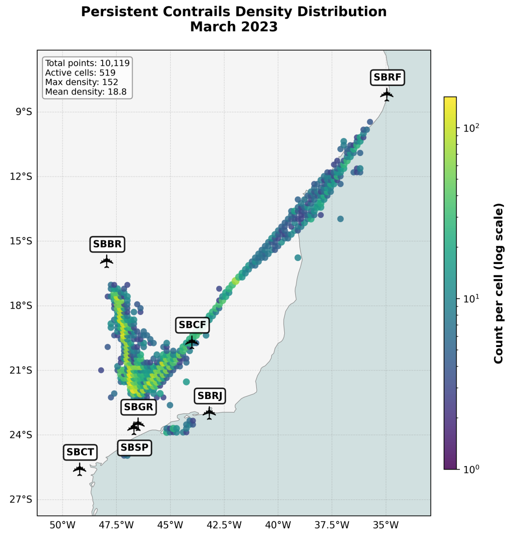

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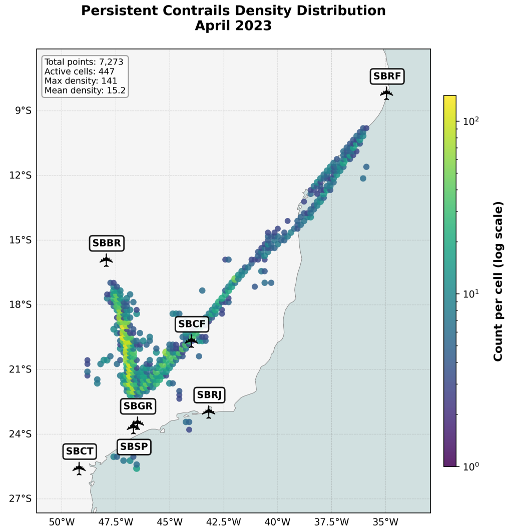
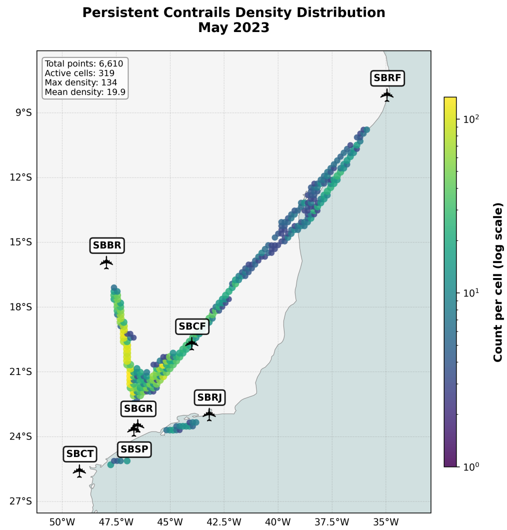
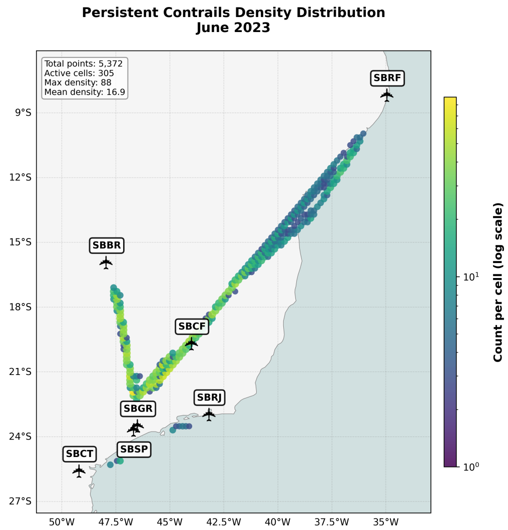


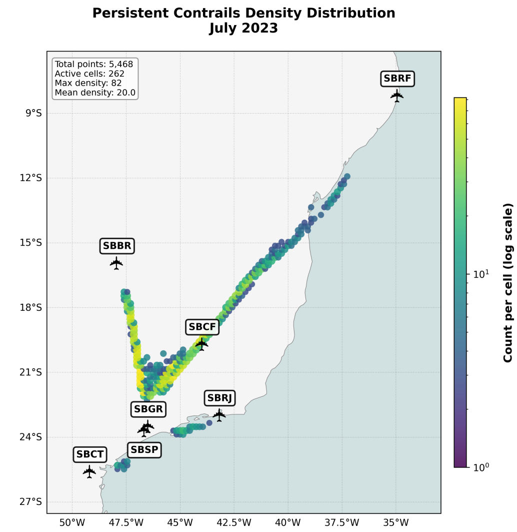
(d) April/2023.



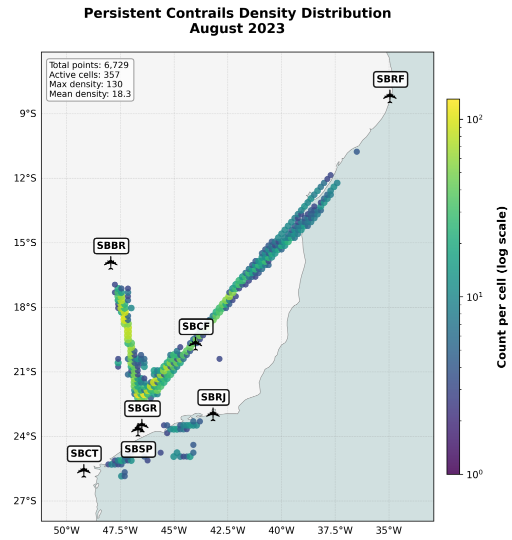
(e) May/2023.



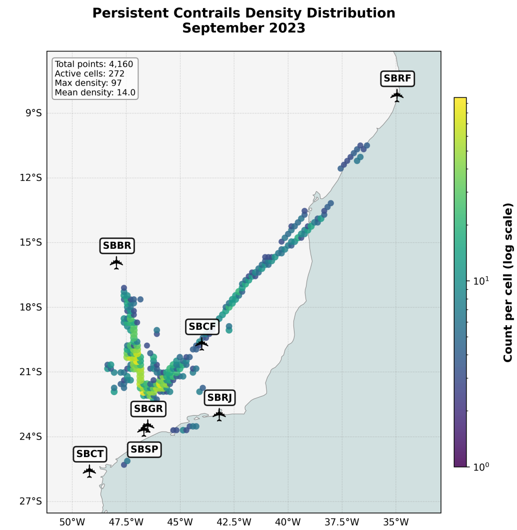
(f) June/2023.



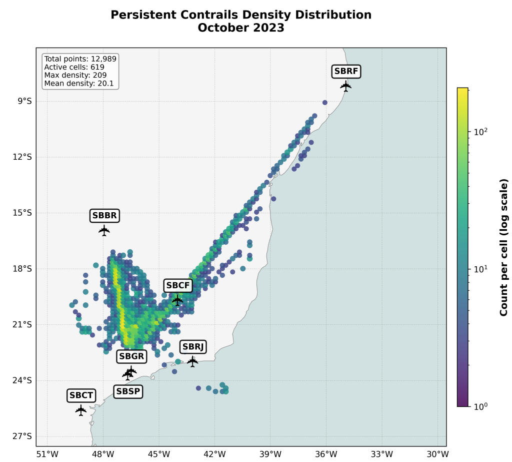
(g) July/2023.



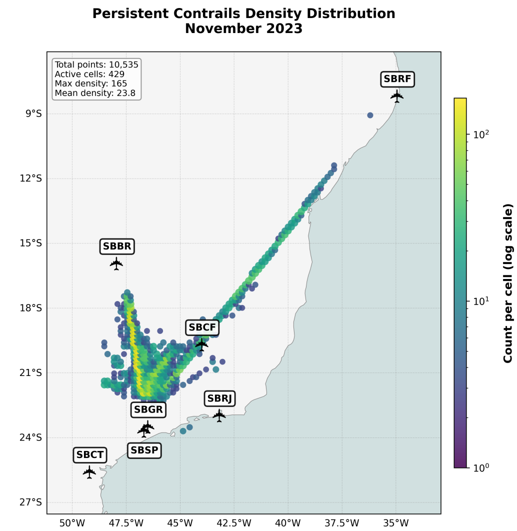
(h) August/2023.



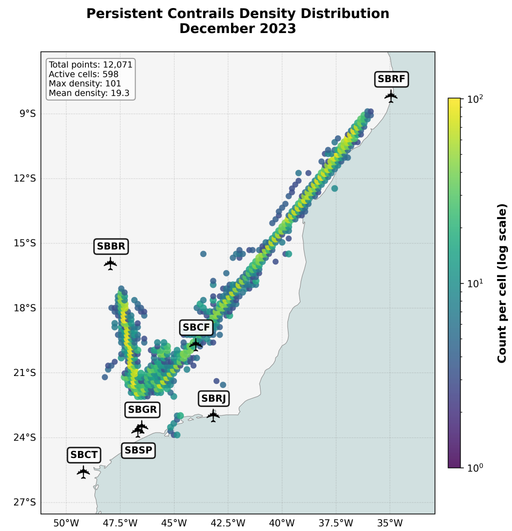
(i) September/2023.



(j) October/2023.



(k) November/2023.



(l) December/2023.

FIGURE 4.4 – Density distribution on logarithmic scale of persistent contrail occurrences for the five busiest domestic routes for each month of 2023.

4.2.1 Analysis of Zero-Contrail Occurrences on Short-Haul Routes

The zero-values recorded for SBRJ-SBSP and SBCT-SBSP are not an anomaly but rather a significant finding that highlights the dominant factors controlling contrail formation. This phenomenon can be explained by an interaction between flight profile and meteorology.

