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A Data-Driven Study

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Contrail Formation and Mitigation in the Japanese Airspace: A Data-Driven Study

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***Abstract*—Estimating contrail formation and proposing effective mitigation strategies have posed significant challenges for the aviation industry in recent years. This study utilizes the Japanese airspace as a case study to address the challenge of assessing and minimizing the environmental impact of contrails. Initially, we introduce a novel combination of meteorological and flight trajectory data sources, followed by a comparative data quality analysis. Drawing on four months of data during different seasons from 2023, we conduct an in-depth analysis of contrail formation within the Japanese airspace, uniquely quantifying contrails with high-resolution data to provide insights into their geographical and seasonal variations. Subsequently, we examine the effectiveness of altitude diversions as a mitigation strategy. Our findings identify clear geographical and seasonal influences on contrail formation in the region. We illustrate that altitude diversions can significantly reduce contrail formation with minimal altitude adjustments of up to 2000 ft. We found that minor altitude diversions can mitigate between 70% and 90% of the persistent contrail formed near the Japan region.**

Notably, the results also highlight a concerning phenomenon: during warmer months, such as July, a higher quantity and percentage of persistent contrails is observed, and a larger proportion of these contrails cannot be mitigated through altitude diversions. This result could intensify positive radiative forcing during warmer periods, underscoring the need for further research into contrail mitigation strategies.

***Keywords*—Contrails, ClimCORE, ECMWF, Japan, OpenSky**

I. Introduction

Sustainability is one of the main challenges facing the aviation industry today. Carbon dioxide emissions, non-CO_2 emissions, and contrails are three factors that negatively impact the global climate. At a short timescale, the most significant individual contributor to aviation's total radiative forcing is the formation of contrail cirrus, albeit with some uncertainties [1]. While carbon dioxide emissions today influence global warming in 20 to 40 years, the warming effect of contrails is immediate [2].

A. Background on contrails and avoidance

Generally, contrails are formed at low temperatures (-40 °C) and at high relative humidity [3]. The formation of contrails can be explained by the Schmidt-Appleman Criterion (SAC) [3]. This thermodynamic model considers ambient pressure, humidity, and the water-to-heat ratio in exhaust plumes. If an aircraft flies through atmospheric conditions that meet the Schmidt-Appleman Criterion, saturation with respect to liquid water occurs, and a contrail is created.

Certain contrails disappear quickly, and these non-persistent contrails have a negligible climate impact [4]. However, persistent contrails with lifetimes of more than a few minutes occur when they do not evaporate when mixed with the environment [5]. These persistent contrails form when the ambient air is supersaturated with respect to ice [6] in ice-supersaturated regions (ISSR). In summary, for persistent contrail formation, two atmospheric conditions must be met:

1) Schmidt-Appleman Criterion, where the temperature must be below a critical temperature.
2) The ambient air is supersaturated with respect to ice, with a relative humidity larger than 100%, in an ice-supersaturated region.

While these ice-supersaturated regions are laterally expansive, they are typically relatively thin, around 200-500 meters [2]. This implies that an aircraft should avoid ice-supersaturated regions by changing its altitude to prevent persistent contrail formation.

Altitude diversions offer an air traffic management solution with minimal safety and emission effects [7], rather than a change in latitudinal or longitudinal positions. A slight increase or decrease in altitude, only a few hundred feet, could prevent the formation of persistent contrails.

Minimizing contrail's radiative forcing is a prompt way of limiting aviation's climate impact without the implementation time required for other effective sustainability measures, such as alternative fuels or aerodynamic aircraft design.

In practice, avoiding contrail forming atmospheric regions involves flying around the region's perimeter or over or under the region [2]. Due to their broad lateral expansiveness, more environmental benefit is gained if the altitude is varied rather than rerouted [8], [9], [10].

B. Area of focus in this study

Eastern Asia and Japan, specifically, were noted by [11], [12], [7] as areas with high contrail prevalence. With the region's increasing air traffic, contrail mitigation and analysis

of an operational strategy in altitude diversions have become increasingly relevant.

In previous work [7], contrail-forming flights were quantified globally, along with their geographical prevalence and the magnitude of the altitude deviations necessary to avoid contrail-forming regions. Using the IGRA weather balloon dataset and flight data from OpenSky, a feasibility study was performed using open-source global data. The analysis in [7] shows strong geographical and seasonal influences for identifying contrail-forming flights.

This study, a research collaboration between Delft University of Technology and The University of Tokyo, focuses on the Japan region particularly, with a new data set and an improved data pipeline. We first evaluate different meteorology and flight data sources and their suitability for this research study. Then, the most available datasets are chosen to study contrail formation during four seasons in 2023 over the Japan region. Lastly, we also focus on examining the potential of avoiding persistent contrails with altitude diversions.

The paper is structured as follows. Section II analyzes different sources of available meteorological data and flight data. Section III provides examples and aggregated results on the contrail over the selected months in 2023. We also provide a detailed analysis and explanation of the particular contrail conditions in Japan. Finally, in sections IV and V, further discussions and conclusions of this research are provided.

