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# Assessing Climate Impact of Contrails: Insights from Japan's High-Density Airspace and Meteorological Conditions

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**Abstract**—Persistent contrails significantly contribute to aviation's climate impact through radiative forcing effects. Japanese airspace, characterized by high traffic density, prevalent short-haul flights, and diverse meteorological conditions, exhibits unique contrail formation patterns requiring tailored mitigation strategies. However, approaches such as altitude adjustments for contrail avoidance may lead to air traffic concentration at specific altitudes, raising aviation safety concerns. Therefore, this study identifies high-impact regions in Japanese airspace where contrail mitigation strategies can be effectively applied. Using the CoCiP model, CARATS Open Data, and ERA5 reanalysis, the analysis highlights critical seasonal and geographical patterns of contrail formation. Based on CARATS Open Data from 2019, which includes 399,541 flights across en route and oceanic airspace, April to June emerge as peak periods for contrail energy forcing (EF), driven by stable, humid atmospheric conditions. High-EF hotspots in southwestern, central, and northern Japan align with dense air traffic routes, with 1.71% of flights accounting for 80% of total contrail EF. A strong correlation between contrail altitude and persistence underscores the effectiveness of altitude adjustments for mitigation. Targeted strategies, such as nighttime altitude changes and interventions in high-EF sectors, could significantly reduce aviation's climate impact. These findings establish a foundation for integrating contrail reduction measures into air traffic management systems in Japan, providing actionable insights for balancing climate benefits and operational safety.

**Keywords**—sustainability, contrails, CARATS Open Data, ECMWF, ERA5 reanalysis, Japan, CoCiP, pycontrails

## I. INTRODUCTION

Sustainability is a pressing challenge for the aviation industry, with carbon dioxide (CO<sub>2</sub>) emissions, non-CO<sub>2</sub> emissions, and contrails significantly impacting the global

climate. While CO<sub>2</sub> emissions contribute to long-term global warming over decades (20 to 40 years), contrails exert a more immediate and substantial warming effect [1]. Among aviation-related climate impacts, contrail cirrus formation currently represents the largest contributor to total radiative forcing on shorter timescales [2], though uncertainties remain regarding its precise impact for an extended time horizon. Overall, aviation accounts for approximately 5% of net anthropogenic climate forcing [3], a proportion expected to rise with increasing air traffic.

Contrails vary in their climate impact depending on their persistence and the atmospheric conditions in which they form. While some contrails dissipate quickly without significant climate effects [4], others persist for over five minutes, evolving into persistent contrails that contribute to radiative forcing. Persistent contrails form in regions of ice supersaturation (ISSR), where atmospheric conditions meet the Schmidt-Appleman criterion (SAC) and are supersaturated with respect to ice [5]. These contrails have a dual effect: scattering solar radiation during the day (cooling) and trapping terrestrial radiation both day and night (warming), with a net warming effect [3].

The Japanese airspace provides a distinctive environment for contrail research, characterized by its high-density air traffic and diverse meteorological conditions [6]–[10]. Recent findings indicate that adjusting flight altitudes within a range of  $\pm 2,000$  feet has the potential to significantly mitigate contrail formation. To support the implementation of such contrail-avoidance strategies, private enterprises, such as Google [11], have developed decision-support tools aimed at providing pilots with optimized flight paths that minimize contrail formation. These tools are currently undergoing trial operations in collaboration with multiple airlines globally.

However, in scenarios of high air traffic congestion, there is a growing concern that contrail mitigation strategies could inadvertently lead to traffic concentration at specific altitudes, potentially posing risks to aviation safety.

The current research aims to evaluate the feasibility and operational effectiveness of a controller support system designed to reduce contrail formation in regions of high mitigation potential, with a specific focus on Japanese-controlled airspace. As an initial step, this study conducts a detailed spatio-temporal analysis to identify when and where contrail formation is most frequent, along with the altitude bands where it is most likely to occur. The findings from this analysis are used to outline key challenges and considerations for the future implementation of contrail-avoidance systems in operational air traffic management.

Following the literature review in Section II, we describe the traffic and weather data utilized in this study, along with the CoCiP methodology, highlighting its potential for streamlining climate impact evaluations (Section III). In Section IV, we analyze the spatio-temporal characteristics and lifetime of persistent contrails, focusing on factors critical for contrail mitigation. Operational implications and findings from CoCiP simulations are discussed in Section V, with concluding remarks on the broader implications of our work in Section VI.

## II. STATE OF THE ART

Recent advancements highlight growing industry-academia collaborations to mitigate the environmental impact of contrails. Google and American Airlines successfully trialed a predictive tool, integrating satellite imagery and weather data to reduce contrails by 54% [11]. Similarly, EUROCONTROL and DLR trials in Europe demonstrated the feasibility of altitude adjustments using predictive models [12]. The study in [13] extended the findings by integrating contrail avoidance strategies into commercial flight planning systems. These efforts underscore the effectiveness of operational strategies to avoid contrails.

Research has also revealed significant geographical and seasonal variations in contrail formation. In the contiguous United States, targeting contrail avoidance during specific seasons, particularly from June to September when contrail formation is most prevalent, could enhance mitigation efforts [1]. In Europe, the impact of reduced air traffic during COVID-19, peaking in the afternoon in alignment with contrail cover [14]. In the North Atlantic region, persistent contrail formation was higher in winter (23%) compared to summer (13%), despite lower overall flight activity during this season [15]. These studies emphasize the importance of meteorological factors, such as temperature and humidity, in contrail formation and persistence.

In contrast, research focusing on Japanese airspace remains limited despite its unique challenges and opportunities. With a high volume of domestic and international flights and diverse meteorological conditions, Japan experiences significant contrail activity [6]–[10]. In [7], [8], 2.2% of flights account for 80% of contrail climate forcing in this

region, suggesting that targeted diversions could significantly mitigate contrail effects. This study also found that contrails causing significant warming are mostly formed between 10:00 and 22:00 local time, with the cooling potential maximized by diverting flights to form cooling contrails between midnight and 15:00 local time. However, this study relied on CARATS Open Data 2012, which excludes oceanic air traffic and lacks even-month data, limiting its comprehensiveness. Most recent research [10] identified seasonal and geographical variations in contrail formation, showing that altitude diversions could mitigate up to 90% of persistent contrails in cooler months, although their effectiveness diminishes in warmer conditions due to higher humidity. Nonetheless, the limited coverage of Japanese airspace in OpenSky data poses a challenge for generalizing these findings.