1. **Dominant Factor:** Flight Profile and Route Length. These are exceptionally short-haul routes: SBRJ-SBSP (avg. 253.7 NM) and SBCT-SBSP (avg. 244.3 NM). Flights on these segments spend a minimal fraction of their time, if any, at the optimal contrail-forming cruise altitudes (8-13 km). The majority of the flight profile consists of climb and descent, passing through these altitude bands too rapidly to trigger the 2-minute persistence filter applied in this study. The aircraft may not reach or maintain a stable cruise altitude within ISSRs.

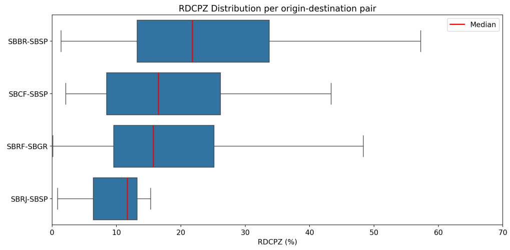
2. **Refuting Meteorology as the Sole Cause:** One hypothesis is that the region (e.g., the Rio-São Paulo corridor) is meteorologically unfavorable for contrail formation. The data disproves this. Using December 2023 (Table A.12) as an example: SBRJ-SBSP recorded RDPCZ of 0.00%. However, in the same month and operating within the same general airspace, the SBBR-SBSP route recorded RDPCZ of 15.8% and the SBRF-SBGR route showed RDPCZ of 13.0%. This conclusively demonstrates that contrail-favorable meteorology (ISSRs) was present in the airspace. The SBRJ-SBSP flights simply did not intersect these layers, almost certainly because their cruise altitudes were too low or their time spent at altitude was too brief.

3. **Synthesis:** The zero-contrail months are the result of a short-haul flight profile and weaker meteorological potential. These short routes are "marginal" contrail formers. In months with exceptionally widespread or vertically thick ISSRs (e.g., May, when SBCT-SBSP peaked at 24.0% RDPCZ, or October, when SBRJ-SBSP peaked at 22.9%), even these short flights can intersect an ISSR long enough to register persistent contrails. In months with weaker or patchier ISSR conditions, these flights fly beneath or around them, resulting in zero persistent contrails. This finding strongly suggests that flight profile is the dominant variable.

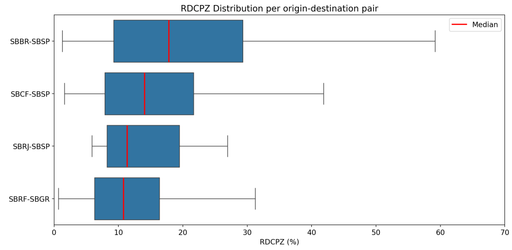
4.2.2 Analysis of Statistical Dispersion

The boxplots of the RDPCZ indicator shown in Figure 4.5 provide a visualization of the variability of contrail formation for individual flights within each route and month. This analysis reveals a critical finding for designing mitigation strategies: the data is highly skewed.[1]

[1] The absence of one or more routes in the boxplot indicates a lack of persistent contrail observations on at least 5 flights for those OD pairs (routes) in the month analyzed (RDPCZ = 0% for all flights).



(a) January/2023.



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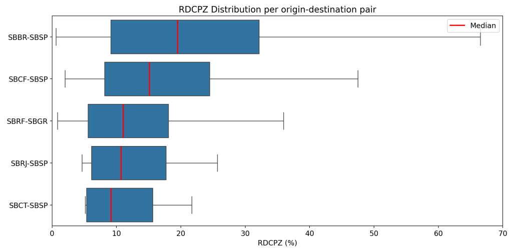

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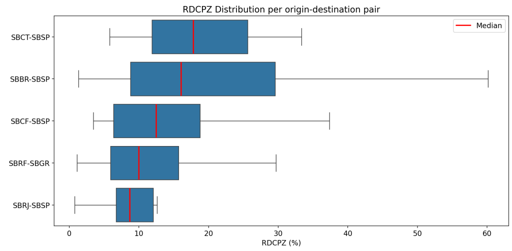

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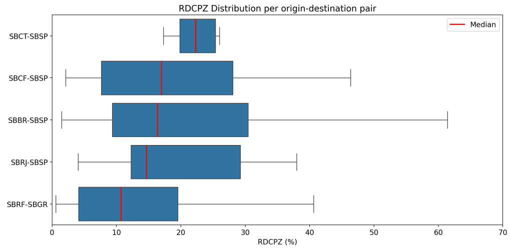
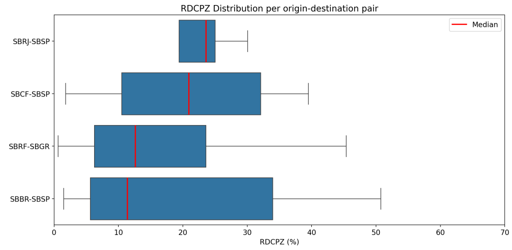


(e) May/2023.



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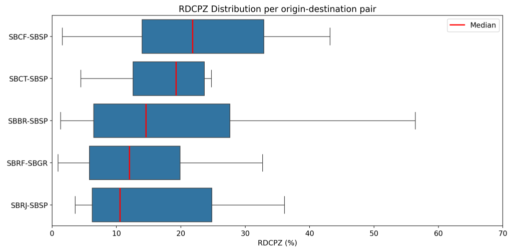

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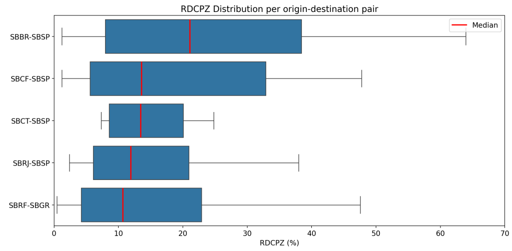

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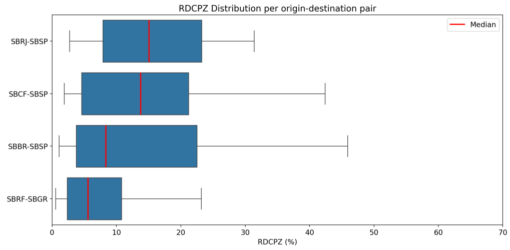
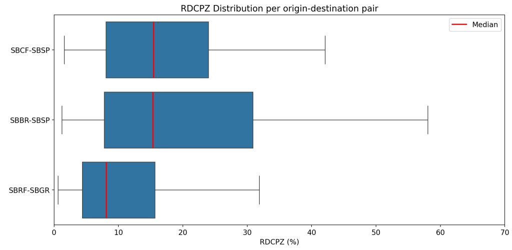


(i) September/2023.



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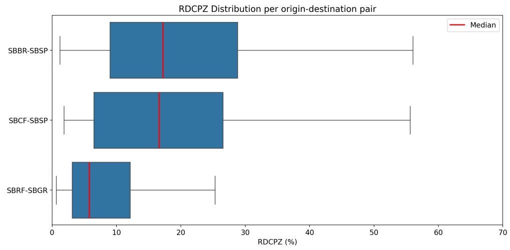

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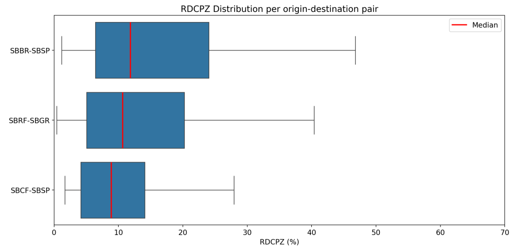


(l) December/2023.

FIGURE 4.5 – Boxplots of the RDPCZ indicator by route for each month in 2023.

For nearly all route-month combinations, for example, SBBR-SBSP on January/2023 (Figure 4.5a) and SBRF-SBGR on February/2023 (Figure 4.5b), the median RDPCZ (the red line, representing the 50th percentile) is significantly lower than the mean (reported in Tables A.1-A.12). Furthermore, the boxes (inter-quartile range, 25th-75th percentile) and upper whiskers (extending to the 90th percentile) are very large.

This skewed distribution indicates that a large share of the flights (e.g., the bottom 50%) produce few to no persistent contrails. The vast majority of the total contrail distance and its associated climate impact is generated by a small fraction of "super-emitter" flights that happen to intersect significant ISSRs. This empirical finding from the Brazilian dataset strongly corroborates international research, which has shown that contrail radiative forcing is dominated by a small number of flights. For instance, it has been noted that night flights, which may account for only 25% of air traffic, can be responsible for 60-80% of the total contrail climate forcing (STUBER *et al.*, 2006). This highly-skewed, event-driven nature is the fundamental justification for contrail mitigation: by identifying and targeting this small fraction of "super-emitter" flights, it may be possible to eliminate a large portion of aviation's non-CO_2 climate impact.

4.2.3 Monthly Analysis

The monthly aggregation of the contrail KPIs reveals a distinct seasonal signal, as shown in Figure 4.6 and Table 4.3.

TABLE 4.3 – Calculated contrail KPIs for each month of 2023, based on the top-5 domestic routes.

