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OpenSky Report 2024: Analysis of Global Flight Contrail Formation and Mitigation Potential

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***Abstract*—With the increasing coverage of the OpenSky, flight data gathered from the network of receivers has become a primary source of open data for aviation research. This year marks ten years of OpenSky. In this report, we employ a year's worth of OpenSky data to analyze the formation of contrails and study the potential mitigation with altitude diversions. Persistent contrails, often formed under humid atmospheric conditions, significantly trap outgoing terrestrial radiation. More insights into contrails are essential for studying aviation climate impact. We estimated the potential formation of persistent contrails based on the numerical weather assimilation data. An efficient approach is employed to fuse meteorology data in our analysis, which allows the fast evaluation of these contrail conditions at a very large scale. We designed a simple yet effective algorithm for flight with persistent contrails to study the shortest altitude diversion that would have prevented the contrail formations. We have estimated that between 5% and 9% of total flight distances each month could have formed persistent contrails. Furthermore, altitude diversions could have mitigated 70% of these contrails.**

***Index Terms*—Sustainability, contrails, meteorology, OpenAP, optimization, OpenSky, open data**

I. Introduction

Founded in 2013, The OpenSky Network [1] operates as a crowdsourced network of ADS-B receivers, consistently gathering surveillance data from equipped aircraft and offering it for scientific purposes. Over the years, its coverage has continuously expanded, with currently over 6,000 sensors registered worldwide. This platform has played a significant role in facilitating research across various domains, including radio frequency, signal security, and many topics related to air traffic management, including safety, efficiency, and sustainability of air transport.

A. OpenSky supported aviation sustainability research

With facilitated access to crowdsourced data, researchers have been explicitly improving the transparency of data-driven studies, especially for aviation sustainability-related topics, including aircraft emissions [2], [3], operation efficiencies [4], [5], [6], and air transport's climate impact [7]. Several recent research studies have also combined OpenSky data and remote sensing data to analyze contrail formations [8], [9], showing potential adoption for open-source data in contrail analysis.

In another recent study [10], some authors of this paper combined OpenSky data with global radiosonde measurements to study the local formation of contrails at these locations and propose simple altitude diversions that could reduce a significant amount of persistent contrail formation. However, the study is limited to the areas where radiosonde stations are available. Moreover, only two hours of flights at midnight and noon were analyzed.

B. Brief background of contrails and impacts

The overall climate impact of aviation results not only from carbon dioxide (CO_2) emissions but also for a significant part from non-CO_2 effects. These include contrails and contrails cirrus formation from emitted water vapor, which represent one of the most significant radiative forcing contributors from the aviation sector [11], [12]. Contrails usually appear at high altitudes with very low ambient temperatures. They can also persist up to a day in the region of the atmosphere where the relative humidity with respect to ice is greater than 100% [13].

Persistent contrail clouds can either reflect sunlight back into space during the day, leading to a cooling effect, or trap large amounts of heat that would otherwise leave the atmosphere, leading to a warming effect. This warming effect dominates according to previous research [12], which suggests a net positive global radiative forcing caused by contrails. However, the significant uncertainties still cause debate regarding the magnitude of the impact.

Since contrail's effects on the climate depend on several parameters, such as altitude and ice-supersaturated regions, one way to reduce them could be to construct flight trajectories that avoid areas that favor contrails being formed. Thus, one key point is determining which flight routes will create contrails.

Recent research has focused on these contrail inventories. Air traffic data obtained through NATS (the UK air navigation service provider) and ECMWF's ERA5 reanalysis data were used to quantify contrail formation in the North Atlantic from 2016 to 2019 in [14]. In [15], CARATS provides flight track data over the Japanese airspace and uses ERA5 data. Data from a commercial airline is used in [16] to assess the feasibility of contrail avoidance based on ECMWF HRES forecast data over several weeks in 2023 and 2024.

C. Contributions of this paper

Building upon this aforementioned work, we analyze the formation of contrails in 2022 with all the available data from the OpenSky Network over the North American, Europe, and the Atlantic region. Approximately 5 TB of raw flight data for the whole year globally are extracted and combined with the entire year of weather data from ERA5 from the European Centre for Medium-Range Weather Forecasts (ECMWF), using fastmeteo, a tool that we recently developped [17]. When necessary, altitude diversion strategies are employed to prevent persistent contrail formation. This extensive analysis will provide concrete conclusions regarding the formation of contrails.

Overall, by exploring the global flight and meteorology data and studying specifically for one region, we aim to bring better insights into contrail formation and mitigation strategies. This report addresses the following research questions:

- What are the statistics on contrail formation on a global scale, subject to the data availability of OpenSky?
- To what extent can altitude diversions prevent the formation of persistent contrails based on openly available data?

The remainder of this paper is structured as follows. Section II presents the necessary background information about the OpenSky Network, ADS-B, and meteorological data. Section III presents the theory and methodology to estimate the localization of persistent contrails and to mitigate them with altitude diversions, and Section IV provides the analyses for contrail formation and mitigation potential through altitude diversions. Section V suggests some further research questions and room for future analyses before we conclude in Section VI.

II. Data sources for flights and meteorology

A. The OpenSky Network

The OpenSky Network is a crowdsourced sensor network that gathers surveillance data for air traffic control (ATC) purposes. Its primary aim is to provide the public access to real-world ATC data and to facilitate advancing and enhancing ATC technologies and processes. Since 2013, the network has been continuously collecting air traffic surveillance data. In contrast to commercial flight tracking networks like Flightradar24 or FlightAware, the OpenSky Network preserves the original Mode S replies received by the sensors in a vast historical database, which researchers and analysts from various fields can access.

Initially, the network consisted of eight sensors located in Switzerland and Germany. Today, it has grown to encompass over 6,000 registered receivers situated worldwide. As of 2024, OpenSky's dataset contains over 10 years of ATC communication data. While the network initially focused solely on ADS-B, it expanded its data range to include the complete Mode S downlink channel in March 2017. Recently, it incorporated other technologies such as FLARM [18] and VHF. The dataset currently comprises more than 35 trillion Mode S replies.

Figure 1 displays the growth and evolution of the network in recent years, which involved the inclusion of dump1090 and Radarcape feeding solutions, as well as the integration of non-registered, anonymous receivers. However, this practice was discontinued in early 2019 to ensure the consistent quality of the feeder data. In March 2020, the number of daily flights decreased by approximately 30% compared to previous levels, reflecting the reduction in air travel worldwide caused by the COVID-19 pandemic. The processing of messages received by the OpenSky Network has been refined to avoid the replication of similar messages received by different receivers, resulting in an artifact that could confuse the reader into thinking that traffic volume did not return to pre-pandemic levels.