Despite these efforts, there has been no comprehensive analysis of contrail hotspots, seasonality, and vertical distribution in Japan. To address this gap, our study aims to provide actionable insights by analyzing the spatial and temporal dynamics of contrail formation in Japanese airspace, utilizing open-access tools and data. Through this approach, we seek to develop effective mitigation strategies tailored to the unique characteristics of this region.

## III. DATA AND METHODOLOGY

### A. Aircraft Trajectory Data and Emission

The CARATS Open Data provides a detailed and high-resolution record of aircraft movements within Japanese airspace, so-called Fukuoka FIR (Flight Information Region). The dataset includes twelve one-week samples of air traffic data, collected monthly between January 2019 and December 2019, containing a total of 399,541 flights with the peak traffic volume before COVID-19. Each flight is associated with an anonymized flight identifier and an ICAO aircraft type code, allowing for the classification of aircraft types while preserving privacy. The 3D positions of flights are captured at intervals of approximately 10 seconds, offering fine-grained insights into aircraft trajectories.

The assignment of aircraft engines, as documented in [16], were utilized alongside the Poll-Schumann model [17], [18] to calculate key parameters, including thrust ( $F$ ) and fuel mass flow rate ( $\dot{m}_f$ ) at each waypoint, as well as the total fuel consumption (TFC) for individual flights. These values ( $F$  and  $\dot{m}_f$ ) were further employed to derive various engine-related metrics. Specifically, these include: (i) the overall propulsion efficiency, a critical factor that affects the likelihood of contrail formation [19]; (ii) the engine thrust setting, expressed as  $F/F_{00,max}$ , where  $F_{00,max}$  represents the maximum rated thrust at sea level under static conditions; and (iii) the turbine-to-compressor inlet temperature ratio ( $T_4/T_2$ ). The latter two parameters were essential for estimating the black carbon emission index (BC) of the aircraft ( $E_{I,BC}$ ). The initial mass were estimated following [20].

The  $E_{I,BC}$  varies depending on the aircraft type and engine power settings and was determined using the Fractal Aggregates (FA) model [7], [21]. This model derives  $E_{I,BC}$  based on the black carbon mass emissions index, as well

as the particle size distribution and morphology. The FA model is particularly advantageous because it leverages widely available data and models for these parameters [7]. These engine parameters are essential for contrail analysis because they directly influence the emission of black carbon particles, which serve as ice-nucleating particles during contrail formation. For example, higher thrust settings and elevated turbine inlet temperatures increase the EI and BC, thereby raising the initial ice crystal number concentration in contrail segments. Accurate estimates of EI and BC are therefore critical to realistically simulate the formation and radiative impact of persistent contrails using the CoCiP model. More information is available in [7], [8].

### B. Meteorological Data

The ERA5 dataset, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), is a comprehensive global atmospheric reanalysis covering the period from 1979 to the present. With a high spatial resolution of approximately 30 km and an hourly temporal resolution, ERA5 delivers detailed insights into atmospheric conditions. The dataset includes key variables such as temperature, humidity, and wind data across all altitudes relevant to commercial aviation, making it particularly valuable for contrail analysis. Furthermore, ERA5 encompasses additional parameters related to atmospheric composition, cloud properties, and radiation. The data is produced through an advanced assimilation process that integrates observations from satellites, aircraft, and ground-based weather stations, ensuring high accuracy and reliability for diverse research and operational applications.

ERA5 provides a vertical resolution of approximately 1000 to 1500 ft in the upper troposphere, which, while adequate for general meteorological studies, may not fully capture thin ice-supersaturated layers critical for contrail persistence. This limitation introduces uncertainty in estimates of the relative humidity with respect to ice (RH<sub>i</sub>), potentially underrepresenting the occurrence of supersaturated regions and persistence and lifetime of contrails [4], [5]. Previous research has indicated that ERA5 reanalysis data often show only weak supersaturation (RH<sub>i</sub> ≈ 100 %) and fail to accurately represent regions with significant supersaturation (RH<sub>i</sub> > 120 %) [22]. To address these limitations, various methods for scaling relative humidity have been proposed [15], [23], [24], with recent studies demonstrating that exponential scaling provides a more accurate adjustment [15].

$$\text{RH}_{i\text{Corrected}} = \begin{cases} \frac{\text{RH}_i}{a}, & \text{if } \frac{\text{RH}_i}{a} \leq 1, \\ \min\left(\left(\frac{\text{RH}_i}{a}\right)^b, 1.65\right), & \text{if } \frac{\text{RH}_i}{a} > 1. \end{cases} \quad (1)$$

We applied this scaling method and adjusted parameters  $a = 0.999$  and  $b = 4.246$  by comparing ERA5 humidity fields with in situ observations from the In-service Aircraft for a Global Observing System (IAGOS) database [25], [26], following [22]. Our use of exponential scaling, validated with IAGOS in-situ observations, addresses this issue to some extent but does not eliminate the inherent resolution-driven uncertainty.

### C. Contrail Cirrus Prediction Model (CoCiP)

The Contrail Cirrus Prediction Model (CoCiP) is a simulation tool with a Runge-Kutta integration designed to model the lifecycle of contrail segments, from their initial formation to eventual dissipation [23]. This study used `pycontrails` [27], an open source project and Python package for CoCiP simulation. A contrail segment forms when two consecutive flight position records meet the Schmidt–Appleman Criterion (SAC) [5]. The initial concentration of ice crystal numbers in the contrails depends on three factors: (i) the non-volatile particulate matter (*nvPM*) emission index ( $EI_n$ ), with a lower bound of  $10^{-13} \text{kg}^{-1}$  to account for ambient aerosols and organic particles; (ii) the ambient temperature ( $T_{amb}$ ), which affects *nvPM* activation rates; and (iii) the fraction of ice particles surviving the wake vortex phase.

CoCiP integrates multiple data sources, including air traffic information (CARATS Open Data in this study), black carbon (BC) emission indices derived from aircraft engine models, and high-resolution meteorological data. Persistent contrail segments, those that endure beyond the wake vortex phase, are simulated at 1800-second time steps until their end of life. This endpoint is reached when the contrail ice crystal concentration falls below the background ice nuclei concentration ( $< 10^3 \text{m}^{-3}$ ), the optical depth ( $\tau_{contrail}$ ) decreases below 0.01, or the lifetime exceeds 24 hours. For each segment, CoCiP computes key parameters, including local contrail radiative forcing ( $RF'$ )—the change in radiative flux over the contrail area. These values are aggregated to estimate metrics such as the annual mean net radiative forcing of contrail cirrus over target regions.