Month	Total distance (NM)	TDPCZ (NM)	RDCPZ (%)	PFCPZ (%)
January	1,468,414	142,753	9.72	30.08
February	1,347,253	94,436	7.01	28.38
March	1,599,704	96,114	6.01	22.40
April	1,395,222	64,573	4.63	17.52
May	1,762,285	70,438	4.00	14.43
June	1,663,274	39,283	2.36	6.63
July	1,782,680	36,720	2.06	7.77
August	1,783,653	45,341	2.54	8.36
September	1,662,735	20,624	1.24	5.64
October	1,663,117	71,201	4.28	16.55
November	1,622,141	58,935	3.63	15.39
December	1,647,131	75,655	4.59	16.38

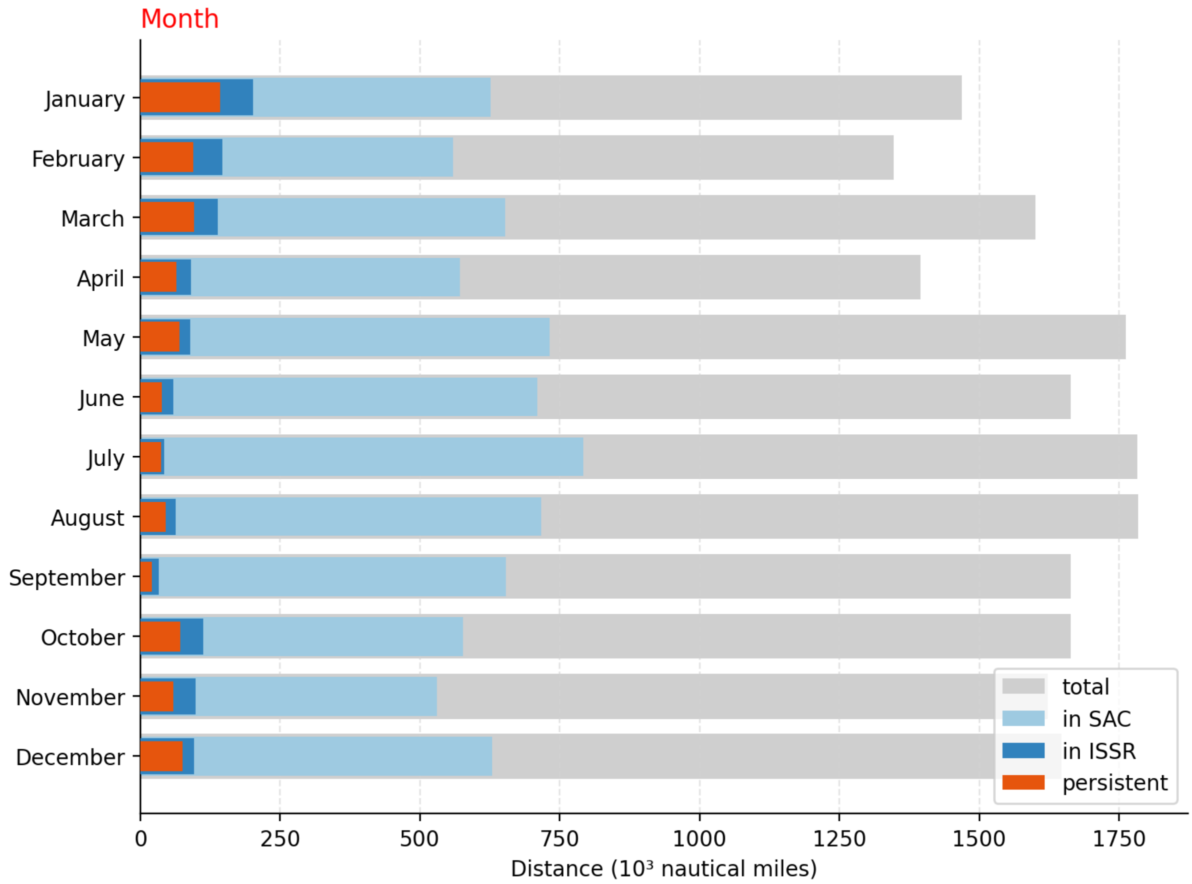


FIGURE 4.6 – Monthly evolution of total distance flown with persistent contrails for the top-5 domestic routes.

TDPCZ values peak in the Southern Hemisphere summer and autumn (January: 142,753 NM; May: 70,438 NM) and reach a distinct minimum in the winter and spring (July: 36,720 NM; September: 20,624 NM). RDPCZ values follow this trend, peaking at 9.72% in January and falling to just 1.24% in September. PFCPZ indicator also peaks in January at 30.08% and falls in September to 5.64%.

This robust seasonal cycle is likely driven by large-scale atmospheric dynamics. The frequency, vertical extent, and magnitude of ISSRs are controlled by synoptic-scale meteorological factors, including the seasonal migration of the tropopause height and the position and strength of the subtropical jet stream. This confirms that contrail potential is a dynamic, seasonally-variable phenomenon that must be actively forecast.

4.3 Evaluation of Contrail Mitigation Potential with Altitude Management

Among feasible operational strategies, one promising approach is tactical altitude adjustment during cruise to avoid atmospheric layers satisfying SAC and ISSR conditions. This strategy is physically viable because ISSRs are often vertically thin, and studies suggest that small vertical adjustments of $\pm 2,000$ ft (a standard flight level change) can be sufficient to exit the supersaturated layer.

To demonstrate the potential of this strategy in the Brazilian context, a case study was conducted on three flights from August 1st, 2023, which exhibited high original RDPCZ values. The simulation varied the cruise altitude in increments of ± 500 ft from the original level, up to $\pm 2,000$ ft for all points along the trajectory during the cruising phase. The results, summarized in Table 4.4, reveal the high potential, but also the significant risks, of this strategy.

TABLE 4.4 – Summarized results of contrail mitigation potential via altitude management.

Flight	**Total distance (NM)**	**Total distance under persistent contrails (NM)**				
		Original altitude	**±500 ft**	**±1,000 ft**	**±1,500 ft**	**±2,000 ft**
SBBE–SBEG	743.11	107.71 (14.5%)	68.92 (9.3%)	57.41 (7.7%)	45.60 (6.1%)	38.00 (5.1%)
SBFI–SBGR	521.69	110.47 (21.2%)	103.17 (19.8%)	0.00 (0.0%)	0.00 (0.0%)	0.00 (0.0%)
SBEG–SBKP	1423.79	209.04 (14.7%)	98.34 (6.9%)	168.94 (11.9%)	177.74 (12.5%)	101.48 (7.1%)

4.3.1 Flight 01: SBBE-SBEG

The analysis of flight 01 from Belém/Val-de-Cans Intl. Airport (SBBE) to Manaus/Eduardo Gomes Intl. Airport (SBEG) provides one of the most critical operational insights of this study, demonstrating the significant risks of uninformed mitigation. Table 4.5 details the mitigation potential results for this flight under different altitude adjustments. Figures 4.7 and 4.8 provide a visualization of the spatial extent of contrail formation for each scenario.

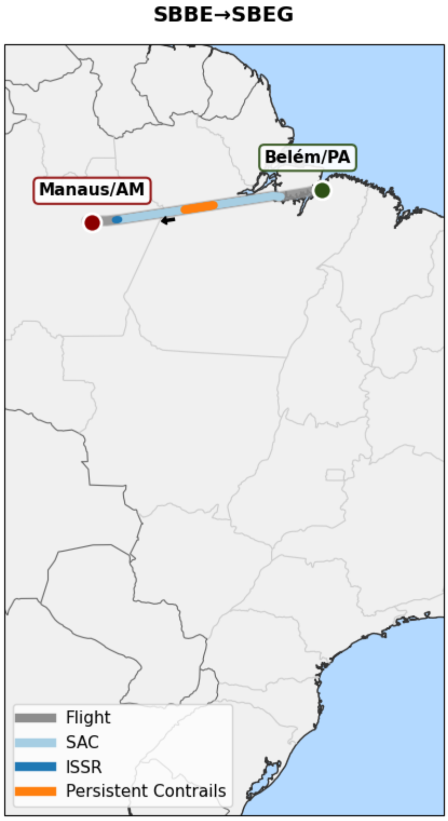
- **Original:** The flight produced 107.71 NM (14.5%) of persistent contrails.
- **Intervention:** Descending proved highly effective; a decrease of 2,000 ft in altitude reduced contrail distance by 64.7%. Climbing, however, was catastrophically counterproductive. A +1,500 ft altitude deviation increased contrail distance by 42.2%, and a +2,000 ft deviation increased contrail distance by a massive 76.1%.
- **Analysis:** This is a "Mitigation Paradox". The data demonstrates that the original flight path (Figure 4.7) was operating just below a thick, persistent ISSR layer. The uninformed "mitigation" strategy to climb (Figure 4.8) moved the aircraft directly into the core of this contrail-forming layer, dramatically increasing its total climate impact.

FIGURE 4.7 – Flight contrail formation without any deviation from the original altitude.

TABLE 4.5 – Contrail mitigation potential with cruise altitude adjustment for a flight between SBBE and SBEG.

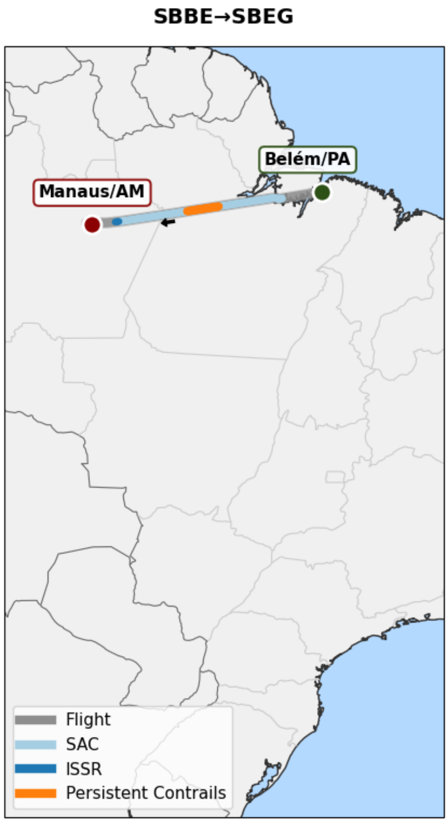
Altitude diversion (ft)	Total distance (NM)	TDPCZ (NM)	RDPCZ (%)	Variation (%)
Original flight	743.11	107.71	14.49	-
-500	743.11	68.92	9.27	-36.01
-1,000	743.11	57.41	7.72	-46.70
-1,500	743.11	45.60	6.14	-57.66
-2,000	743.11	38.00	5.11	-64.72
+500	743.11	89.09	11.99	-17.28
+1,000	743.11	96.37	12.97	-10.52
+1,500	743.11	153.14	20.61	+42.19
+2,000	743.11	189.69	25.53	+76.12

(a) Flight contrail formation with a deviation of -500 ft in altitude.