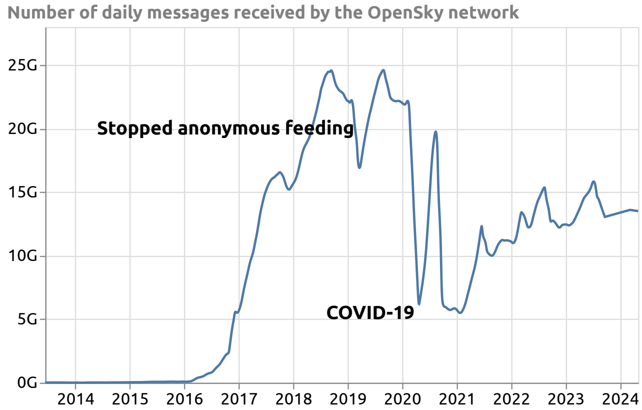

Fig. 1: Daily messages received by OpenSky over time from 2013 to 2024

The global data reception of the OpenSky Network relies entirely on its crowdsourced network of receivers, primarily consisting of enthusiasts, academics, and other supporting institutions. The coverage provided by each individual sensor is limited by the range of the antennas' line of sight, typically around 400–500 km for the best-performing antennas that reach the radio horizon. The main areas of organic growth of any such crowdsourced network effectively serve as a proxy for densely populated and wealthier regions worldwide. Between 2018 and 2024, the network's global coverage (see Fig. 2) reached a saturation point that is typical of most crowdsourced networks, with most new sensors significantly enhancing reception at lower altitudes in areas already covered in Europe, the US, and other developed countries. However, notable coverage expansions can still be observed in the Middle East, South Asia, and New Zealand.

In addition to the payload of each Mode S down link transmission, OpenSky also stores supplementary metadata. This metadata includes precise timestamps (suitable for multilateration), receiver location, and signal strength, depending on the receiver hardware. For further details on the history, architecture, and use cases of OpenSky, please refer to [2], [19], [20], [21] or visit the website at https://opensky-network.org.

B. Space-based ADS-B

Geographical regions such as deserts and oceans lack ground-based coverage due to physical constraints. To address this limitation, commercial ADS-B providers partially rely on space-based ADS-B and ADS-C data. With space-based ADS-B, a constellation of low-altitude satellites attempts to receive and decode ADS-B messages from aircraft in the troposphere and forward positional information to ground-based stations.

Automatic Dependent Surveillance–Contract (ADS-C) also uses satellite links to overcome communication limitations in remote areas, allowing aircraft to share data with Air Traffic Services Units (ATSUs) through negotiated agreements. Unlike ADS-B, which broadcasts to all, ADS-C messages are exclusively sent to the ATSUs involved in the specific contract. Each ADS-C report includes essential information like aircraft position, time, and precision level, with advanced reports containing additional data outlined in the contract. The

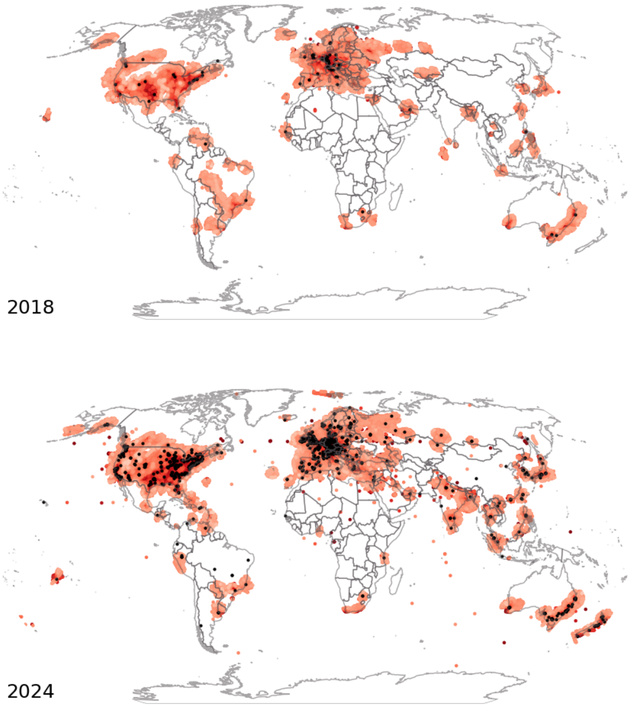

Fig. 2: OpenSky's global coverage in 2018 and 2024

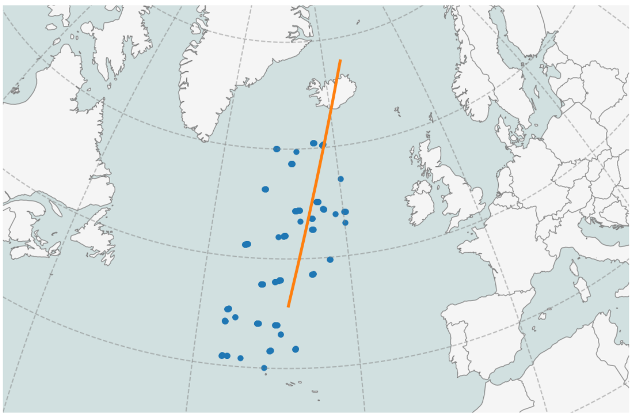

Fig. 3: Example of the satellite trajectories on March 1st, 2022, together with observed ADS-B flight data within 5 minutes.

OpenSky Network is also in the process of collecting and integrating ADS-C data, with the first pilot projects underway and limited data already available [22].

In this paper, we benefit from ADS-B satellite data collected in March 2022 by a constellation of Spire satellites following various orbits (equatorial, sun-synchronous, 37 degrees, 51.6 degrees, and 83/85 degrees inclination). Figure 3 shows the trajectory of one of those satellites during a short interval of 5 minutes (in orange) together with the trajectories of a number of aircraft flying eastbound. In practice, every aircraft is seen by a satellite during an interval of about 1 minute before being out of range of the satellite. Even with a constellation of many satellites, necessary to adequately cover a large area such as the Northern Atlantic region, it is not possible to get the same granularity of trajectory data as with ground-based ADS-B.