CoCiP also calculates the contrail energy forcing ( $EF_{contrail}$ ), which represents the cumulative climate forcing of a contrail segment. This is determined by integrating the product of the segment's ( $RF'$ ), length ( $L$ ), and width ( $W$ ) over its lifetime ( $t$ ) [28].

$$EF_{contrail} = \int_{t_0}^{t_{end}} RF'(t) \cdot L(t) \cdot W(t) dt \quad (2)$$

The resulting  $EF_{contrail}$  can be aggregated to assess the climate impact of individual flights or entire air traffic systems.

## IV. RESULTS

### A. Seasonal Trends in Contrail Formation

Figure 1 presents the daily outputs of key contrail parameters, revealing distinct seasonal trends throughout 2019. The dashed vertical lines in Fig. 1 indicate transitions between months, providing a clear visual representation of these seasonal fluctuations. Table I provides a summary of fleet-aggregated values, including comparative statistics from a previous study [7], which analyzed six weeks of CARATS Open Data from May 2012 to March 2013. These results serve as a historical baseline to contextualize our 2019 simulations and to highlight changes in contrail characteristics due to updated humidity scaling methods and broader airspace coverage, including oceanic sectors. The metrics presented

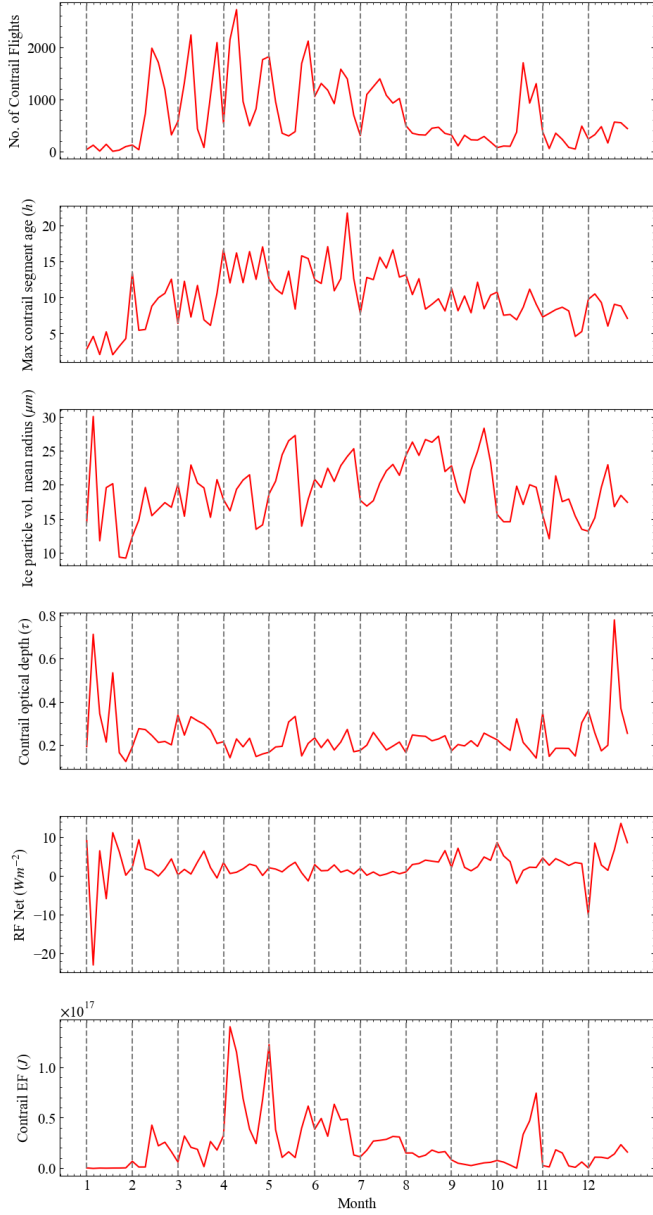


Figure 1: Daily simulation results of contrail-related metrics for 2019 based on CARATS Open Data. The six panels display (from top to bottom): the number of contrail flights, maximum contrail segment age (hours), ice particle volume mean radius ( $\mu\text{m}$ ), contrail optical depth ( $\tau$ ), net radiative forcing (RF) of contrails ( $\text{Wm}^{-2}$ ), and contrail effective forcing (EF, J). Dashed vertical lines indicate the transitions between months

TABLE I. Fleet-Averaged Contrail Statistics, Which Are Simulated with CoCiP Using Meteorological Inputs of ERA5 and Flight Inputs of CARATS Open Data.

Fleet Averaged CoCiP Outputs	May 2012 to Mar. 2013 (6 weeks) [7]	Jan. 2019 to Dec. 2019 (12 weeks)
total number of flights forming contrails	29,875	61,267
% of flights forming contrails	20.0	15.3
% of flight distance forming contrails	7.37	12.5
mean contrail segment age (h)	3.01	1.96
maximum contrail segment age (h)	23.9	23.6
ice particle volume mean radius ( $\mu\text{m}$ )	13.0	20.1
contrail optical depth ( $\tau$ )	0.154	0.287
SW RF ( $\text{W m}^{-2}$ )	-4.48	-6.69
SW LF ( $\text{W m}^{-2}$ )	6.39	7.619
net RF ( $\text{W m}^{-2}$ )	1.91	0.927
contrail EF ( $\times 10^{18}$ J)	5.31	1.92
EF per flight distance ( $\times 10^8$ J $\text{m}^{-1}$ )	0.421	0.193
EF per contrail length ( $\times 10^8$ J $\text{m}^{-1}$ )	7.17	0.452
% flights responsible for 80% contrail EF	2.44	1.71

<sup>a</sup>Note that the previous study [7] used constant humidity scaling.

in Fig. 1 and Table I reflect different aspects of contrail dynamics and climate impact. For example, the shortwave (SW) and longwave (LW) radiative fluxes quantify the opposing radiative effects of contrails—cooling due to solar reflection and warming due to infrared trapping. The net RF is their combined result. The ice particle volume mean radius is an indicator of crystal growth, which influences contrail optical depth and lifetime. Together, these metrics provide a comprehensive view of the physical and radiative properties of persistent contrail.

Importantly, maximum contrail segment age shows a clear peak from April to June in Fig. 1, corresponding to stable and humid atmospheric conditions at cruising altitudes. These months are associated with longer contrail lifetimes due to reduced sublimation rates and stable atmospheric layers. Contrail optical depth ( $\tau$ ) also experiences significant spikes in January and December, but the mean values of the ice particle volume sharply increase starting in January, peaking from April to June. This trend, coupled with extended contrail durations, results in stronger net radiative forcing (RF) and energy forcing (EF) during the spring and early summer months. The higher ice particle volume in these months indicates more substantial contrail persistence and a greater potential for warming.