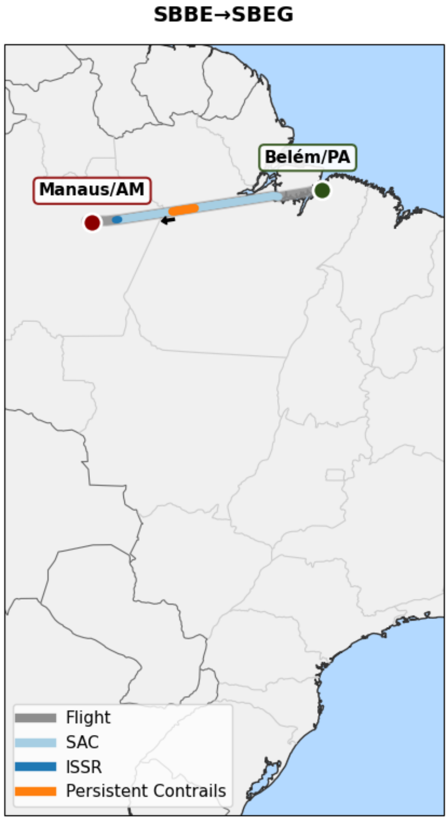
(b) Flight contrail formation with a deviation of +500 ft in altitude.

(c) Flight contrail formation with a deviation of -1,000 ft in altitude.



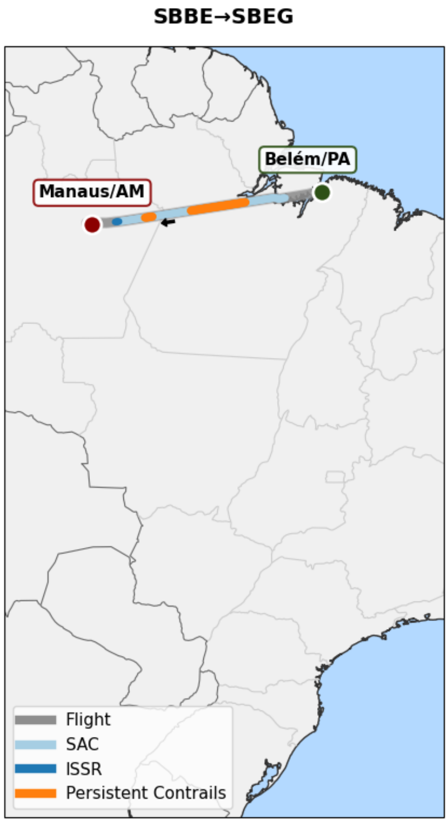
(d) Flight contrail formation with a deviation of +1,000 ft in altitude.

(e) Flight contrail formation with a deviation of -1,500 ft in altitude.



(f) Flight contrail formation with a deviation of +1,500 ft in altitude.

(g) Flight contrail formation with a deviation of -2,000 ft in altitude.



(h) Flight contrail formation with a deviation of +2,000 ft in altitude.

FIGURE 4.8 – Impact of cruise altitude deviations of up to 2,000 ft on contrail formation for a flight between SBBE and SBEG.

4.3.2 Flight 02: SBFI-SBGR

Flight 02 from Foz do Iguaçu/Cataratas Intl. Airport (SBFI) to São Paulo/Guarulhos Intl. Airport (SBGR) represents a perfect proof-of-concept for contrail mitigation, as detailed in Table 4.6 and visually illustrated in Figures 4.9 and 4.10.

- **Original:** The flight traversed 110.47 NM in persistent contrail conditions, equating to 21.2% of its total distance (Table 4.6).
- **Intervention:** A simulated altitude decrease of 1,000 ft up to 2,000 ft reduced the persistent contrail distance by 100%, eliminating the contrail impact.
- **Analysis:** This is the "best case" scenario. The original flight profile was probably operating within a persistent ISSR. A minor, operationally standard 1,000 ft altitude change was sufficient to move the aircraft into a dry, non-ice supersaturated region/layer, completely eliminating its non-CO_2 climate impact from contrails for this flight.

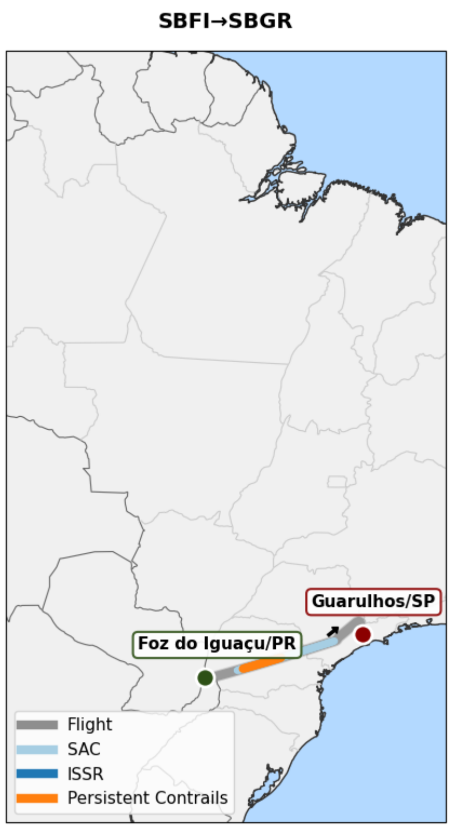
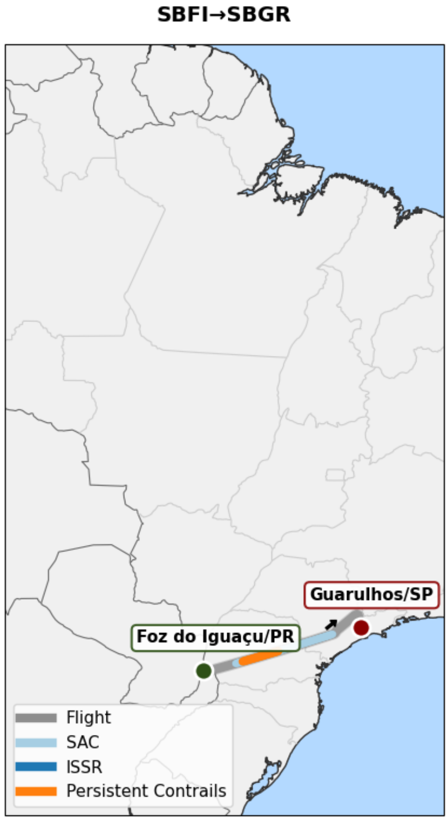


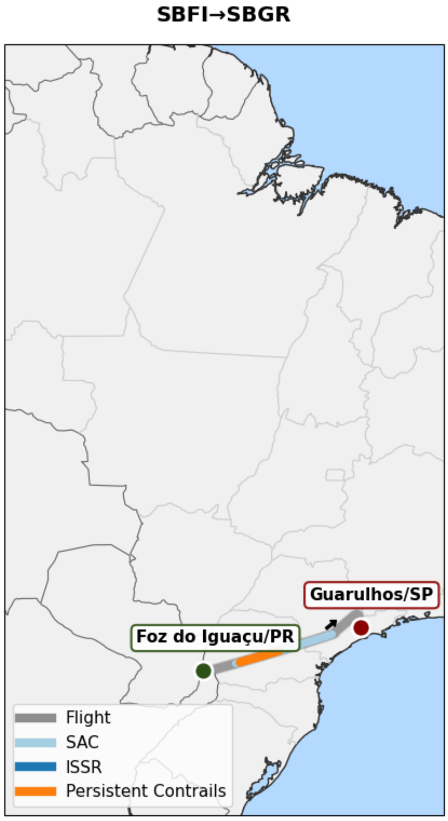
FIGURE 4.9 – Flight contrail formation without any deviation from the original altitude.

TABLE 4.6 – Contrail mitigation potential with cruise altitude adjustment for a flight between SBFI and SBGR.