II. Data

Meteorological data are required to determine regions where contrails, especially persistent contrails, are prone to form. Parameters including temperature, pressure, and humidity are essential for calculating the contrail formation conditions, which involve the Schmidt-Appleman criterion and identification of ice-supersaturated regions. Flight data are also necessary to evaluate whether trajectories intersect with these sensitive regions. This section explains the data sources used.

A. Meteorological data

In this study, we evaluated three different sources of meteorological data to support the analysis of contrail formation. These are the MSM (Meso Scale Model), ClimCORE, and ERA5 data. The first two sources are from the Japan Meteorological Agency, and the last one from ECMWF (European Centre for Medium-Range Weather Forecasts). However, only one day of data (November 12, 2018) is available for MSM and ClimCORE for comparison.

For the large-scale study in this paper, we rely on the ECMWF ERA5 data, which is fully open and available.

1) The Meso-Scale Model: The MSM refers to the Grid Point Value (GPV) numerical forecast model the Japan Meteorological Agency provided. The MSM is used for weather warnings, advisories, very short-range forecasts of precipitation, and aviation forecasts covering Japan. It offers 78 and 39-hour forecasts every 3 hours.

Temperature and relative humidity data are available for contrail analysis at different pressure altitudes. However, the data for relative humidity is available only up to the 300 hPa pressure level (approximately 30,000 feet altitude).

2) ClimCORE: The ClimCORE (Strategic Social Co-creation Hub based on Regional Meteorological Data and Advanced Academic Research) project was established to overcome some of the limitations of MSM. This project is a collaboration between the University of Tokyo's Institute for Advanced Studies and the Japan Meteorological Agency.

The ClimCORE data consists of meteorological data obtained through regional reanalysis using operational MSM data and observation data from satellites and other sources in collaboration between the University of Tokyo's Institute for Advanced Studies and the JMA. In Japan, where medium-scale phenomena such as typhoons and localized heavy rainfall are common, there is a high demand for high-resolution meteorological data, prompting the initiation of this project.

The atmospheric reanalysis data for Japan and its surrounding seas, RRJ-ClimCORE, has a temporal resolution of one hour, a horizontal resolution of 5 km, and 96 vertical layers. Unlike MSM data, it also provides data for relative humidity above the 300 hPa pressure level. Additionally, regarding major structures, both MSM and ClimCORE are largely similar, with ClimCORE capable of representing finer structures. This capability is believed to enable more detailed analysis compared to MSM data. However, since the reanalysis is ongoing, unlike MSM data, not all meteorological data can be utilized. Furthermore, it is also necessary to verify whether the finer structures align with reality using observational data, such as radiosonde data.

Figure 1 illustrates the vertical profiles of the temperatures and relative humidities of two cities (Sapporo and Ishigaki). It is possible to see that ClimCORE has better availability at higher altitudes. The measurements of humidities are also different from MSM.

In Table I, we also show the parameters of the ClimCORE data that can support the analyses of contrails.

TABLE I: Model-Level parameter in ClimCORE

Parameter	Description
U	x-axis wind
V	y-axis wind
W	Vertical wind
QVa	Specific humidity
QCa	Cloud water mixing ratio
QIa	Cloud ice mixing ratio
QRa	Rain mixing ratio
QSa	Snow mixing ratio
QGa	Hail mixing ratio
QKE	Turbulent kinetic energy
T	Temperature
P	Atmospheric pressure
DENS	Air density

3) ECMWF ERA5 data: The European Centre provides the ECMWF ERA5 for Medium-Range Weather Forecasts, and the dataset includes global atmospheric reanalysis data from 1979 to the present. This dataset has a high spatial resolution of around 30 km and a temporal resolution of one hour.

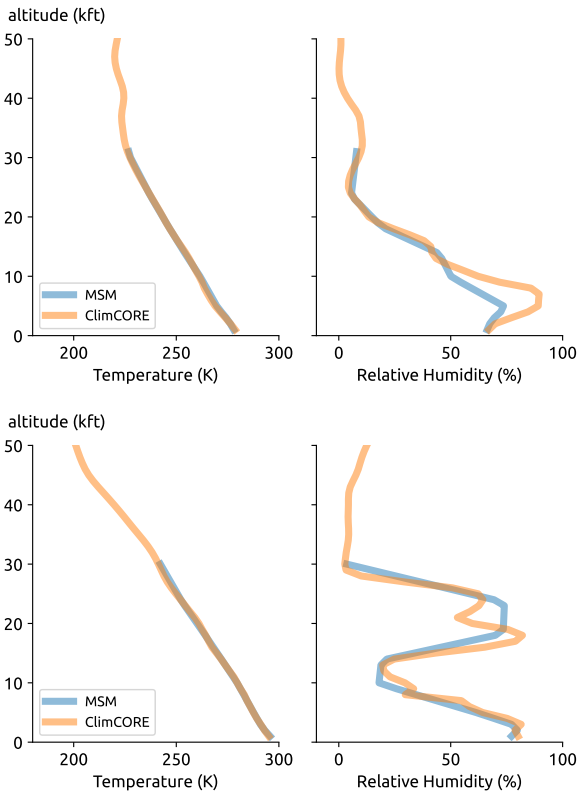

Figure 1. Comparison of MSM, ClimCORE, and Radiosonde. The top figure shows the temperature and humidity at Sapporo, and the bottom figure shows the parameters for Ishigaki.