In Table I, our current dataset comprises 12 weeks of representative data across all months of 2019, offering improved temporal coverage and operational relevance. On average: (i) 15.3% of flights result in contrail formation; (ii) contrails cover 12.5% of the total flight distance; (iii) the mean lifetime of a contrail segment is 1.96 hours; (iv) the optical depth ( $\tau$ ) averages 0.287; (v) the net radiative forcing (RF) is  $0.927 \text{ W m}^{-2}$ , and the effective radiative forcing

(EF) totals  $1.92 \times 10^{18}$  J; and (vi) only 1.71% of flights are responsible for 80% of the total contrail EF. These values underscore the disproportionate climate impact of a small subset of flights, suggesting targeted mitigation strategies could significantly reduce contrail-related climate forcing.

### B. Geographical Distribution of Contrail EF

Figure 2 illustrates the seasonal and spatial distribution of contrail energy forcing (EF), with notable variations across different months. The highest EF values, indicated by red tones, appear predominantly from April to July, coinciding with the humid atmospheric conditions that support prolonged contrail formation. April and June are particularly significant, showing persistent high EF values across central and southwestern Japan. These regions align with major air traffic corridors, such as those connecting Tokyo with other international hubs in East Asia. The high air traffic volume during these months amplifies contrail formation, leading to a more significant radiative impact. In contrast, EF values are considerably lower in winter (e.g., January and December), reflecting less favorable meteorological conditions for contrail persistence. Some contrails exert a net cooling effect due to dominant shortwave reflection, especially when formed during midday with high solar irradiance. In contrast, contrails formed at night primarily contribute to warming. The monthly variations in Fig. 2 are driven by changes in sunlight hours, humidity profiles, and traffic density.

TABLE II. Total EF, Contribution Rate and Cumulative Contributions by Sector.

Sector	Total EF ( $\times 10^{17}$ [J])	Contribution Ratio [%]	Cumulative Contribution Ratio [%]
A03	3.62	18.85	18.85
A02	1.40	7.30	26.15
A01	1.22	6.38	32.53
F07	1.19	6.22	38.75
F14	1.07	5.58	44.33
F15	0.88	4.58	48.91
F01	0.81	4.22	53.13
F17	0.75	3.91	57.04
F10	0.64	3.30	60.34
F09	0.61	3.20	63.54
T92	0.57	2.94	66.48
F11	0.56	2.92	69.40
F12	0.54	2.81	72.21
A04	0.52	2.69	74.90
T93	0.50	2.61	77.51
F08	0.47	2.45	79.96

Figure 3 reveals significant disparities in energy forcing (EF) across different airspace sectors, with the value summarized in Table II. Sector A03 stands out with the highest EF, accounting for 18.85% of the total, followed by sectors A02 and A01, which contribute 7.30% and 6.38%, respectively. Together, these three oceanic sectors account for over 30% of the total EF, underscoring their crucial role in the overall radiative forcing caused by contrails. The widespread spatial distribution of EF across these sectors reflects their continuous contribution throughout the year, particularly over oceanic regions where favorable meteorological conditions for contrail persistence are more common.

Other significant sectors contributing to contrail energy forcing (EF) include F07 (6.22%), F14 (5.58%), F15 (4.58%), and F01 (4.22%), which together account for 53.13% of the total EF combining with A01 to A03. As shown in Fig. 2, EF values for F14 and F15 peak during April and June, while F01 peaks in May. Sector F07, in contrast, maintains consistently high EF throughout the year. This uneven distribution highlights the concentration of contrail-related climate impacts in specific en-route sectors with dense air traffic and atmospheric conditions favorable for contrail formation. These findings emphasize the need for targeted interventions in high-impact areas to maximize mitigation efforts.

While Fig. 2 shows that contrail energy forcing (EF) is visually more intense over mainland Japan during certain months, oceanic sectors A01–A03 exhibit the highest cumulative EF in Table II and Fig. 3. This apparent discrepancy arises from the difference in representation: Fig. 2 shows EF intensity per unit area on a grid basis, whereas Table II aggregates total EF values over entire sectors. Oceanic sectors cover significantly larger areas, and although their per-area EF density may appear moderate, their cumulative contribution becomes dominant due to their spatial extent and consistent contrail activity. Therefore, despite not appearing as bright hotspots in the monthly maps, these oceanic sectors represent critical regions for effective mitigation strategies.

### C. Diurnal Patterns and Radiative Effects

Figure 4 shows a clear diurnal pattern in contrail energy forcing (EF), highlighting significant temporal variations in climate impact throughout the day. The highest daily EF, recorded on April 23, 2019, reached a peak value of 140 PJ, coinciding with a period of intense contrail activity from April to June. Diurnal trends reveal that contrails formed between 3:00 PM and 5:00 AM predominantly contribute to warming, as they trap outgoing longwave radiation without the mitigating effect of reflected sunlight. On the other hand, contrails formed during daylight hours exhibit a more balanced radiative effect, where the warming due to longwave trapping is partially offset by the cooling effect from reflected solar radiation. This finding suggests that the timing of contrail formation plays a critical role in determining their net climate impact, with nighttime contrails contributing more to warming.

### D. Contrail Altitudes and Persistence

As depicted in Figure 5, monthly contrail formation altitudes exhibit a clear seasonal pattern. Median altitudes peak in June and July, coinciding with the summer months, and decrease from August onwards as atmospheric conditions become less favorable for high-altitude contrail formation. Higher summer altitudes reflect an elevated tropopause and increased humidity, promoting persistent contrail formation, whereas lower winter altitudes result from stable stratification and reduced convective activity. This finding suggests that altitude adjustments targeting specific altitude bands