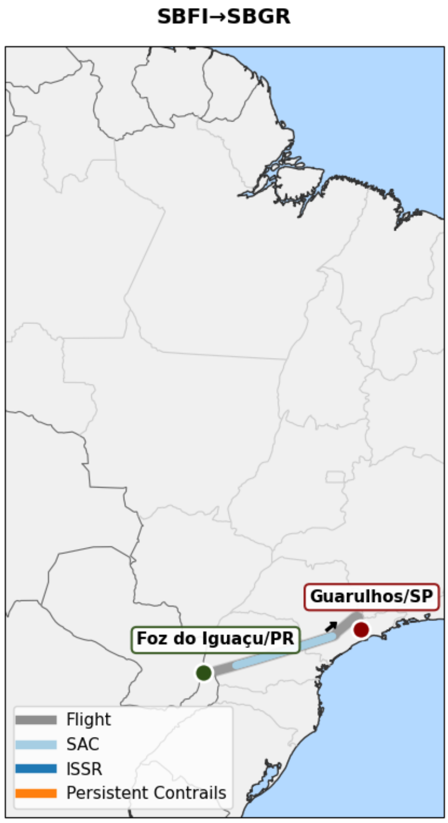
Altitude diversion (ft)	**Total distance (NM)**	**TDPCZ (NM)**	**RDPCZ (%)**	**Variation (%)**
Original flight	521.69	110.47	21.18	-
-500	521.69	103.17	19.78	-6.61
-1,000	521.69	0.00	0.00	-100.00
-1,500	521.69	0.00	0.00	-100.00
-2,000	521.69	0.00	0.00	-100.00
+500	521.69	114.59	21.97	+3.73
+1,000	521.69	95.40	18.29	-13.65
+1,500	521.69	49.51	9.49	-55.19
+2,000	521.69	42.98	8.24	-61.09



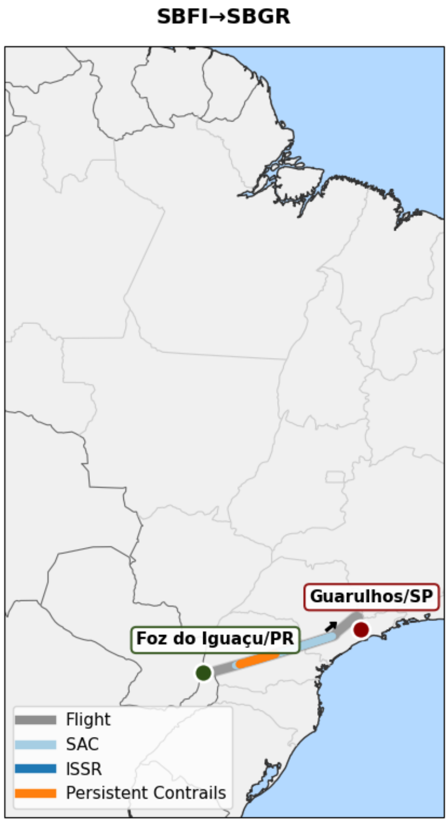
(a) Flight contrail formation with a deviation of -500 ft in altitude.



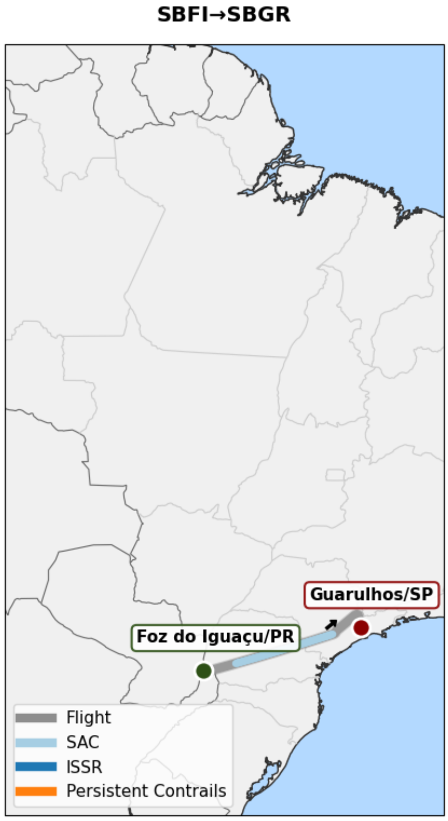
(b) Flight contrail formation with a deviation of +500 ft in altitude.



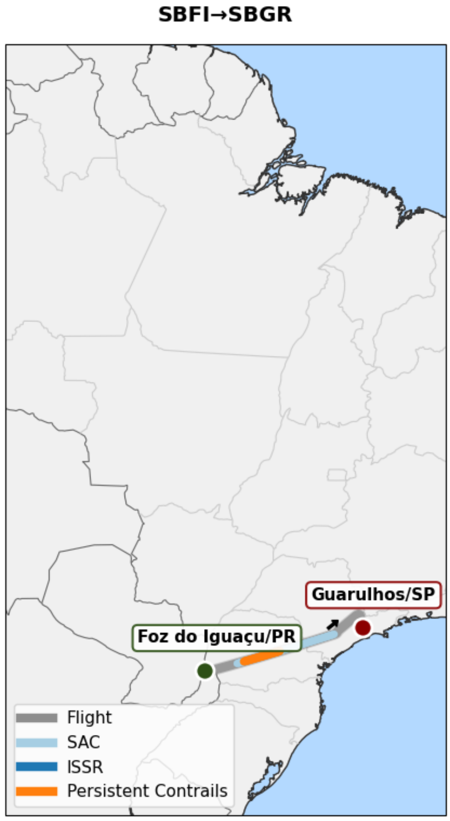
(c) Flight contrail formation with a deviation of -1,000 ft in altitude.



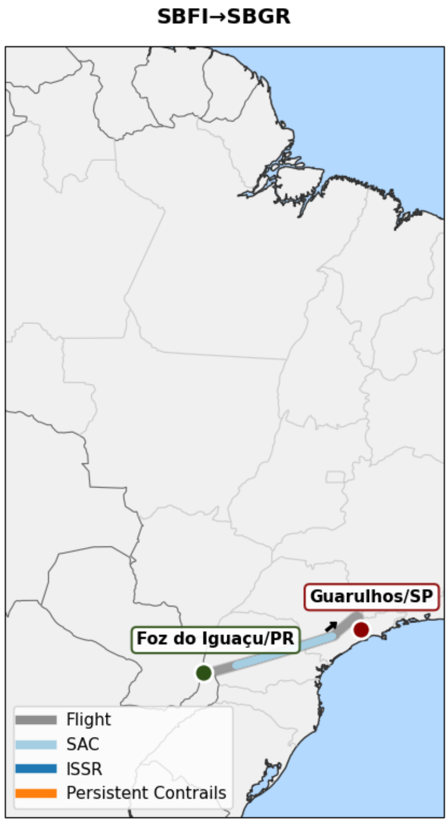
(d) Flight contrail formation with a deviation of +1,000 ft in altitude.



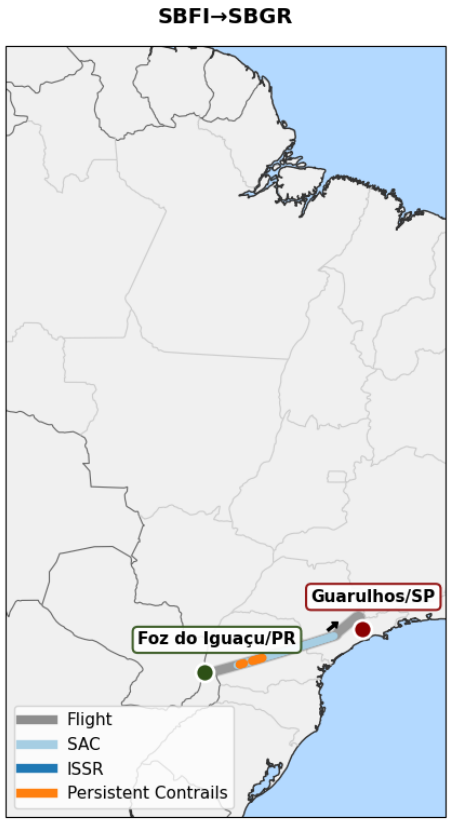
(e) Flight contrail formation with a deviation of -1,500 ft in altitude.



(f) Flight contrail formation with a deviation of +1,500 ft in altitude.



(g) Flight contrail formation with a deviation of -2,000 ft in altitude.



(h) Flight contrail formation with a deviation of +2,000 ft in altitude.

FIGURE 4.10 – Impact of cruise altitude deviations of up to 2,000 ft on contrail formation for a flight between SBFI and SBGR.

4.3.3 Flight 03: SBEG-SBKP

The analysis of flight 03 from Manaus/Eduardo Gomes Intl. Airport (SBEG) to Campinas/Viracopos Intl. Airport (SBKP) emphasizes the complexity of ISSR geometry. Table 4.7 details the mitigation potential results for this flight under different altitude adjustments. Figures 4.11 and 4.12 provide a visualization of the spatial extent of contrail formation for each scenario.

- **Original:** The flight generated 209.04 NM (14.7%) of persistent contrails.
- **Intervention:** The mitigation results are non-linear. The optimal strategy was a +500 ft deviation, which reduced contrail distance by more than 50%. A larger +1,000 ft climb was less effective, reducing contrails by only 19.2%. A -2,000 ft descent was also highly effective, yielding a 51.4% reduction.
- **Analysis:** This case demonstrates that ISSRs are not simple, flat layers. The aircraft was likely flying through a patchy, tilted, or complex-structured region. This proves that a "one-size-fits-all" mitigation rule (e.g., "always climb 1,000 ft") is suboptimal. The most effective mitigation requires precise knowledge of the 3D structure of the ISSR to identify the nearest ice supersaturated region airmass.