The ERA5 dataset provides global coverage of temperature, humidity, and wind data across all altitudes relevant to commercial flight operations for contrail analysis. Additionally, the ERA5 data includes variables related to atmospheric composition, cloud properties, and radiation. The dataset is assimilated with observational data from satellites, aircraft, and ground-based weather stations.

B. Flight trajectory data

For this study, two data sources are available: CARATS (Collaborative Actions for Renovation of Air Traffic Systems) and OpenSky data. After considering the advantages and disadvantages, we chose OpenSky data to conduct the contrail evaluation and mitigation studies. In the following, we detail the rationale for this choice.

1) CARATS data: CARATS is a flight traffic dataset ENRI (Electronic Navigation Research Institute) provided. It has coverage over Japan's four area control center (ACC) areas: Sapporo ACC, Tokyo ACC, Fukuoka ACC, and Naha ACC.

The positions of the flights in CARATS are tracked and calculated by the radar system [13]. The parameters of the flight include the timestamp (at 10-second intervals), pseudo flight number, latitude, longitude, altitude, and aircraft type.

There are also some disadvantages of this dataset. The dataset is only available up to 2020. Secondly, the flight is anonymized. The callsigns and ICAO transponder addresses are unavailable, making it difficult to combine with external aircraft databases. The lack of data from 2020 makes it challenging to adopt CARATS data in this study.

2) OpenSky: The OpenSky Network is a crowd-sourced network consisting of several thousands of Automatic Dependent Surveillance-Broadcast receivers [14]. Thanks to the community contributors, it has relatively good coverage in Japan. However, the total coverage is still less than CARATS data.

Compared to CARATS, the OpenSky trajectories include additional parameters like callsigns and transponder codes. The data availability is also much higher, as the delay in historical data is only a couple of days.

For this study, four months of data from OpenSky in 2023 is downloaded for analysis. The months are January, April, July, and October, covering the seasonal changes in meteorological conditions and flights. In Figure 2, we show one day of traffic data from both CARATS and OpenSky to compare the two datasets.

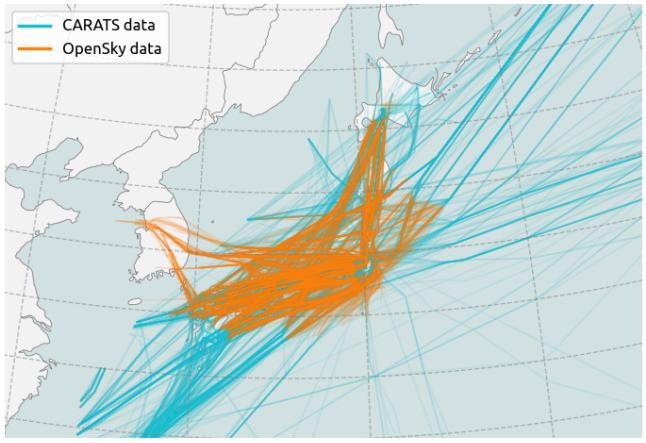

Figure 2. Coverage comparison between CARATS and OpenSky.

III. Analysis

A. Comparison of different meteorological models for contrail research

In this study, meteorological data, including ClimCORE data, was compared to confirm that the predictions of meteorological data from each model roughly aligned. The temperature and relative humidity over ice, which were related to contrail formation conditions, were compared.

Additionally, due to the absence of relative humidity data above approximately 30,000 feet in MSM data, the predicted results of temperature and relative humidity at 30,000 feet were compared. Data from November 12, 2018, was used, for which ClimCORE reanalysis had been completed.

Figures 3 and 4 illustrate the temperature and relative humidity distribution over ice predicted by MSM and ClimCORE,

respectively. These figures revealed that meteorological data roughly coincided across the models in the horizontal direction.

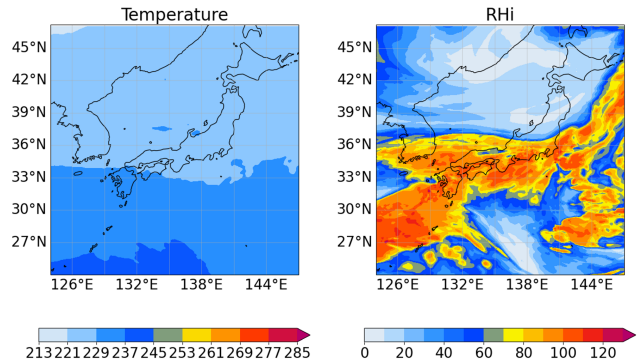

Figure 3. Temperature and relative humidity from MSM at 30,000ft.