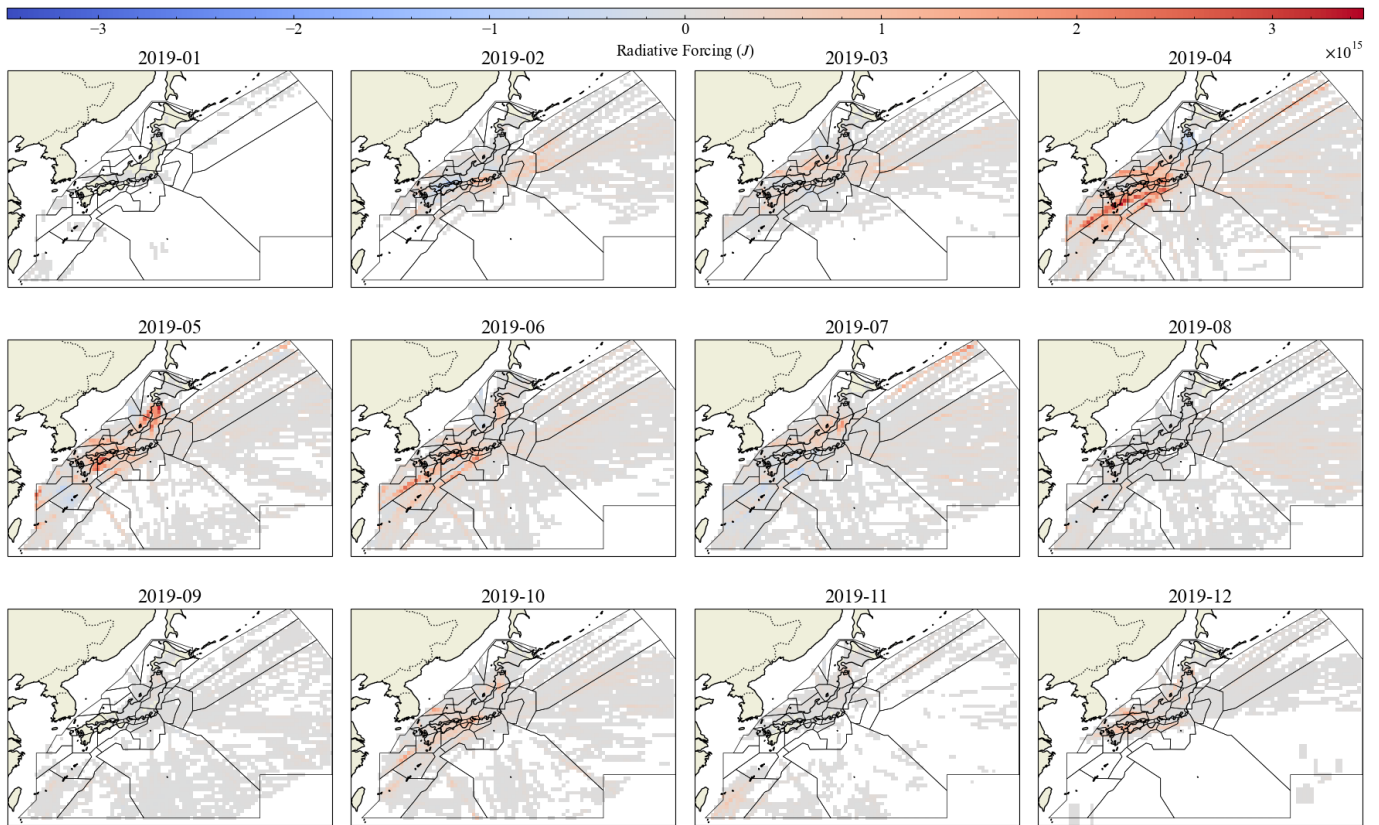


Figure 2: Monthly plots of Contrail Energy Forcing (J). The maps show energy forcing values computed at a  $0.5^\circ$  latitude-longitude grid resolution, highlighting regional and seasonal variations in radiative forcing caused by aviation-induced contrails over Japanese airspace.

could be an effective mitigation strategy, particularly during high-impact periods.

Fig. 5 also shows that the interquartile range (IQR) of contrail formation altitudes is wider during the winter months and narrower in summer. This pattern reflects the seasonal variability of the tropopause height and humidity distribution in the upper troposphere over Japan. In Japan, the thermal tropopause rises in summer (approximately 12-14 km  $\approx$  39,000-46,000 ft) and decreases in winter (approximately 10-11 km  $\approx$  33,000-36,000 ft). During summer, commercial aircraft cruising at approximately 12 km ( $\approx$  39,000 ft) are more likely to enter ice supersaturated regions (ISSR) near or just below the tropopause, where persistent contrails are favored. The increase in water vapor content in summer leads to vertically thick ISSRs and increased contrail persistence and radiative forcing, as observed in previous studies [10]. In contrast, during winter, the lower tropopause causes high-altitude aircraft to fly in the dry stratosphere, reducing the likelihood of persistent contrails at higher levels. Instead, contrail formation tends to occur at lower altitudes within scattered humid layers. According to [29], persistent contrails typically form around 1.5 km ( $\approx$  5,000 ft) below the thermal tropopause and often correspond to the level of the jet stream. Seasonal changes in tropopause height and upper-level wind patterns over Japan thus shape the vertical distribution of contrail formation. Moreover, since few aircraft operate at

low altitudes, the observed contrails in winter are more widely distributed in altitude, contributing to the wider IQR seen in Fig. 5. These findings highlight the critical role of seasonal tropopause dynamics and vertical humidity structure in determining contrail altitude and persistence.

Figure 6 illustrates a strong positive correlation between contrail formation altitude and their maximum age, indicating that contrails formed at higher altitudes tend to persist for longer durations. This trend is particularly prominent during the summer months, with contrails formed approximately 39,000 ft exhibiting significantly longer lifetimes compared to those formed at lower altitudes. In contrast, winter contrails, which typically form at lower altitudes, are more susceptible to rapid sublimation and show shorter persistence. The extended lifetimes of high-altitude contrails in summer can be attributed to favorable atmospheric conditions near the tropopause, such as lower wind shear and higher humidity, which promote ice crystal stability and reduce sublimation rates. This finding underscores that avoiding high-altitude contrail formation during critical periods, such as summer months with elevated tropopause levels, could substantially reduce the overall radiative forcing.

Figure 7 compares relative humidity over ice (RH<sub>i</sub>) and wind conditions above the tropopause on January 11 (lowest EF) and June 22 (highest EF), 2019, revealing distinct seasonal variations that influence contrail formation and