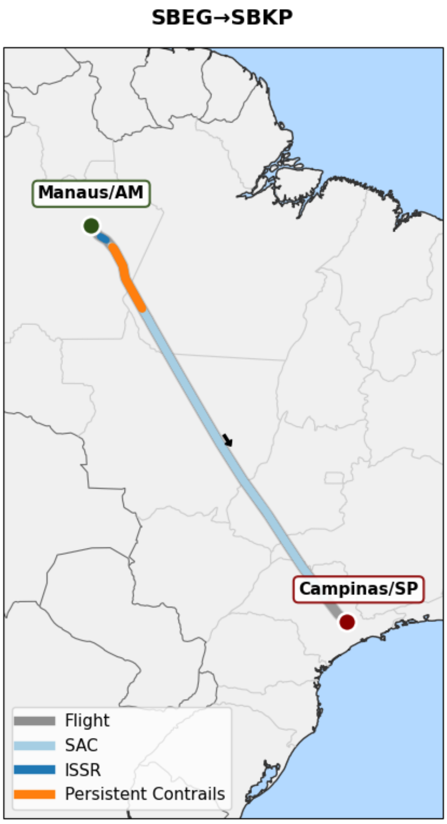
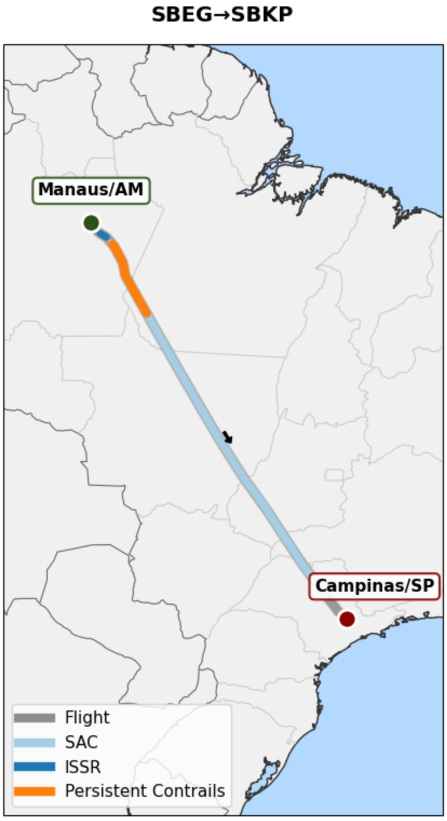


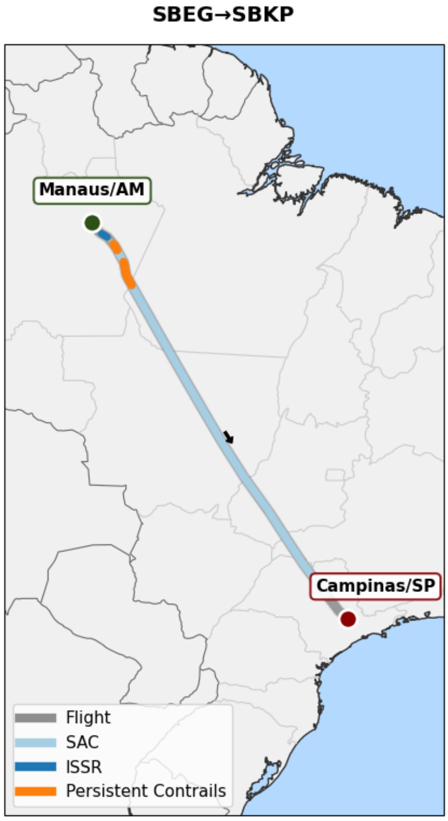
FIGURE 4.11 – Flight contrail formation without any deviation from the original altitude.

TABLE 4.7 – Contrail mitigation potential with cruise altitude adjustment for a flight between SBEG and SBKP.

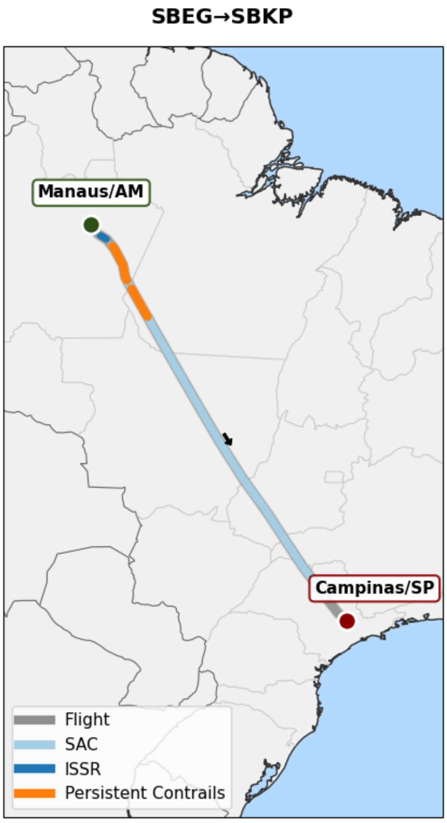
Altitude diversion (ft)	Total distance (NM)	TDPCZ (NM)	RDPCZ (%)	Variation (%)
Original flight	1423.79	209.04	14.68	-
-500	1423.79	228.13	16.02	+9.13
-1,000	1423.79	213.66	15.01	+2.21
-1,500	1423.79	186.65	13.11	-10.71
-2,000	1423.79	101.48	7.13	-51.45
+500	1423.79	98.34	6.91	-52.96
+1,000	1423.79	168.94	11.87	-19.18
+1,500	1423.79	177.74	12.48	-14.97
+2,000	1423.79	160.37	11.26	-23.28



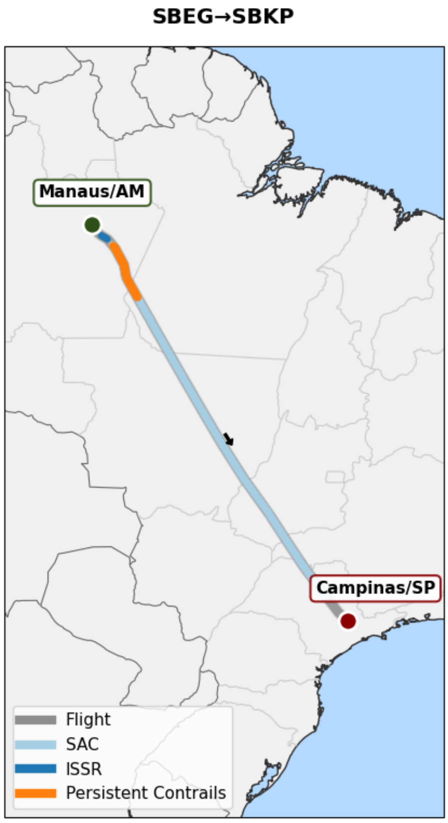
(a) Flight contrail formation with a deviation of -500 ft in altitude.



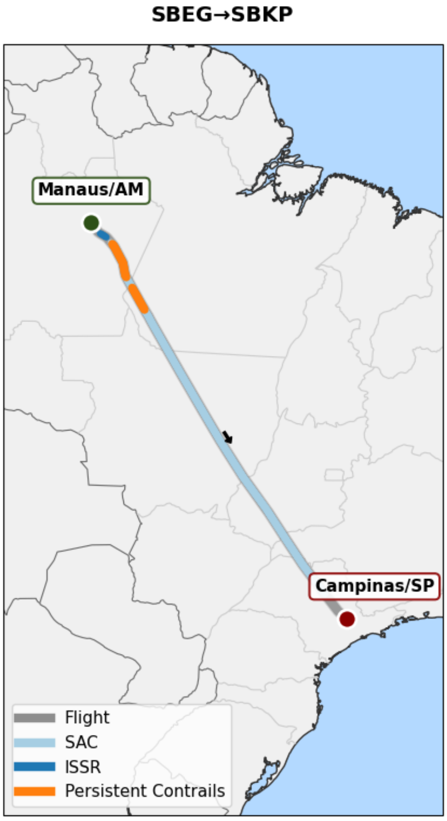
(b) Flight contrail formation with a deviation of +500 ft in altitude.



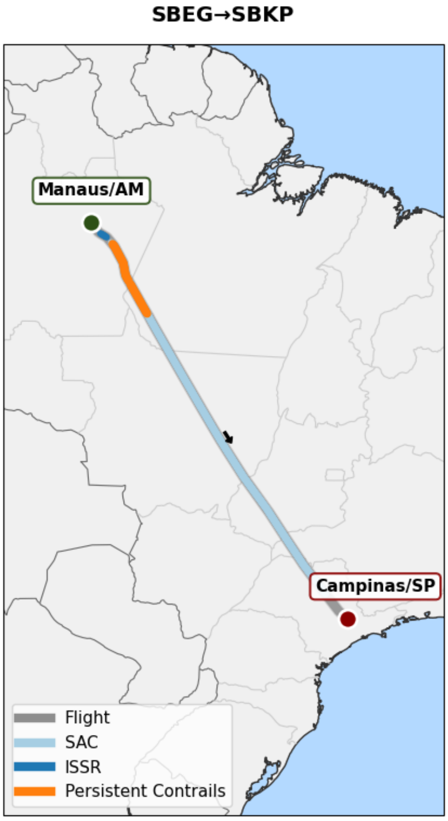
(c) Flight contrail formation with a deviation of -1,000 ft in altitude.



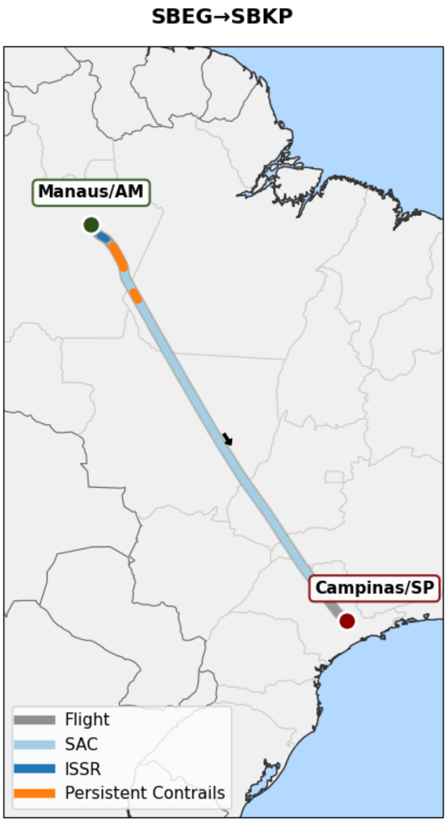
(d) Flight contrail formation with a deviation of +1,000 ft in altitude.