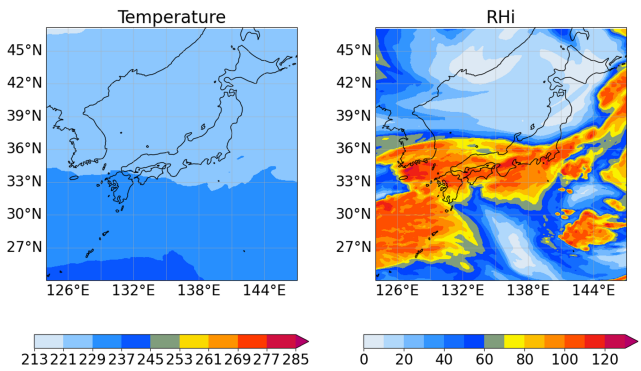

Figure 4. Temperature and relative humidity from ClimCORE at 30,000ft.

Figure 5 shows the discrepancies between MSM and ClimCORE data (ClimCORE - MSM). For temperature, the error remains within 1 K for most regions, with an average of -0.13 K. For relative humidity, the error is within 20% for most areas, with an average of 0.33%.

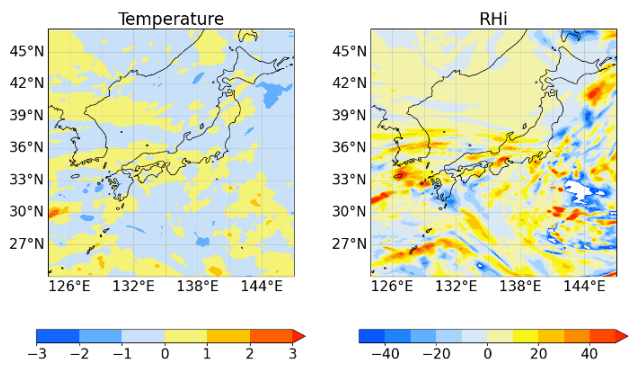

Figure 5. Difference between ClimCORE and MSM at 30,000ft

Furthermore, when comparing the vertical profiles of temperature and relative humidity over ice in Figure 1, a close alignment was observed between MSM data and ClimCORE data in terms of temperature and relative humidity with respect to ice with high precision. However, slight discrepancies in the relative humidity values suggested that ClimCORE could represent finer structures.

In Figure 6, we also illustrate the temperature humidity from the same date at the same altitude for the ECMWF data to serve as a comparison. We can see that the estimated temperature is similar. However, compared to Figure 4, the ClimCORE appears more detailed for humidity. This can be reflected in the much sharper boundaries of relative humidities in ClimCORE data.

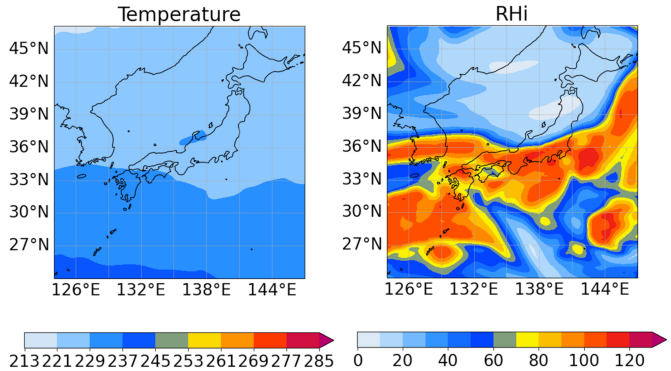

Figure 6. Temperature and relative humidity from ECMWF at 30,000ft.

B. *Seasonal analysis based on OpenSky flights*

This analysis focuses on the seasonal variations in the contrail forming conditions. First, the total flight distance over all the flights in the Japanese airspace is calculated as the base for reference, capturing the seasonal change in the number of flights.

Based on the flights from OpenSky, we obtain the meteorological conditions using the *fastmeteo* tool [15], which can efficiently download the EAR5 data and provide fast interpolations of temperature and humidity along all trajectories.

Table II shows the aggregated results over the four months in 2023. The first column shows the total flight distance, in nautical miles, from all flights for a given month within the selected airspace. The second column displays the total distance from flights that pass over regions where the Schmidt-Appleman Criterion is valid. The third column shows the distance where trajectories experience ice supersaturation. Finally, the last columns indicate the total flight distance when persistent contrails could have occurred based on the Schmidt-Appleman Criterion and ice-supersaturated region.