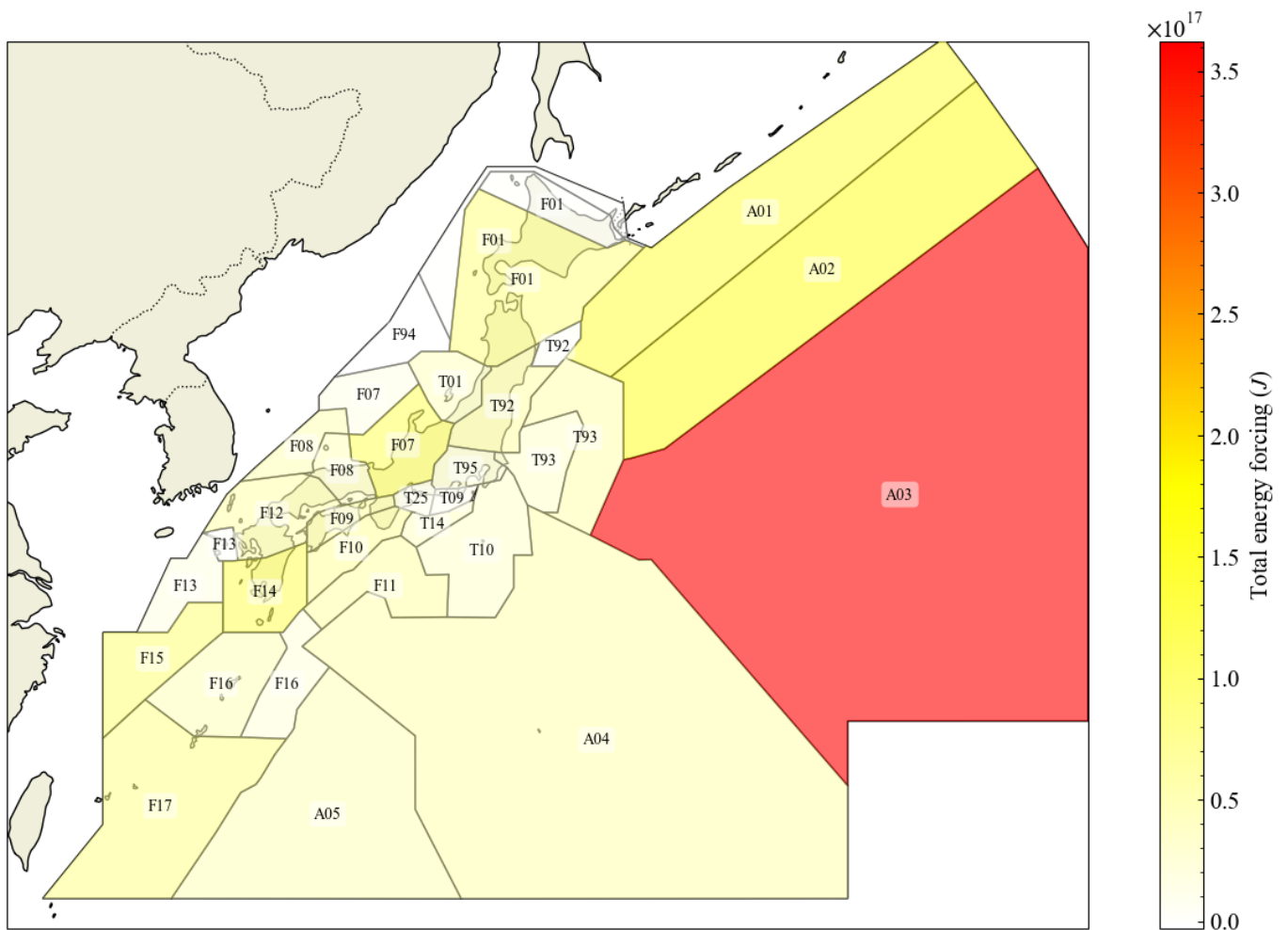


Figure 3: Total energy forcing (EF) distribution across sectors based on CARATS Open Data (2019). The plot visualizes the EF values for individual airspace sectors. The color gradient indicates the magnitude of EF, with red representing the highest values and yellow indicating lower values.

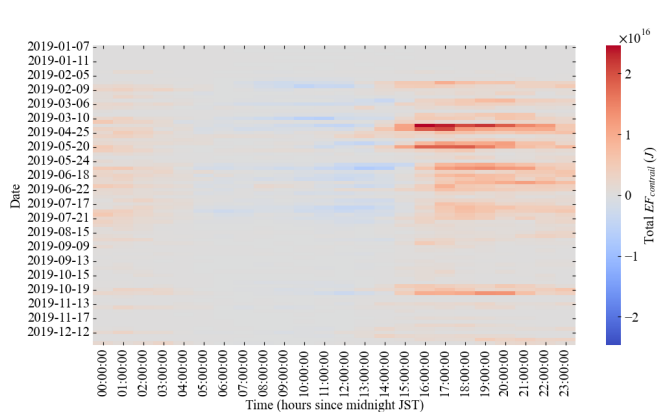


Figure 4: Temporal distribution of total contrail energy forcing (EF) over Japanese airspace by date and time in 2019. The data highlights seasonal and diurnal variations, with peak EF occurring during specific months and hours of the day.

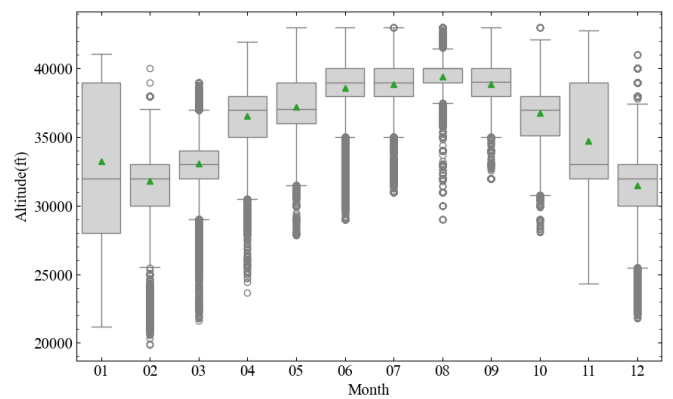


Figure 5: Monthly box plot of contrail formation altitudes over Japanese airspace in 2019 with the mean values (green dot). The plot illustrates the seasonal trend of contrail altitudes, highlighting variations in median, interquartile range, and extreme values across different months.

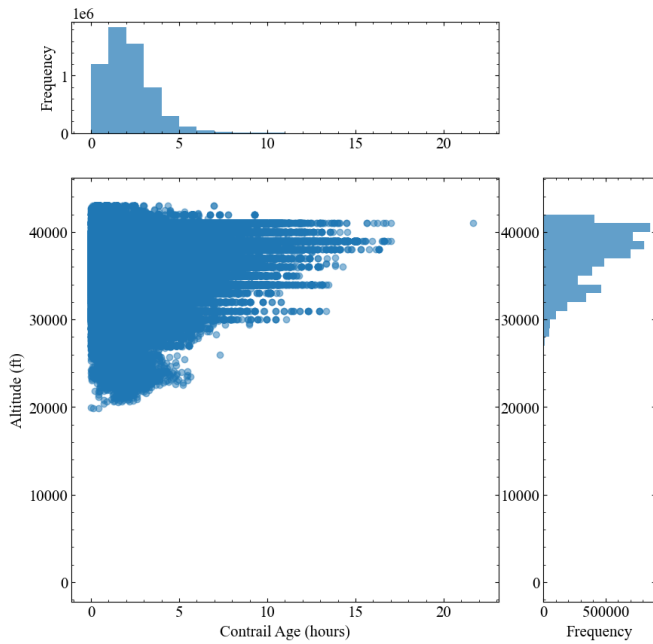


Figure 6: Scatter plot of maximum contrail age versus contrail formation altitude over Japanese airspace. The plot shows the relationship between the altitude of contrail formation and their persistence, with trends highlighting seasonal variations and atmospheric influences.