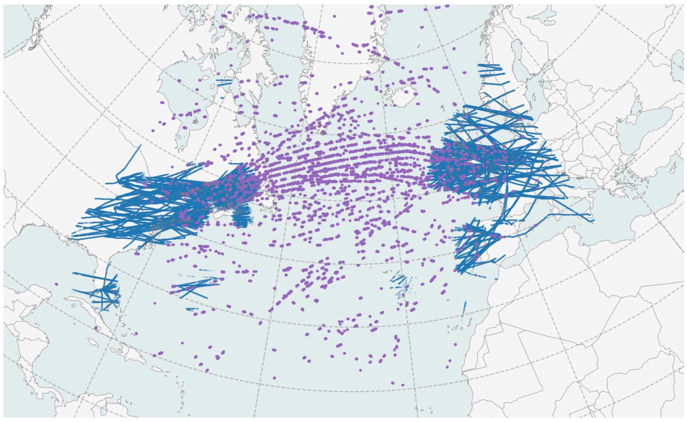

Fig. 4: An Example of ADS-B data over the Northern Atlantic region [6] (blue: OpenSky data, purple: space-based ADS-B)

Even though the trajectories we analyze over the Northern Atlantic Ocean do not benefit from the same sampling rate as we get from on-ground receivers, it is sufficient to get a clear idea of its trajectory along the North Atlantic Tracks (NAT) published on that day (Figure 4). For our analyses, we use the `traffic` library [23] to merge trajectories collected from both The OpenSky Network receivers and the Spire satellite constellation and only used the satellite data to fill the gaps over the Atlantic Ocean.

C. *Meteorological data*

Temperature and relative humidity from the meteorological data are required to estimate contrail formation and persistence. They are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 dataset [24]. The dataset has a resolution of 0.25 degrees horizontally. In this study, data below the pressure altitude of 100 hPa (approximately 53,000 ft) are used.

To facilitate easy access to the ERA5 data, a previously developed library, `fastmeteo` [17], is used to download and process the data from the Google ARCO-ERA5 data storage. The data is provided in a cloud-optimized format. This version of ERA5 converts the commonly used GRIB data files to Zarr data format, which is efficient in storing meteorological data from ERA5 as compressed N-dimensional arrays [25].

The `fastmeteo` tool also provides a fast interpolated method, which allows gigabytes of flight trajectory data to be processed in a matter of tens of seconds. The interpolation provides estimated meteorological conditions at any given position based on data from the ERA5 grid.

III. Estimation and Mitigation of Contrails

A. *Estimation of persistent contrails*

Generally, contrails form at low temperatures (-40 °C) and high relative humidity conditions [13]. The specific atmospheric conditions are governed by the Schmidt-Appleman criterion (SAC) [26]. When an aircraft flies through temperatures below the SAC, saturation with respect to liquid water occurs, leading to the formation of contrails.

Not all contrails affect the climate equally. When meteorological conditions satisfy the SAC, a contrail may disappear quickly. The persistence of contrail is determined by the humidity of the air. In order to allow persistent contrails to be formed, the ambient air also needs to be super-saturated with respect to ice, which means the relative humidity over ice should exceed 100%. These regions are identified as Ice Super Saturated Region (ISSR).

Much of the theory behind contrail formation used in this study is quite established and can be found in literature, such as [13] and [26]. The implementation of the SAC, ISSR, and determination of persistence of contrails based on flight data and meteorological data are described in detail in [17]. Figure 5 below shows an example of determining the conditions of persistent contrails under an example pressure (here 240 hPa).

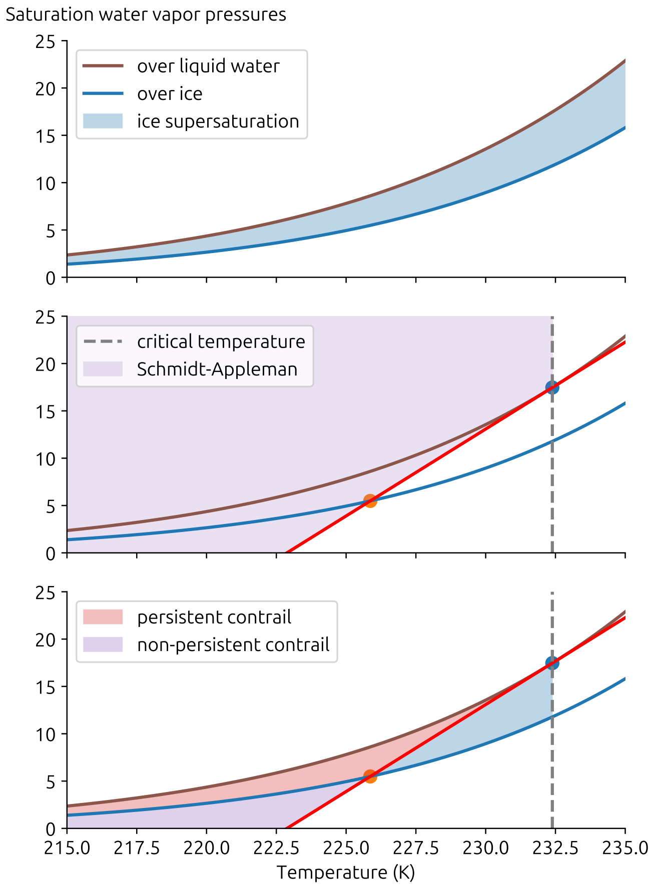

Fig. 5: Contrail forming criteria including the determination of SAC thresholds and ISSR conditions at an example given pressure condition.

To briefly explain our inference process, the meteorological information for all flights over the year 2022 is first estimated from the ERA5 data using the aforementioned `fastmeteo` tool. Then, the SAC and ISSR conditions associated with each data point are determined based on temperature and humidity information. We estimate whether persistent contrails could form at each data point along the trajectory with these two criteria. We only consider segments containing persistent contrail for more than three minutes in the analysis.

In Figure 6, we illustrate an example flight and different contrail formation conditions along the trajectory. We can see

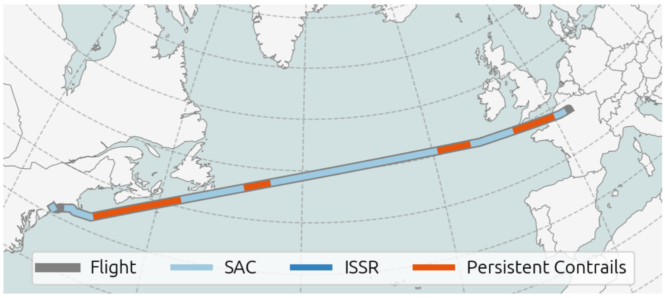

Fig. 6: Contrail formation conditions at the original altitude of an example flight on 10 January 2022, determined based on the meteorological data from ERA5. In this example, ISSR conditions and persistent contrails overlap with unnoticeable differences.

a vast majority of the flight satisfies the Schmidt-Appleman criterion due to the cold temperatures. However, only sections of the trajectory experience ice supersaturation, which would theoretically allow for persistent contrail formation.

B. Altitude diversions

Following the flight altitude-based contrail mitigation strategy proposed in [10], we conduct a large-scale study to determine whether small altitude diversions would help mitigate some contrails in the region of interest. The percentage of persistent contrail that could have been avoided is also studied.