TABLE II: Seasonal statistics on contrail formation (distance, in nautical miles)

	Total distance	SAC	ISSR	Contrail
January	24,698,000	18,417,000	332,000	92,000 (0.7%)
April	26,296,000	18,140,000	3,708,000	2,424,000 (9.2%)
July	31,386,000	13,801,000	4,515,000	2,462,000 (7.8%)
October	20,855,000	13,420,000	533,000	286,000 (1.4%)

Based on the OpenSky data, the total flight distance is between two to three million nautical miles. These results can

also be visualized in Figure 7 for better inspection. Different criteria for persistent contrails are shown in different shades of blue. The orange represents the formation of persistent contrails.

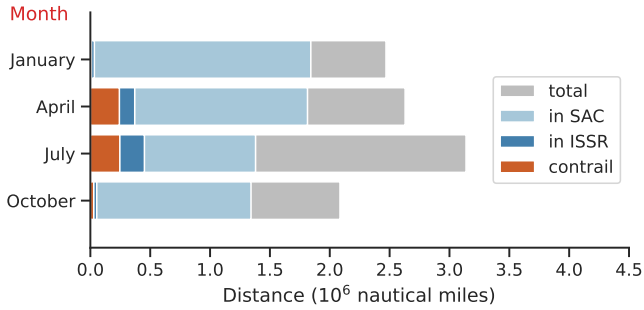

Figure 7. Total flight distance and portions that are related to different contrail forming conditions.

In this figure, we can see several interesting observations related to contrail forming conditions. In January and April, large portions of flights experience meteorological conditions where the Schmidt-Appleman Criterion applies, representing the potential of contrail formations. The ice-supersaturated regions, affecting the persistency of the contrails, are distributed differently. They mostly appear in April and July. When combining both conditions, we can see that the formations of the most persistent contrails are during April and July. They count up to 9% of all the total flight distances.

C. Altitude diversions to mitigate contrails

Once the formation of persistent contrails has been determined, we can further study whether simple mitigation strategies could have been applied to reduce the amount of persistent contrails. Here, we want to evaluate the effect of altitude diversions, as the airspace routes are highly structured, and lateral diversions may introduce more disruptions to existing air traffic.

The altitude diversion is also limited to 2,000 ft, aiming to bring relatively minor changes from the current operations. It is also a diversion that can be performed considering the aircraft's performance in most conditions. Six alternative altitudes ranging from -2000 ft to +2000ft, with steps of 500 ft, for all flight positions experiencing persistent contrail formation conditions were evalutated.

The persistent contrail forming conditions at all six alternative altitudes are calculated to determine the altitude that requires the minimum deviation to prevent the persistent contrail formations. In Figure 8, we can see an example for January 13, 2023, where the flights are illustrated in blue. Persistent contrails, estimated based on the meteorological conditions from ERA5 data, are displayed in red.

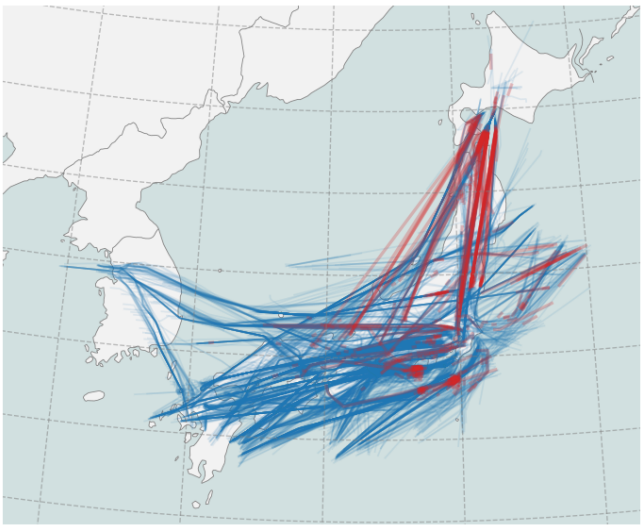

Figure 8. Example of one day of flights (in blue) and ones with persistent contrail forming conditions (in red).

In the sub-plots of Figure 9, we visualize only the persistent contrails (in red) and those mitigated with the minimum amount of altitude diversions (in green).

The first sub-plot shows the persistent contrails at their original flight altitude. The second, third, and last figures show flights that successfully mitigated the persistent contrails, visualized over the data from the first sub-plot. When examined closely, we can see that many of the persistent contrails on this day can already be mitigated with a small diversion of 500 ft.

Figure 10 shows the final results where all six alternative altitudes have been considered. Here, we illustrate the persistent contrails that are mitigated with altitude diversions in green, and the remainder of persistent contrails that cannot be mitigated are shown in red. We can see that only a small portion of the persistent contrails are not avoidable on this chosen date.

Table III shows the avoidance of persistent contrails for altitude diversions over the entire four months. The first two columns show the total flight distance and distances of persistent contrails. Then, the following four columns represent the persistent contrail distances that could have been avoided with respective altitude changes. The last column shows the

TABLE III: Distances (in nautical miles) statistics related to contrails and mitigation through altitude diversions.