persistence. On June 22, RHi values close to 100% are concentrated in southeastern Japan, accompanied by relatively low wind speeds, indicating stable, humid conditions that favor contrail persistence. In contrast, the January 11 data reveal a all spatial distribution of RHi values below 90%, particularly over northern and central regions, coupled with stronger and more variable wind patterns. The higher RHi observed in June correlates with higher humidity and limited atmospheric mixing, allowing contrail ice particles to persist longer. Conversely, the increased wind speeds and widespread dry areas in January limit contrail formation over a larger spatial extent and may reduce their localized climate impact through faster dispersion. These insights can inform the design of seasonal, region-specific mitigation strategies that account for varying atmospheric conditions to optimize climate benefits.

## V. DISCUSSION

Before interpreting our results, we remind the reader of our main objectives. The key research question was "When, where, and how much is the persistent contrail with high climate impact formed in Japanese airspace, and how should we mitigate it?" This question was the first step toward clarifying the effectiveness of a controller assistance system to help avoid contrails. To answer this, we conducted CoCiP simulations using the `pycontrails`. For comprehensive traffic, we utilized CARATS Open Data from 2019, focusing on peak traffic observed in recent years. Within this framework, traffic data were integrated with the Poll-Schumann model, and emissions were calculated in

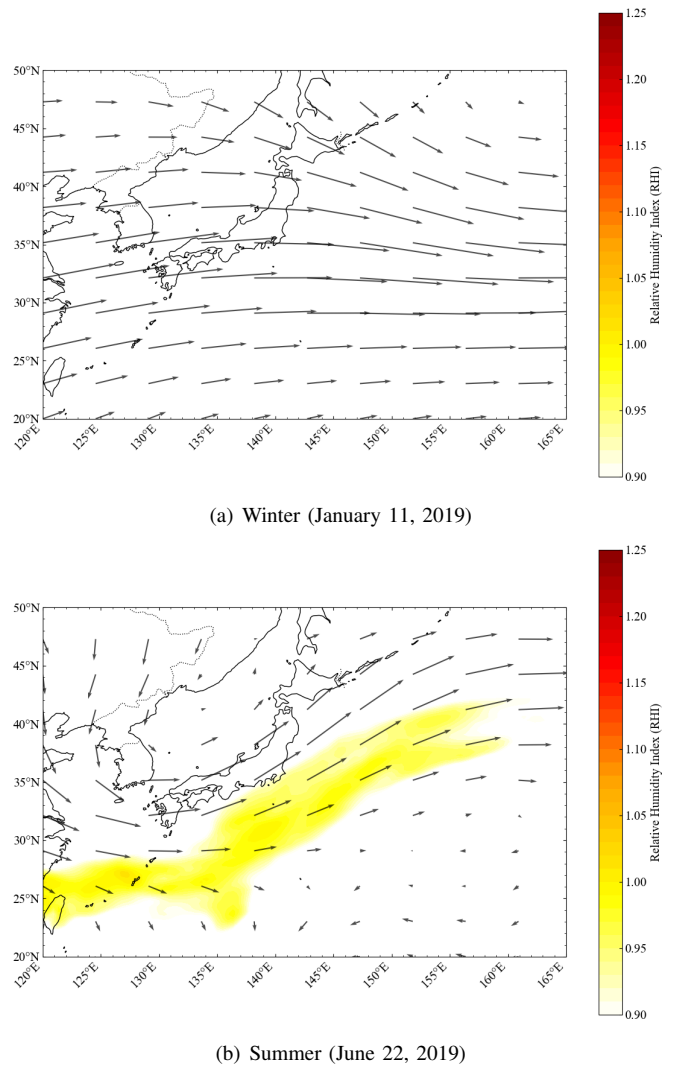


Figure 7: Comparison of relative humidity over ice (RHi) and wind conditions above the tropopause on January 11, 2019 and June 22, 2019. Color shading represents RHi, with values above 90% indicating favorable conditions for contrail persistence. Arrows depict wind direction and speed, with longer arrows indicating higher wind speeds.

conjunction with ERA5 meteorological data. These emission data were then used to predict contrail lifecycle dynamics within the CoCiP model. Based on our insights from the analyses, we propose the following actionable strategies for contrail mitigation in Japanese airspace:

- 1) Specific en-route sectors such as F07, F14, F15, and F01 should be prioritized for altitude adjustments during high-EF periods from April to June between 15:00 and 05:00 (night hours).
- 2) Mitigation strategies, including changing flight level and rerouting, should be extended to oceanic sectors (A01, A02, A03) throughout the year, if possible.
- 3) Encouraging contrail formation during daylight hours (05:00–15:00) in carefully selected regions due to traffic could complement nighttime mitigation efforts.

The reasons for these messages will be discussed in each subsection, with the key findings compared to related studies.

#### A. Quantifying Contrails and Their Climate Impact

Our findings indicate that persistent contrails contribute substantially to radiative forcing, totaling  $1.92 \times 10^{18}$  J, with significant seasonal and geographical variations as shown in Table I, Fig. 1 and Fig. 2. The result showed that 1.71% of flights responsible for 80% of contrail EF, which is smaller than the North Atlantic (12%) in [15], underscoring the need for targeted mitigation strategies. This aligns with [7], [8], which emphasized targeting high-impact flights for mitigation in CARATS Open Data 2012.

#### B. Temporal Effect

The diurnal and seasonal trends identified in our study corroborate findings in [14], [15], where contrail radiative effects peak during nighttime hours due to trapped longwave radiation as shown in Fig. 4. Notably, April and June, which were missed in [7], [8], exhibited the highest contrail energy forcing (EF), aligning with high traffic volumes and favorable meteorological conditions. This temporal pattern is critical, as the analysis over the North Atlantic [15] showed persistent contrail formation more prevalent in winter despite lower traffic levels, a finding partially mirrored in our winter data. However, unlike the conclusions on reduced summer contrail forcing in [15], our data revealed substantial summer impacts over Japan, suggesting regional differences in atmospheric and traffic conditions.