The choice of the altitude diversion range is aligned with [10], within 2,000 ft from the original altitude. This diversion is assumed to be within the performance allowance of these flights. Furthermore, it has been approved to cause marginal safety risk and minor changes in fuel consumption by [10].

Eight alternative altitudes (separated by steps of 500 ft) are considered to avoid the persistent contrails. At these different

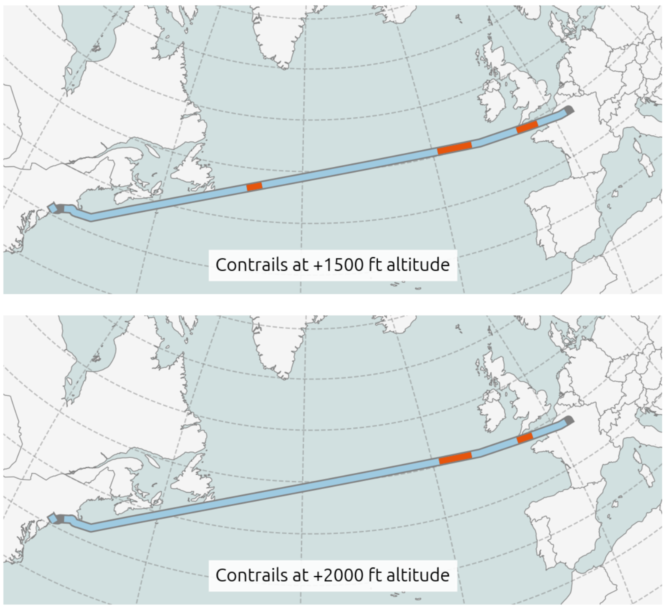

Fig. 7: Potentially contrail mitigation strategy and results at two different flight altitudes. In both cases, ISSR conditions and persistent contrails mostly overlap.

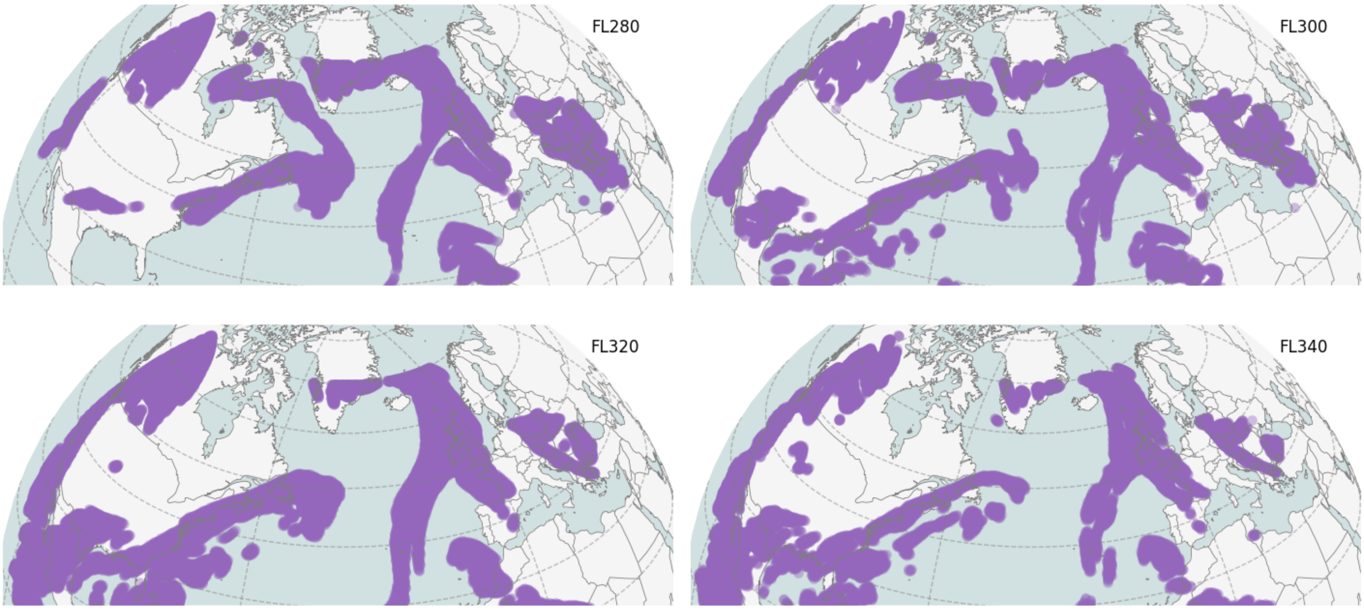

Fig. 8: Regions prone to the formation of persistent contrails on 10 January 2022 at 08:00 UTC

flight altitudes, the contrail formation and persistent criteria (SAC and ISSR) are evaluated, and the minimum deviation that prevents the persistent contrail is obtained for each trajectory point (sampled at 30 seconds). If there is no available alternative altitude for the data point, the original altitude is maintained, and we consider the contrail cannot be avoided with reasonable altitude diversions.

Based on the example from Figure 6, we show the example of potential mitigation at two different alternative altitudes in Figure 7. Based on the persistent contrail distance indicated in orange, the total contrails created by this flight could have been significantly reduced at these new altitudes.

IV. Analysis

In this section, we perform an in-depth analysis explaining the formation of contrails based on the large-scale flight data containing all flights in 2022 for Northern America, Europe, and the Atlantic regions. First, we illustrate one day of flights to show the magnitude of contrail regions. After that, we provide the overall statistics of the total distance of contrails and mitigation potentials.

A. Contrail persistent regions and the estimated contrails

Persistent contrails often form in regions with higher humidity and lower temperatures. Figure 8 illustrates the regions prone to persistent contrail formations at 08:00 UTC on 10 January 2022. In this figure, most of the regions are located in the coastal areas of North America and Europe, with examples of four different altitudes. Knowing these regions at all altitudes, we can infer the segments of flight that could have produced contrails. The calculations are optimized as the computation can be fully vectorized. As a result, Figure 9 shows estimated contrail formation over the entire region for a single day: all flight trajectories over this day are drawn in blue, and persistent contrails are illustrated in red.

The contrail persistent regions change over the course of a day and differ from other days. However, for this example day, if we compare Figure 8 and 9, we can see a general alignment between contrail formation regions (in purple) and the portions of the flights (in red) with persistent contrails.

B. Total contrail distance over the one year

To better understand the statistics of contrails over the entire year, we apply the same process to flights all year. We then group the distance statistics by month to provide an aggregated overview of potential contrail distances.

In Figure 11, we illustrated these statistics in bar charts. Each line of bars shows the monthly total distance (in gray), segments in SAC regions (in light blue), segments with ice supersaturation (in dark blue), and segments determined to have formed persistent contrail (in orange). Note that all colored bars start at zero and partially overlap in each line.