	Total distance	Contrail distances	+/-500ft	+/-1000ft	+/-1500ft	+/-2000ft	remainder
January	24,698,000	92,000	-34,000 (-37%)	-19,000 (-21%)	-12,000 (-13%)	-7,000 (-8%)	9,000 (10%)
April	26,296,000	2,424,000	-518,000 (-21%)	-526,000 (-22%)	-312,000 (-13%)	-271,000 (-11%)	613,000 (25%)
July	31,386,000	2,462,000	-536,000 (-22%)	-398,000 (-16%)	-377,000 (-15%)	-269,000 (-11%)	647,000 (26%)
October	20,855,000	286,000	-93,000 (-33%)	-72,000 (-25%)	-39,000 (-14%)	-22,000 (-8%)	35,000 (12%)

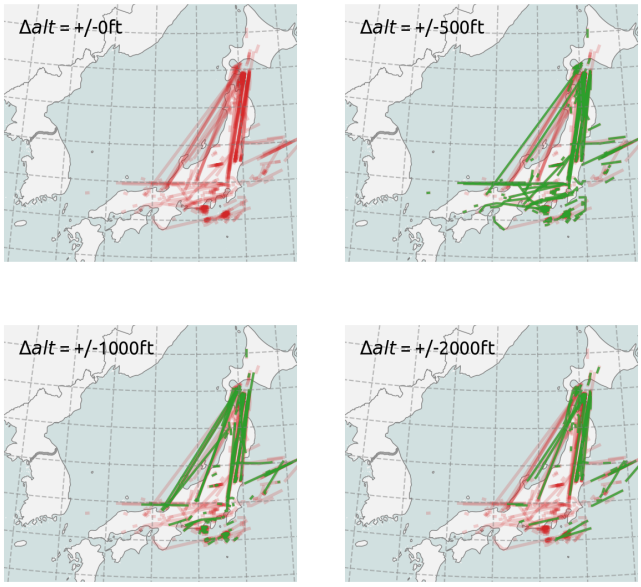

Figure 9. Persistence contrails that can be mitigated with different altitude diversions (in green colors).

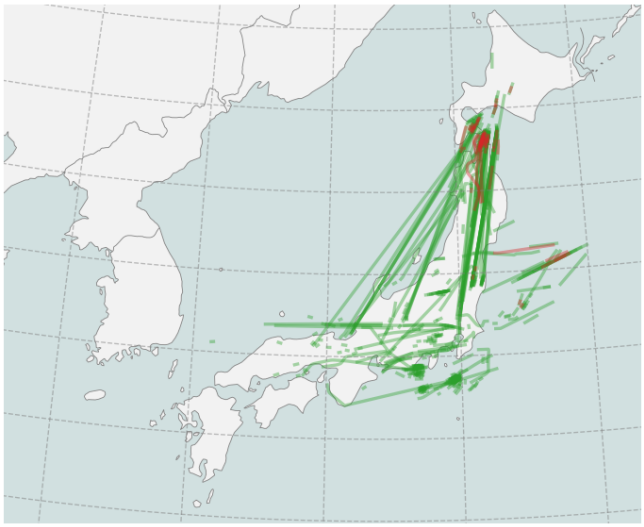

Figure 10. Example of the final remaining persistence contrails that cannot be mitigated with the desired altitude diversions.

remainder of the contrail distance that can not be avoided within the maximum of 2000 ft altitude changes.

Figure 11 also visualizes the percentage of reduced persistent contrails. Each of the pie charts represents one of the four months in 2023. Different altitude diversions are shown in shades of blue, and the remainder are indicated in orange. We can observe the large differences among the months in different seasons. Compared to April and July, as there are much less persistent contrails in January and October, it is also more likely to avoid these contrails by smaller diversions in these months. This is mainly due to the large vertical regions with higher humidities during April and July.

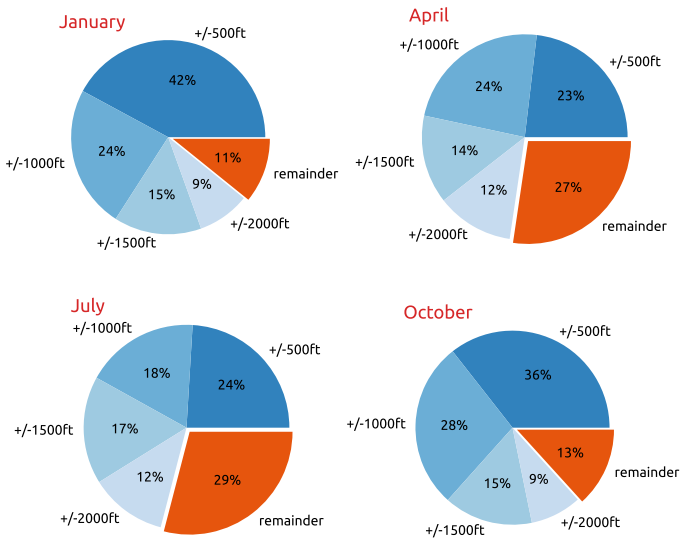

Figure 11. Percentage of persistent contrails avoided with altitude diversions.