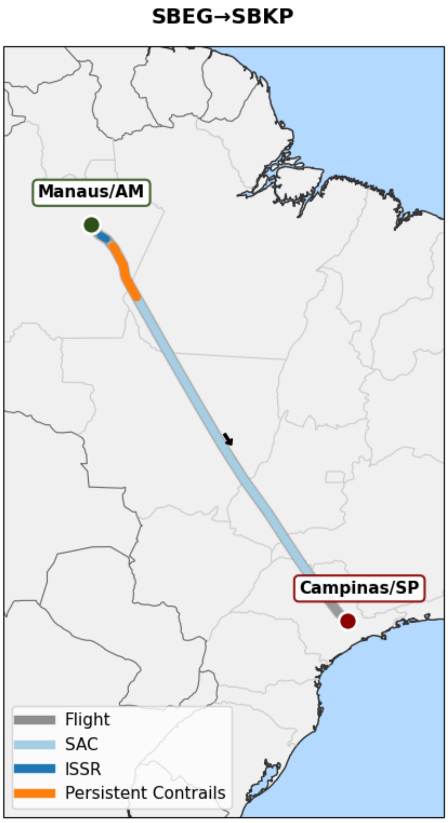
(e) Flight contrail formation with a deviation of -1,500 ft in altitude.



(f) Flight contrail formation with a deviation of +1,500 ft in altitude.



(g) Flight contrail formation with a deviation of -2,000 ft in altitude.



(h) Flight contrail formation with a deviation of +2,000 ft in altitude.

FIGURE 4.12 – Impact of cruise altitude deviations of up to 2,000 ft on contrail formation for a flight between SBEG and SBKP.

4.4 Contrail Mitigation with Altitude Management: Challenges for Implementation

The results of the case study demonstrate significant theoretical potential for persistent contrail mitigation with cruise altitude adjustments. In optimal scenarios (e.g., Flight 02), tactical vertical deviations of -1,000 ft up to -2,000 ft eliminated 100% of the distance flown in persistent contrail zones. However, transitioning this theoretical potential to viable operational implementation faces four critical, interdependent challenges: the fundamental climate tradeoff, meteorological uncertainty, operational safety, and airspace capacity. These challenges are discussed below.

4.4.1 The Climate Tradeoff: CO_2 Emissions vs. Contrail Radiative Forcing

The primary consideration is the inherent climate tradeoff in the altitude deviation strategy. Avoiding persistent contrail regions may require flying at non-optimal altitudes, inducing a penalty: reducing short-term radiative forcing from contrails at the cost of increased long-term CO_2 emissions.

Research, however, demonstrates this tradeoff is vastly favorable. The radiative forcing from contrail cirrus is widely recognized as aviation's largest non-CO_2 climate impact, with a magnitude comparable to, or potentially exceeding, the cumulative impact of all aviation CO_2 emissions. In contrast, the CO_2 penalty associated with effective vertical deviations is marginal, with estimates ranging from 0.23% to 2.24% (ELMOURAD, 2023).

This tradeoff can be further optimized: the contrail warming effect (trapping long-wave radiation) occurs continuously, but the cooling effect (reflecting short-wave solar radiation) only occurs during the day. Consequently, night time contrails exert a disproportionately large net warming impact as analyses indicate that night flights, while only representing 25% of air traffic, are responsible for 60% to 80% of the total contrail climate forcing. By strategically focusing mitigation only on these high-impact night flights, the average fleet-wide fuel penalty drops to just 0.16% , eliminating the majority of the problem at a near-negligible CO_2 cost (ELMOURAD, 2023).

Therefore, while the CO_2-contrail tradeoff exists, evidence suggests the net climate benefit of mitigation is massive and the CO_2 penalty is operationally manageable, assuming the mitigation is implemented with precision.

4.4.2 Meteorological Uncertainty

The primary barrier is the scarcity of high-resolution atmospheric data. The International Air Transport Association (IATA) highlights that a lack of real-time, high-resolution data on humidity and temperature at cruise altitudes is the main impediment to accurate contrail forecasting.

The aforementioned assumption of precision is the central challenge: the efficacy of any mitigation strategy is fundamentally contingent on the ability to accurately predict the location, altitude, thickness, and duration of ISSRs.

ISSRs are often vertically thin phenomena, with thicknesses from 100 m to 1,000 m, and are spatially and temporally transient. Global reanalysis models, like the ERA5 used in this work, have vertical and temporal resolutions that are too coarse to adequately capture these thin layers. The 4D interpolation process inevitably "blurs" or "smears" these layers, underestimating their magnitude or overestimating their vertical thickness.

The results of Flight 01 provide direct empirical proof of this risk. A simulated deviation of +2,000 ft resulted in a 76.12% increase in RDPCZ (Table 4.6). This phenomenon, the "Mitigation Paradox", probably occurs when the aircraft is flying in a safe (dry, non-ISSR) layer immediately below or above an ISSR layer that the low-resolution model failed to detect accurately. The tactical deviation, intended to mitigate, moves the aircraft directly into the core of the ISSR layer, catastrophically worsening the climate impact.

This paradox demonstrates that a mitigation strategy based on imprecise forecasts is not merely ineffective; it is actively counterproductive. It incurs the CO_2 penalty of the deviation while simultaneously increasing the contrail's radiative forcing. It is possible to conclude that contrail mitigation implementation is, in essence, a problem of high-accuracy data science and meteorological forecasting, requiring significant advances in atmospheric instrumentation and modeling.

4.4.3 Impact on Operational Safety and ATC Complexity

In the current Air Traffic Management (ATM) paradigm, trajectories are not autonomous. Any tactical deviation from the filed flight plan, whether vertical or horizontal, requires explicit analysis, coordination, and authorization from an air traffic controller to ensure minimum separation and other safety operational measures.

The introduction of widespread tactical deviations for contrail mitigation can directly impact operational safety by potentially increasing Air Traffic Control (ATC) complexity and controller workload:

1. **Increased ATC Workload:** Each tactical request adds an unplanned task for the controller, who must assess conflict risk, coordinate with adjacent sectors, and issue clearance. In high-density sectors, multiple simultaneous requests could quickly saturate controller workload.

2. **Increased Conflict Potential:** The introduction of dynamic, unpredictable, and non-standardized trajectories increases the intrinsic complexity of separation management.

Although ATC complexity can potentially increase, recent operational tests in European airspace (e.g., Maastricht Upper Area Control) concluded that the increase in actual conflicts generated by vertical deviations was minimal, and the associated safety risks were considered "almost negligible," provided the deviations are properly coordinated by ATC (SAUSEN *et al.*, 2024).

Therefore, the primary challenge appears to be managing controller workload and sector complexity, rather than collision risk per se. Implementation would require new standard operating procedures and, ideally, decision-support tools for ATC to analyze and approve/deny climate-based deviation requests in real-time.

4.4.4 Impact on Airspace Capacity

The impact on airspace capacity is the macro-systemic consequence of increased ATC complexity. Airspace capacity is a finite resource, managed via a rigid structure of predefined routes (airways) and flight levels to ensure an orderly, predictable traffic flow.

If tactical contrail mitigation is widely adopted, it could invalidate existing sector capacity models. For example, on a dense route like SBBR-SBSP, if forecasts indicate a large ISSR at FL370, it is likely all aircraft planned for that level will request tactical deviations, likely to FL350. This would create instantaneous saturation of FL350, exceeding the sector's monitoring capacity and forcing ATC to deny mitigation requests for traffic flow reasons, rendering the strategy ineffective. This scenario illustrates a conflict between climate optimization (avoiding ISSRs) and ATM system optimization (maximizing flow and capacity).

This analysis suggests that relying purely on tactical (in-flight) deviations may not be a scalable solution for high-density airspace. A more viable solution, explored in the literature, is the integration of mitigation into strategic flight planning. In this model, ISSR forecasts are integrated into airline Operational Control Center (OCC) tools hours before departure. The system suggests altitude adjustments that are incorporated into the filed flight plan, making the climate-optimized trajectory "standard" for ATC from the start. This strategic approach minimizes tactical disruption, ATC workload, and capacity impacts, representing the most probable path for operational implementation.

5 Final Considerations

This chapter consolidates the central contributions of this work, acknowledges its methodological limitations, and proposes a detailed roadmap for future work, aligned with the research guidelines and operational challenges identified.

5.1 Conclusion

This work conducted a quantitative data-driven analysis of flight contrail formation in the Brazilian airspace, advancing understanding of the non-CO_2 environmental impacts of domestic air traffic. We integrate historical aircraft tracking data and meteorological data for one year of flight operations and apply physical models using the Schmidt-Appleman Criterion (SAC) and Ice Super Saturated Region (ISSR) condition to assess the likelihood of persistent contrail formation along flown trajectories. The environmental analysis focused on the five busiest domestic routes and was enabled by the development and application of novel contrail-related performance indicators.

The results showed that persistent contrails likely formed for 17.5% of the more than 40,000 flights analyzed, but with a significant variability in the extent of the impact. The spatial analysis revealed that contrails are not restricted to specific areas and appear even in low-latitude regions. The temporal analysis also emphasized the clear seasonal patterns in the occurrence of persistent contrail conditions.

Building on the characterization of contrail formation, we assessed the potential of operational strategies for contrail avoidance and environmental impact mitigation through case studies. We found that altitude management involving small vertical deviations - up to $\pm 2,000$ ft - can theoretically provide substantial mitigation potential, achieving 100% reduction in the distance flown within persistent contrail zones in some scenarios. Nevertheless, the analysis highlighted the highly complex three-dimensional structure of ISSRs and the critical importance of accurate, high-resolution meteorological forecasts to support effective altitude adjustments. This requirement presents a major operational challenge: mitigation strategies based on low-resolution meteorological data risk not only failing to reduce contrails but potentially worsening aviation's climate impact while also imposing additional fuel costs.