It is also worth noting that the accuracy of calculated flight distance depends on the coverage of the OpenSky network. We employed algorithms to reconstruct complete flight trajectories containing gaps of less than six hours, including most transatlantic flights. Nevertheless, there is a small portion of incomplete trajectories and missing flights in the data.

C. Altitude diversion for reducing persistent contrails

The contrail-sensitive regions usually have a shallow depth. This provides a convenient way to mitigate the contrails vertically without diverting from the original flight paths. In this study, we calculated vertical diversion possibilities for all flights in 2022 in the region of interest.

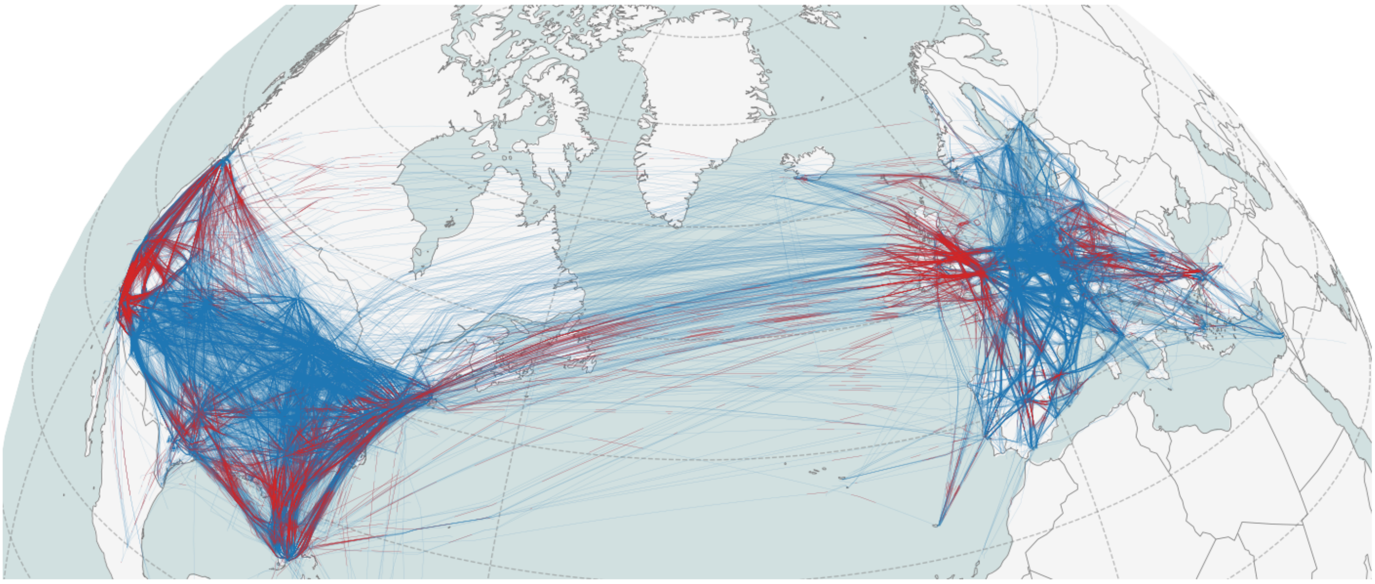

Fig. 9: The formation of persistent contrails over Europe and the United States for all flights on 10 January 2022 (blue: flight trajectories, red: persistent contrails)

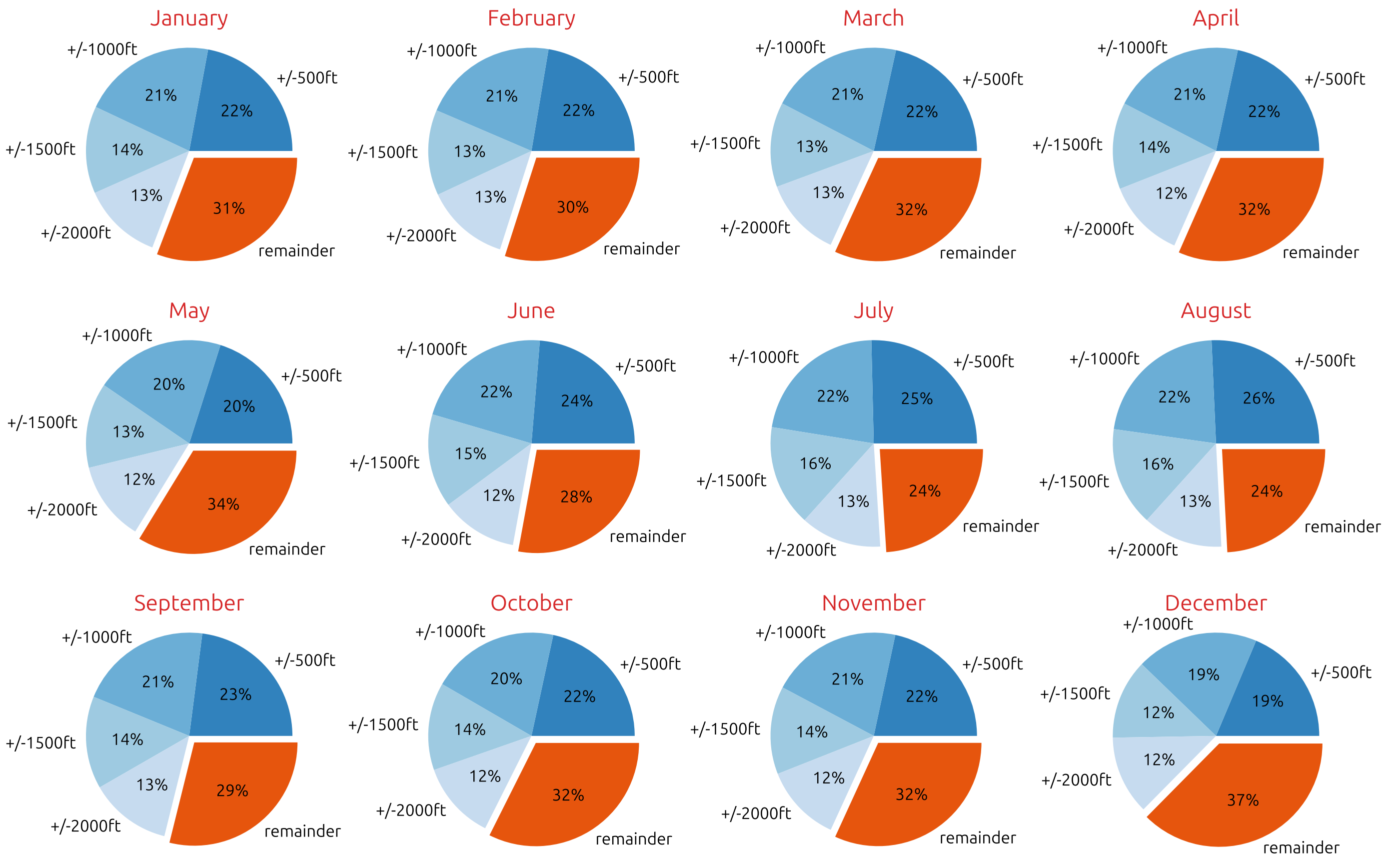

Fig. 10: The percentage of contrails that could have been prevented with altitude diversions over the months of 2022