To further explain the phenomena, we can explore the contrail forming conditions, including the Schmidt-Appleman criterion and the ice-supersaturated regions. The pie charts in Figure 12 and Figure 13 illustrate the altitude diversions required to avoid these two conditions during the different months. The results can also be related to the previous Figure 7.

Firstly, regarding the formation of contrails, we want to see whether altitude diversions can avoid the region where the Schmidt-Appleman Criterion is valid. Then, we want to check whether seasonal differences exist during the four months of 2023.

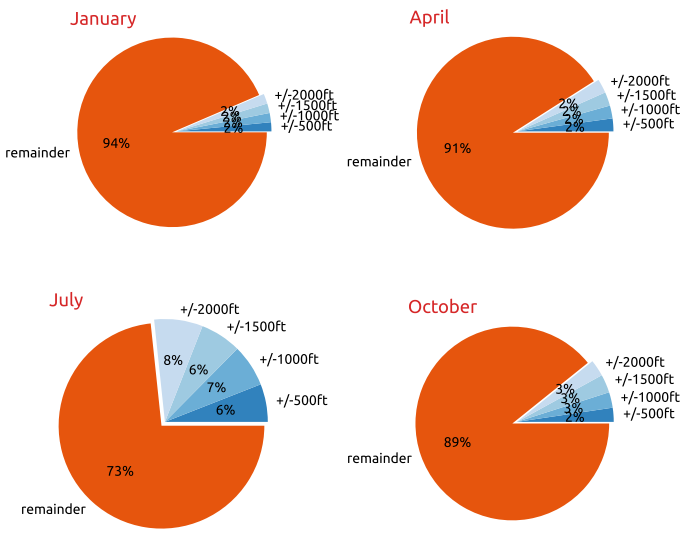

Figure 12. Percentage of flight distance avoiding SAC with altitude diversions.

In Figure 12, we can observe that in January, April, and October, it is difficult to fly outside of the regions that satisfy

the Schmidt-Appleman Criterion. This reflects a generally colder temperature, which is generally the case for these months. However, it is easier to achieve altitude diversions in hotter months, like July. The trends correlated well with our understanding of the temperatures during these four months.

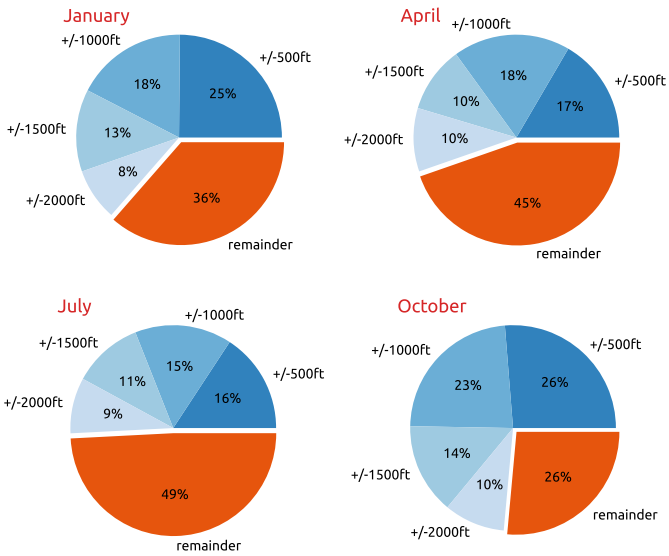

Figure 13. Percentage of flight distance avoiding ISSR with altitude diversions.

Different results can be seen in Figure 13 when we evaluate the avoidance of ice-supersaturated regions with vertical diversion. We can discover that the hotter the month is, the harder it is to avoid these ice-supersaturated regions. This is very likely due to the high humidity in the warmer months. The statistics in this figure align with the previous Figure 11, which also confirmed that ice supersaturation is a more critical factor in forming persistent contrails.

IV. Discussion

A. Weather models

In this study, we analyze different weather models that can be used for contrail studies in the Japanese airspace. Samples data from two models, MSM and ClimCORE, are provided by the Japan Meteorological Agency. One open data, ERA5, is used for comparison. We have discovered that the MSM data is unsuitable for aviation studies as the maximum altitude supported by this dataset is only around 30,000 ft, below the typical cruise altitude of commercial aviation.

Comparing the ClimCORE and ERA5 data, we also discover that ClimCORE has higher lateral variations, indicating better measurement accuracy due to local meteorological information for data assimilation. Vertically, it also has better resolutions at higher altitudes, which makes it an ideal data source for contrail studies at cruise flight levels.

However, as only one day of ClimCORE data from 2018 is available for this study, we have to rely on the ERA5 data for the rest of the paper for contrails analysis over 2023. We also usef *fastmeteo* to rapidly process ERA5 data stored in Zarr format to boost the computation efficiencies of our analysis.