Adjusting flight altitudes remains the most widely studied method for contrail avoidance, particularly effective during nighttime when traffic density is lower, reducing the risk of conflicts [8]. In Japan, where summer contrail formation is significant, integrating real-time weather monitoring with predictive tools such as CoCiP can facilitate effective altitude adjustments and routing decisions. Daytime operations, on the other hand, present a potential opportunity to utilize the cooling effects of contrails by encouraging their formation during periods of high solar radiation. However, while innovative, this approach faces considerable uncertainties regarding the magnitude and duration of the cooling effect, driven by a limited understanding of contrail microphysics and their interactions with atmospheric conditions. In addition, the cooling effect is generally less pronounced than the warming impact of contrails. Therefore, prioritizing strategies to reduce warming contrails may offer greater practical benefits as a mitigation approach.

#### C. Geographical Effect

Persistent contrail hotspots were concentrated in central and southwestern Japan, as well as northern regions during specific months, as shown in Fig. 2. These patterns resonate with [6], [9], which identified southern and eastern Asia as contrail formation zones. Although [30] highlighted the limited persistence of contrails in northern Europe due to low relative humidity, our findings indicate that humid and dynamic conditions in Japan's airspace, particularly during summer, contribute to higher EF values. Furthermore, oceanic

sectors such as A01 to A03, which were not considered in [7], [8], contributing 32.53% of total EF as summarized in Table II, underscore the importance of targeted interventions in regions with high impact, as emphasized by [9].

Contrail mitigation strategies must account for differences between oceanic and en route airspace. Our findings showed that one-third of contrail energy forcing (EF) occurs in oceanic regions, as summarized in Table II, highlighting the potential for broader altitude adjustments in these less constrained areas. In contrast, en route airspace requires more targeted interventions in specific hotspots such as F07, F14, F15, and F01, visualized in Fig. 3 due to its higher traffic density and complexity. Recent studies underscore the impact of diverse traffic patterns on controller workload [31], which requires strategies that not only reduce traffic density but also address traffic complexity by adjusting routes or departure times for high-impact flights.

#### D. Flight Level and Lifetime

Our analysis revealed a strong correlation between contrail formation altitude and persistence as described in Fig. 6. Contrails formed at higher altitudes ( $\approx 39,000$  ft) during the summer months exhibited extended lifetimes, consistent with findings in [10]. This is attributed to stable atmospheric conditions near the tropopause, including low wind shear and high relative humidity as visualized in Fig. 7, which improve the stability of ice crystals. The study in [1] similarly noted the benefits of higher cruise altitudes in mitigating contrail formation. However, unlike their focus on avoiding ISS regions, our findings suggest that optimizing FL allocation across seasons can further enhance mitigation efforts.

In Japan, airspace is separated at FL335 [32], with seasonal variations influencing the formation of contrails. During summer, contrails predominantly form above FL335, while winter sees formation across both upper and lower airspace, as shown in Fig. 5. Given the high traffic density at FL400 and FL410 during summer, aircraft often have limited options for climbing to avoid contrail formation. Consequently, many aircraft are required to descend by 2,000 or 4,000 feet. Such descent maneuvers, characterized by increased drag, result in higher fuel consumption compared to climbing operations as argued in [9]. In contrast, altitude changes to avoid winter contrails may require crossing sector boundaries, increasing inter-sector communication demands. This could increase the controller workload, making it essential to develop efficient coordination protocols to manage such transitions while maintaining operational effectiveness.

#### E. Contrail Avoidance Operationalization

Building on the operational feasibility highlighted in [9], [13], our study underscores the potential of integrating contrail mitigation strategies in ATM of Japan. The study in [13] demonstrated a 94% success rate in rerouting warming contrails, while our findings suggest similar opportunities, particularly by targeting specific flight corridors and high-EF sectors. The challenge of balancing operational costs with environmental benefits, as discussed in [15], remains central to contrail avoidance strategies. Our results further facilitate

the possibility of small-scale altitude adjustments, which can mitigate significant warming effects without disrupting overall traffic flow, a point also supported by [14] during the COVID-19 traffic downturn. However, the current reliance on reanalysis weather data, such as ERA5, presents a limitation for operational planning, as these datasets represent past conditions rather than future forecasts. To implement contrail mitigation strategies in real-world operations, predictive weather data will be essential to enable accurate and timely altitude and route adjustments.

This study will be able to benefit from our existing Human-in-the-Loop (HITL) simulation environments and Human-Machine Interface (HMI) [33], which will be redesigned to support altitude adjustments for contrail mitigation. However, the choice between onboard avoidance strategies [11], [13] and controller-led approaches [12], remains unresolved. Future HITL simulation experiments will be key in evaluating the feasibility and effectiveness of these methods in the context of Japanese airspace, providing insights to guide their integration into ATM systems.

## VI. CONCLUSIONS AND OUTLOOK

This study has provided a foundational analysis of contrail formation dynamics in Japanese airspace, identifying high-impact regions and periods for targeted mitigation. The results revealed that significant contributions of EF from a small subset of flights and specific airspace sectors, such as A01–A03 in oceanic sectors and F07, F14 to F15 and F01 in en route sectors. The correlation between the altitude of contrail formation and persistence highlights the operational potential of altitude adjustments, particularly during high EF periods from April to June. These findings underscore the feasibility of targeting high-impact flights and regions for contrail mitigation, with strategies such as nighttime altitude adjustments and rerouting offering promising climate benefits. For example, 1.71% of flights were shown to represent 80% of the total EF of the contrail, demonstrating the disproportionate impact of a small fraction of air traffic. While this study focuses on Japan’s airspace, the findings may be generalizable to other high-density, meteorologically diverse regions such as Southeast Asia or coastal regions of East Asia. The methodology and identified patterns could inform contrail mitigation strategies in similarly constrained airspaces with high traffic volumes and complex weather dynamics.

Future research should focus on operationalizing these insights through advanced tools such as CoCiP and HITL simulations to evaluate their real-time feasibility. However, it is critical to recognize that the accuracy of predictive models cannot be taken for granted. Comprehensive error evaluation and validation are necessary steps before these models can be reliably applied in ATC operations.

Specific areas for further investigation include the following.

- 1) Exploring framework of vertical diversion, rerouting, and rescheduling, which balances climate benefits and fuel/delay penalties to ensure sustainable and cost-effective implementations.

- 2) Developing HMI between ATCos/Pilots and predictive tools to support altitude adjustments and route optimizations.
- 3) Contrail formation over oceanic regions (e.g., sectors A01–A03) remains underexplored and represents an opportunity for a broader application of mitigation strategies.

By addressing these challenges, the findings of this study can contribute to a more sustainable aviation system tailored to the unique characteristics of Japanese airspace. These efforts align with global goals to mitigate the impact of aviation climate while maintaining operational efficiency.

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