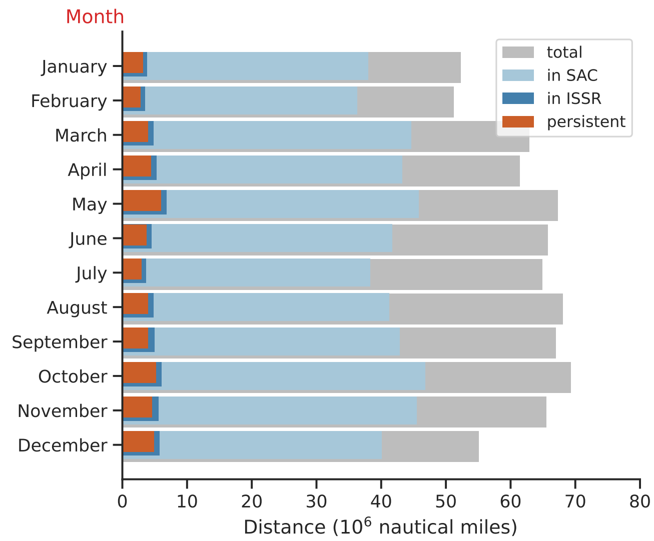

Fig. 11: Total flight distance and portions that are related to different contrail forming conditions for all the months in 2022

Figure 10 shows the altitude diversion necessary to avoid creating persistent contrails following the methodology presented in III-B. The reductions in persistent contrails in percentages are calculated and grouped by diverted altitudes. Across the 12 months, we can see that around 70% of the persistent contrails can be mitigated with an altitude diversion of less than or equal to 2,000 ft (FL20). In other words, only about 30% of persistent contrails cannot be avoided by applying altitude diversions commonly applied in our current airspace structure. We can also see more contrail mitigation potential in the summer months, reflected by the lower percentage of unavoidable contrails. This can be related to ISSRs being thinner in the summer, caused by seasonal changes in the tropopause and temperature [27].

Table I provides a quantitative overview of the contrail distance and mitigation potentials for the months of 2022. This number reflects the illustration from Figure 11 and Figure 10. The distances are rounded to 1,000 nautical miles in this table. In the contrail column, we can observe that between 5% and 9% of the total flight trajectories are estimated to have produced persistent contrails.

It is worth noting that Table I records the flight distance through the contrail-forming regions. However, only segments larger than three minutes are considered to avoid outliers. This way of counting contrails is also why the numbers do not strictly add up to 100% of the total flight distance.

D. Contrails in the North Atlantic region

Due to the limited receiver coverage over the Atlantic, the reconstructed trajectories from OpenSky differ from the actual flight trajectories. We can observe that in Figure 9, not all strictly follow the North Atlantic Track system (by more than the Standard Lateral Offset Procedure distances). To closely study the formation of the contrails, space-based flight data from Spire has been used to reconstruct the actual tracks over the North Atlantic region. Figure 12 shows more accurate positions of a subsample of flights in March 2022, containing flights departing and arriving at the coasts of Europe and North America.

Based on the visual inspection of this month's trajectory data, the North Atlantic Organised Track System can be clearly observed in the figure. Using the same methodology proposed earlier, we analyze the formation of contrails and study the potential of mitigation with minimum altitude alteration of existing tracks (trajectories).

Figure 13 shows the different contrail formation statistics between trajectories reconstructed from only OpenSky data and trajectories reconstructed with Spire data in March 2022. We can see a slight underestimation of contrails with only OpenSky data. The number of flights differs because only flights between the coasts are included in the space-based subsample, and hence, the percentage of contrail distances is shown in the figure. Overall, persistent contrails count for around 5% and 6% of the total flight distance in these two subsets of data.

Similarly, based on the more accurate trajectories that include space-based ADS-B observations, we have performed the same altitude diversion strategy to study the contrail mitigation

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

	Total distance	Contrail	+/-500ft	+/-1000ft	+/-1500ft	+/-2000ft	remainder
January	523,229,000	32,041,000 [6%]	-6,459,000 (-22%)	-6,129,000 (-21%)	-3,997,000 (-14%)	-3,669,000 (-13%)	9,022,000 (31%)
February	512,474,000	28,071,000 [5%]	-5,799,000 (-22%)	-5,505,000 (-21%)	-3,475,000 (-13%)	-3,404,000 (-13%)	7,766,000 (30%)
March	628,990,000	39,601,000 [6%]	-7,831,000 (-22%)	-7,581,000 (-21%)	-4,821,000 (-13%)	-4,548,000 (-13%)	11,584,000 (32%)
April	614,694,000	44,673,000 [7%]	-8,806,000 (-22%)	-8,477,000 (-21%)	-5,534,000 (-14%)	-5,057,000 (-12%)	12,889,000 (32%)
May	672,770,000	59,662,000 [9%]	-10,872,000 (-20%)	-11,017,000 (-20%)	-7,216,000 (-13%)	-6,738,000 (-12%)	18,260,000 (34%)
June	657,438,000	37,515,000 [6%]	-8,066,000 (-24%)	-7,404,000 (-22%)	-4,991,000 (-15%)	-4,083,000 (-12%)	9,490,000 (28%)
July	649,078,000	29,365,000 [5%]	-6,777,000 (-25%)	-5,903,000 (-22%)	-4,234,000 (-16%)	-3,391,000 (-13%)	6,409,000 (24%)
August	681,109,000	40,032,000 [6%]	-9,338,000 (-26%)	-8,031,000 (-22%)	-5,647,000 (-16%)	-4,548,000 (-13%)	8,788,000 (24%)
September	670,247,000	39,792,000 [6%]	-8,320,000 (-23%)	-7,555,000 (-21%)	-5,249,000 (-14%)	-4,645,000 (-13%)	10,459,000 (29%)
October	692,919,000	52,276,000 [8%]	-10,279,000 (-22%)	-9,528,000 (-20%)	-6,525,000 (-14%)	-5,824,000 (-12%)	15,414,000 (32%)
November	655,203,000	46,078,000 [7%]	-9,143,000 (-22%)	-8,695,000 (-21%)	-5,813,000 (-14%)	-5,140,000 (-12%)	13,450,000 (32%)
December	550,760,000	48,790,000 [9%]	-8,364,000 (-19%)	-8,580,000 (-19%)	-5,602,000 (-12%)	-5,525,000 (-12%)	16,777,000 (37%)