B. Flight data

Similarly, two options for the flight data have been presented at the start of this research: CARATS data from ENRI and OpenSky data from the OpenSky Network. OpenSky data is a well-known source of fully open data that has supported many research studies in air transportation. CARATS is a new open data source provided by ENRI, which has better coverage than OpenSky over Japanese airspace. However, the availability of CARATS data is limited. Currently, only data until 2020 is available.

Hence, we choose to focus on the OpenSky data to explore contrail formation and avoidance during the four months of 2023. The entire ecosystem of tools for OpenSky is also developed, as *pyopensky* is available to download historical data, and *traffic* is available for convenient processing of the trajectory data from OpenSky.

It is also worth mentioning that OpenSky may suffer from coverage limitations and data outages. In Japan, the coverage is relatively good. However, data availability can be quite low for other airspace in Asia.

C. Statistics on contrail formation and avoidance

In [7], contrail diversion was studied at a large scale using open meteorological data from radiosondes, unlike ERA5 data. The measurements from the radiosondes are only available at specific locations (see Figure 14). The vertical accuracy and resolution from the radiosonds are much higher than ERA5 data and thus yield more accurate results.

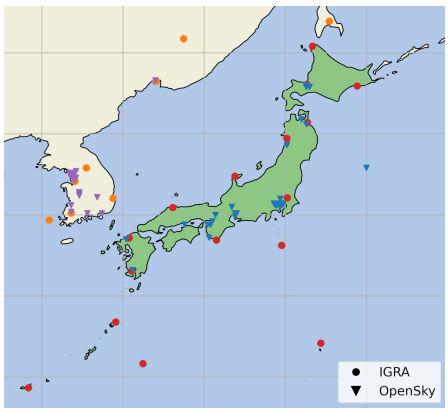

Figure 14. Radiosonde stations from the Integrated Global Radiosonde Archive (IGRA) and OpenSky receiver locations around Japan airspace.

Contrails from [7] are counted based on flights because only small regions around the radiosonde stations are selected at midnight and noon. This paper employs a different way of counting contrails: the flight distance through the contrail-forming regions. This new approach was adopted because of the dense and lengthy trajectories used in this paper. This way of counting contrails is also why the percentages in Tabel II do not add up to 100% strictly. When counting for flight distance, segments of less than 5 minutes are ignored.

D. Safety and emissions caused by altitude changes

Safety and excess carbon emissions are often two factors of concern when flight diversion due to contrails is proposed. In our earlier study [7], we analyzed the relationship of altitude diversion with safety and emissions based on a dataset at a global scale. It has been found that the increase in conflicts and intrusions due to these altitude diversions is marginal when the maximum altitude change is limited to 2000 ft. This change in altitude could cause excess emissions, with a median between 0.25% and 2% at the large scale. However, as shown by [7], estimation of emissions is difficult without knowledge of aircraft mass. Furthermore, other factors like cost index and airspace constraints could all affect the optimality of fuel and emissions when diversion for contrails is required.

E. Seasonal variations

Figure 11 shows strong seasonal variations between January, April, July, and October. More contrails can be avoided in January and October with smaller altitude diversions. In April and July, not only are there more contrails, but a larger percentage of contrails cannot be avoided with the maximum 2000 ft diversions.

This likely indicates that the ice-supersaturated regions are much thicker vertically during the hotter months when the humidity is generally high. This hypothesis can be partially confirmed with the analyses performed in Figures 12 and 13, where we can see different distributions of contrail forming conditions based on Schmidt-Appleman criterion and ice supersaturated regions.

This insight may also lead us to an interesting (or worrying) conclusion, which indicates that during the warmer months, the higher humidity may cause unavoidable persistent contrail, providing higher positive radiative forcing during warmer months. More research is required to examine this phenomenon further.

V. Conclusion

This study quantifies contrail formations in the Japanese airspace by first investigating a new integration of meteorological and flight trajectory data. The qualities of different data sources are examined through the comparative analysis of data from MSM, ClimCORE, and ECMWF ERA5 alongside OpenSky flight data. Recommendations for this dataset are made for future studies.

For the more extensive temporal analysis for 2023, we have used ERA5 and OpenSky data to study contrails' geographical and seasonal dynamics. Our research confirms the significant impact of geographical location and seasonal variations on contrail formation, with a marked increase in persistence observed during the warmer months, particularly in July.

The efficacy of altitude diversions proposed by previous studies as a contrail mitigation strategy has been evaluated, demonstrating that adjustments within 2000 ft can significantly reduce contrail formation. We found that small altitude diversions can mitigate between 70% and 90% of the persistent contrail formed near the Japan region.

Furthermore, our findings underscore a new insight: during warmer months, a substantial portion of persistent contrails remain unaffected by altitude diversions, potentially increasing their negative climatic impact. This observation points to the pressing need for further exploration of contrail mitigation strategies, especially in their warming effect.

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