5.2 Limitations and Future Work

The development of this work faced limitations and methodological challenges. First, the computational bottleneck. Fusing high-resolution 4D trajectory data (millions of points) with 4D meteorological reanalysis grids (ERA5) is an extremely computationally intensive process. The processing time for multi-year analyses and the local storage of terabytes of meteorological data proved prohibitive for the available resources, limiting the mitigation analysis to targeted case studies. Second, the simplifications in 4D interpolation. The linear interpolation methodology between ERA5 reanalysis grid points is a simplification of true atmospheric physics. ERA5 provides data at hourly temporal resolution and vertical resolution by pressure levels. However, ISSRs are frequently thin layers (e.g., < 500 m) and transient phenomena. Linear interpolation between grid points "blurs" or "smears" these thin layers, failing to capture their boundaries accurately. This methodological simplification can lead to inaccuracies in the spatiotemporal characterization of ISSRs. Finally, the analysis draws on state-of-the-art physical models of contrail formation, though these models require further empirical validation.

The conclusions and limitations identified in this work provide a clear roadmap for the continuation and deepening of this research line. The following steps are proposed:

1. **Refinement of ISSR Vertical Modeling:** To overcome the 4D interpolation limitation, it is essential to improve the modeling of ISSR vertical thickness. Instead of relying exclusively on global reanalysis (ERA5), future work should integrate data with higher vertical resolution, such as local radiosondes (when available) or employ mesoscale meteorological models to more accurately simulate the fine structure of the upper troposphere.

2. **Solving the Computational Bottleneck via Parallel Processing:** To enable multi-year larger scale analyses, the computational bottleneck identified must be resolved through employing parallel computing libraries in Python that are designed to scale data analysis (e.g., xarray, pandas) across multiple CPU cores or machine clusters. Parallelizing the 4D interpolation task would allow analyses that currently take several hours or days to be executed in hours or minutes.

3. **Validation with Remote Sensing Data:** The current methodology estimates the likelihood of contrail formation based on state-of-the-art physical models, but does not observe its actual occurrence or persistence. Empirical validation is a critical next step and can potentially be addressed as follows:

    - Utilize satellite image data (e.g., Moderate Resolution Imaging Spectroradiometer - MODIS) for detecting linear cirrus clouds, comparing the location and timing of satellite detections with the model's predictions;

- Utilize space-based lidar (e.g., Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations - CALIPSO) to validate the altitude and vertical thickness of the contrail-formed cirrus.

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Appendix A - Monthly Contrail KPIs for the Top-5 Domestic Routes

TABLE A.1 – Indicators of persistent contrails by route (Jan/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	48,434.50	203,267.63	23.8	70.0
SBCF–SBSP	15,522.67	87,393.68	17.8	46.2
SBCT–SBSP	127.23	746.50	17.0	0.5
SBRF–SBGR	93,615.96	517,823.74	18.1	90.1
SBRJ–SBSP	314.63	2,898.67	10.9	0.9

TABLE A.2 – Indicators of persistent contrails by route (Feb/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	45,441.93	225,898.84	20.1	64.2
SBCF–SBSP	12,036.05	81,764.12	14.7	36.6
SBCT–SBSP	0.00	0.00	0.0	0.0
SBRF–SBGR	102,345.27	561,102.66	18.2	72.3
SBRJ–SBSP	271.94	2,450.63	11.1	0.5

TABLE A.3 – Indicators of persistent contrails by route (Mar/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	46,132.20	209,338.01	22.0	53.8
SBCF–SBSP	15,910.36	93,602.34	17.0	39.3
SBCT–SBSP	196.49	1,715.08	11.5	1.3
SBRF–SBGR	43,918.23	339,570.24	12.9	67.8
SBRJ–SBSP	674.14	4,941.67	13.6	1.4

TABLE A.4 – Indicators of persistent contrails by route (Apr/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	33,236.82	161,360.94	20.6	41.1
SBCF–SBSP	5,733.67	39,347.39	14.6	18.9
SBCT–SBSP	367.67	2,054.09	17.9	1.6
SBRF–SBGR	31,989.93	270,445.12	11.8	63.6
SBRJ–SBSP	294.30	2,799.33	10.5	1.1

TABLE A.5 – Indicators of persistent contrails by route (May/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	32,563.55	155,667.17	20.9	33.5
SBCF–SBSP	10,741.90	55,931.32	19.2	23.1
SBCT–SBSP	366.13	1,513.45	24.2	1.0
SBRF–SBGR	32,514.17	261,089.37	12.5	50.1
SBRJ–SBSP	1,082.44	5,545.81	19.5	1.4

TABLE A.6 – Indicators of persistent contrails by route (Jun/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	11,184.02	57,723.31	19.4	12.9
SBCF–SBSP	5,325.00	25,557.76	20.8	10.9
SBCT–SBSP	135.86	929.54	14.6	0.7
SBRF–SBGR	24,122.28	138,501.51	17.4	28.0
SBRJ–SBSP	258.16	1,206.48	21.4	0.3

TABLE A.7 – Indicators of persistent contrails by route (Jul/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	13,353.67	73,309.38	18.2	18.5
SBCF–SBSP	5,677.91	25,367.47	22.4	10.8
SBCT–SBSP	432.33	2,543.81	17.0	1.8
SBRF–SBGR	18,132.77	132,837.84	13.7	20.4
SBRJ–SBSP	848.75	5,286.82	16.1	1.4

TABLE A.8 – Indicators of persistent contrails by route (Aug/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	17,846.17	75,206.39	23.7	17.8
SBCF–SBSP	7,484.52	41,163.27	18.2	16.7
SBCT–SBSP	541.28	3,665.84	14.8	2.5
SBRF–SBGR	21,422.88	142,169.26	15.1	25.2
SBRJ–SBSP	1,080.10	7,494.09	14.4	1.9

TABLE A.9 – Indicators of persistent contrails by route (Sep/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	9,900.81	69,806.53	14.2	16.9
SBCF–SBSP	3,223.14	21,303.56	15.1	9.1
SBCT–SBSP	96.81	488.39	19.8	0.4
SBRF–SBGR	8,506.53	109,433.16	7.8	20.7
SBRJ–SBSP	328.31	2,046.10	16.0	0.6

TABLE A.10 – Indicators of persistent contrails by route (Oct/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	39,454.26	195,721.41	20.2	46.8
SBCF–SBSP	9,406.57	50,049.24	18.8	19.3
SBCT–SBSP	30.97	238.38	13.0	0.2
SBRF–SBGR	27,075.88	249,754.83	10.8	47.6
SBRJ–SBSP	354.10	1,193.48	29.7	0.3

TABLE A.11 – Indicators of persistent contrails by route (Nov/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	33,215.31	167,591.14	19.8	42.0
SBCF–SBSP	10,004.61	57,305.36	17.5	23.1
SBCT–SBSP	0.00	0.00	0.0	0.0
SBRF–SBGR	19,306.34	222,928.20	8.7	43.1
SBRJ–SBSP	161.75	1,612.21	10.0	0.3

TABLE A.12 – Indicators of persistent contrails by route (Dec/2023).

Route	TDPCZ (NM)	Total Distance (NM)	RDPCZ (%)	PFPCZ (%)
SBBR–SBSP	21,312.69	134,901.89	15.8	36.6
SBCF–SBSP	3,777.99	32,930.81	11.5	13.2
SBCT–SBSP	25.25	265.29	9.5	0.2
SBRF–SBGR	55,100.08	423,023.92	13.0	71.0
SBRJ–SBSP	0.00	0.00	0.0	0.0

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5. TÍTULO E SUBTÍTULO:

Analysis of Flight Contrail Formation in the Brazilian Airspace

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8. PALAVRAS-CHAVE SUGERIDAS PELO AUTOR:

Contrail formation; Radiative forcing; Domestic flight trajectories; Mitigation strategies

9. PALAVRAS-CHAVE RESULTANTES DE INDEXAÇÃO:

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10. APRESENTAÇÃO: **(X) Nacional** **( ) Internacional**

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11. RESUMO:

Aviation's environmental impact extends beyond carbon dioxide (CO_2) emissions from fuel combustion and includes significant non-CO_2 effects. Among these, the formation of contrails and cirrus clouds driven by the condensation of water vapor in aircraft exhaust at high altitudes stands out as a major contributor to aviation's overall radiative forcing, leading to a net warming effect on the Earth's climate. This study investigates the contrail phenomenon within the Brazilian airspace and discusses potential strategies and challenges for mitigating its environmental impacts. Using one year of flight trajectory and meteorological data, we conduct a spatiotemporal analysis of contrail occurrence along major domestic routes, providing novel insights into the environmental performance of Brazilian air traffic. We find that persistent contrails likely formed for 17.5% of the analyzed flights, appearing across wide areas and even in low-latitude regions. The results also highlight the strong seasonal variability and non-linear behavior of contrail impacts. Based on this data-driven assessment of contrail formation, we propose new performance indicators for contrail monitoring and evaluate the potential contribution of contrail-avoidance strategies for environmental impact mitigation. Ultimately, this work contributes to a better understanding of non-CO_2 emissions in the domestic airspace and supports efforts to improve the overall environmental performance of Brazilian aviation.

12. GRAU DE SIGILO:

(X) OSTENSIVO **( ) RESERVADO** **( ) SECRETO**