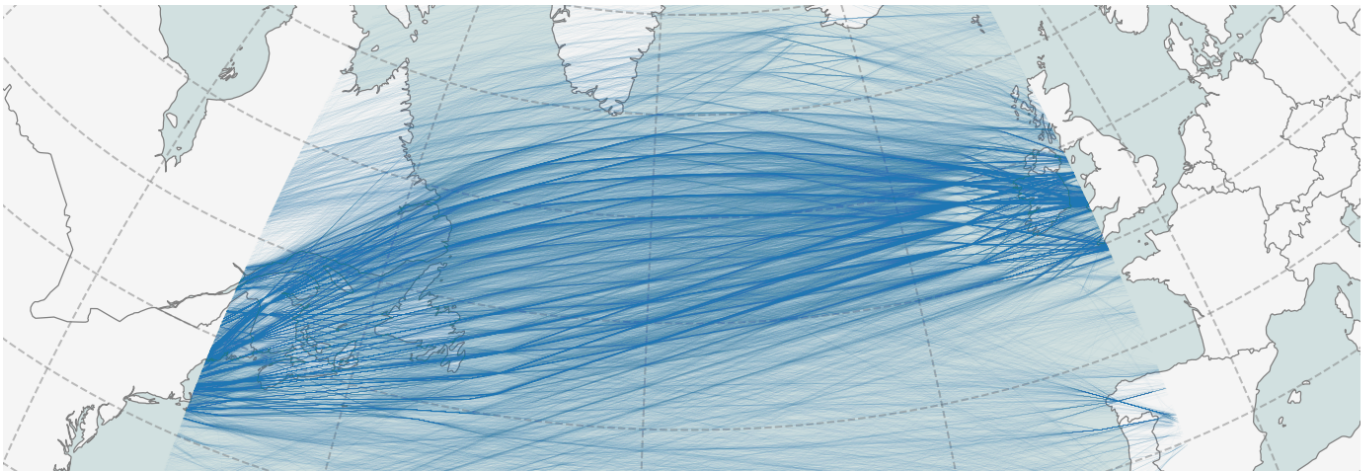

Fig. 12: One month of trajectories over the North Atlantic region, reconstructed from OpenSky and space-based ADS-B from Spire. The North Atlantic Organised Track System can be distinguished among the clusters of trajectories.

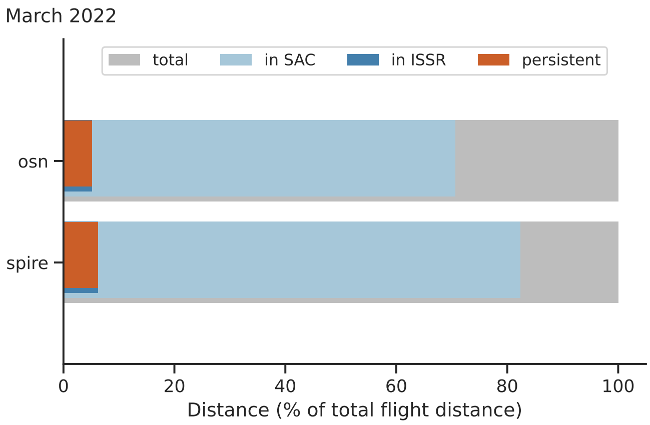

Fig. 13: Percentage of flight routes experiencing contrail forming conditions along the North Atlantic Tracks, March 2022

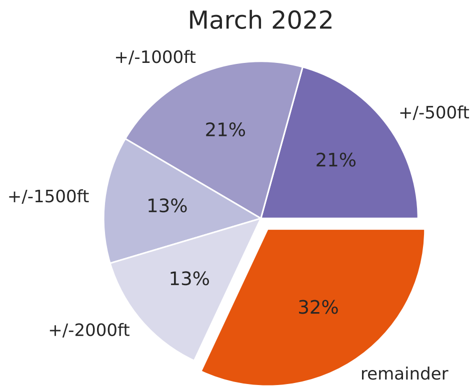

Fig. 14: Contrail reduction potential for flights along the North Atlantic Tracks, March 2022. Based on trajectories reconstructed with space-based ADS-B data from Spire.

potential. The result is shown in Figure 14. When comparing the results from Figure 10, we can see that the statistics over the Atlantic Ocean agree with the statistics in March for the entire region in this study.

V. Discussion

A. *Selection and processing of flight data*

For the analysis of this paper, we make use of the *state vector* data from the OpenSky from the regions of the world with the heaviest air traffic. All flights within the United States, Europe, and between the United States and Europe are extracted for analysis in this paper. To extract data efficiently, we first use the aggregated flight lists from OpenSky to identify the flights with corresponding departure and destination airports within these regions. When flights are reconstructed, only those longer than 30 minutes are kept for analysis.

For transatlantic flights, large sections of the flight trajectories over the Atlantic may be missing due to limited ground coverage. An algorithm is developed to reconstruct the full trajectory by considering the time gap in data segments (less than six hours) and the aircraft identifiers. This way, the flight states in the missing parts of trajectories during the cruise are linearly extrapolated. This linear extrapolation may not fully align with the actual trajectory and can cause some uncertainties in contrail estimation. Besides space-based ADS-B data (often proprietary and only commercially available), open ADS-C data gathered by OpenSky [22] would potentially mitigate this shortcoming in data gaps in the future.

Ample attention is also paid to data processing. Since many flights span over two days, we extract the flight based on its starting time (the first time observed by OpenSky receivers), and we generate a daily dataset based on the starting time of flights. This way, no flights are counted twice. We can also ensure small segments (less than 30 minutes) of flights before or after UTC 00:00 are discarded in the analysis. Lastly, based on the `traffic` library, all flights are sampled at 30-second intervals to provide a consistent resolution for the analysis.

B. Safety and emission considerations

One of the main debates in the aviation sustainability community is the trade-off between contrail avoidance and potentially induced fuel consumption and carbon emissions. Furthermore, contrails should never be avoided at the cost of hindering air traffic's safety in terms of minimal separation.

We chose not to proceed with the safety analysis based on the results obtained in an early study [10], where the potential loss of separation induced by altitude diversion with coordination is in the magnitude of single digits. The minimum safe separation area is 1,000 ft vertical separation and 5 nm in the horizontal plane. This means there is almost no extra workload for air traffic controllers to solve extra conflicts.

From the same study [10], we also concluded that the excess emission is marginal, which is between 0.25% and 2%, considering the uncertainty in aircraft mass. This also agrees with previous studies like [28], [29]. Hence, in this study, we only focused on the potential of contrail mitigation, assuming marginal and acceptable trade-offs for emissions and safety.

C. Limitations

This study relies on the theoretical model to determine the formation and persistence of the contrails, especially the Schmidt-Appleman criterion. The model relies on some engine performance assumptions, which could lead to inaccuracy and uncertainty in the contrail formation.

The persistent contrail is closely related to the estimation of ice super-saturated regions. To obtain these in the chosen airspace, we rely on information from the ECMWF ERA5 data, which contains temperature and humidity and is assimilated from different data sources. The inherent accuracy and bias could affect the estimation of ISSR and the persistent contrails based on flight data. The data assimilation tends to smoothen out original measurements at a larger spatial and temporal scale. The local variation can be missing from this data. To further validate the estimated control, satellite remote sensing-based techniques could be employed on a large scale to cross-validate our estimations.

Furthermore, as contrails are not stationary, the dispersion and transformation of contrails into cirrus clouds have additional impacts on the climate. These are not the focus of this paper, which is focused on estimating the persistent contrail at the formation based on available flight and meteorological data.

VI. Conclusion

This paper presents a new use case for large-scale ADS-B data gathered by the OpenSky Network.

We present an analysis of the formation of potential persistent contrails from flights carried out in 2022 for Northern America, Europe, and the Atlantic regions. The entire year of state vector data is obtained and used for this analysis, together with ERA5 meteorological data from ECMWF. Our analysis shows that each month, between 5% and 9% of the total flight trajectories could have produced persistent contrails, which count for quite significant total contrail distances.

Mitigation strategies focused on altitude diversion are also examined in this paper. A significant portion of contrails can be mitigated by allowing flights to divert from their original altitude by a maximum of 20 flight levels. In summary, around 70% of persistent contrails are avoidable with an altitude change of less than or equal to 2,000 ft. This would significantly reduce the total contrail distance to around 2% of the total flight distance.

One month of space-based ADS-B data from Spire in the Atlantic region is used to more accurately examine the contrail formation and mitigation in the region where OpenSky lacks coverage. We find a small underestimation of contrail formations without the space-based data.

Since we mainly focus on the use case of OpenSky data in this paper, we also acknowledge some limitations, including the reliance on theoretical models, which could differ from actual flight conditions. Additionally, estimating ice super-saturated regions relies on ECMWF ERA5 data, which may contain inherent accuracy and bias issues. Despite these limitations, our study provides a valuable contribution to the understanding of contrail formation and mitigation through an open large-scale flight data drive approach, which could benefit the ongoing research and debates on flight contrails and the magnitude of their climate impact.

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References

[1] M. Schäfer, M. Strohmeier, V. Lenders, I. Martinovic, and M. Wilhelm, "Bringing up OpenSky: A large-scale ADS-B sensor network for research," in *Proceedings of the 13th International Symposium on Information Processing in Sensor Networks*, 2014, pp. 83–94.

[2] J. Sun, L. Basora, X. Olive, M. Strohmeier, M. Schäfer, I. Martinovic, and V. Lenders, "OpenSky Report 2022: Evaluating aviation emissions using crowdsourced open flight data," in *Proceedings of the 40th Digital Avionics Systems Conference*, Sep. 2022.

[3] J. Sun, X. Olive, and M. Strohmeier, "Environmental Footprint of Private and Business Jets," in *Proceedings of the 10th OpenSky Symposium*, Delft, The Netherlands, Dec. 2022. doi: 10.3390/engproc2022028013

[4] R. Dalmau, P. Very, and G. Jarry, "On the causes and environmental impact of airborne holdings at major european airports," *Journal of Open Aviation Science*, vol. 1, no. 2, 2023. doi: 10.59490/joas.2023.7198

[5] H. Hardell, T. Polishchuk, and L. Smetanová, "Investigation of point merge utilization worldwide using OpenSky Network data," *Journal of Open Aviation Science*, vol. 1, no. 2, 2023. doi: 10.59490/joas.2023.7218

[6] J. Sun, A. Tassanbi, P. Obojski, and P. Plantholt, "Evaluating transatlantic flight emissions and inefficiencies using space-based ADS-B data," in *Proceedings of the 13th SESAR Innovation Days, Sevilla, Spain*, Dec. 2023. doi: 10.61009/SID.2023.1.41

[7] A. Salgas, J. Sun, S. Delbecq, T. Planès, and G. Lafforgue, "Compilation of an open-source traffic and CO2 emissions dataset for commercial aviation," *Journal of Open Aviation Science*, vol. 1, no. 2, 2023. doi: 10.59490/joas.2023.7201

[8] R. Chevallier, M. Shapiro, Z. Engberg, M. Soler, and D. Delahaye, "Linear contrails detection, tracking and matching with aircraft using geostationary satellite and air traffic data," *Aerospace*, vol. 10, no. 7, 2023. doi: 10.3390/aerospace10070578

[9] E. Roosenbrand, J. Sun, and J. Hoesktra, "Contrail altitude estimation based on shadows detected in landsat imagery," in *Proceedings of the 13th SESAR Innovation Days, Sevilla, Spain*, Dec. 2023. doi: 10.61009/SID.2023.1.06

[10] E. Roosenbrand, J. Sun, and J. Hoekstra, "Contrail minimization through altitude diversions: A feasibility study leveraging global data," *Transportation Research Interdisciplinary Perspectives*, vol. 22, Nov. 2023. doi: 10.1016/j.trip.2023.100953

[11] D. S. Lee, D. W. Fahey, P. M. Forster, P. J. Newton, R. C. Wit, L. L. Lim, B. Owen, and R. Sausen, "Aviation and global climate change in the 21st century," *Atmos. Environ.*, vol. 43, no. 22, Jul. 2009. doi: 10.1016/j.atmosenv.2009.04.024, 2009

[12] D. Lee, D. W. Fahey, A. Skowron, M. Allen, U. Burkhardt, Q. Chen, S. Doherty, S. Freeman, P. Forster, J. Fuglestvedt, A. Gettelman, R. D. León, L. Lim, M. Lund, R. Millar, B. Owen, J. Penner, G. Pitari, M. Prather, R. Sausen, and L. Wilcox, "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018," *Atmos. Environ.*, vol. 244, p. 117834, Jan. 2021. doi: 10.1016/j.atmosenv.2009.04.024, 2009

[13] U. Schumann, "On conditions for contrail formation from aircraft exhausts," *Meteorologische Zeitschrift*, vol. 5, no. 1, Mar. 1996. doi: 10.1127/metz/5/1996/4

[14] R. Teoh, U. Schumann, E. Gryspeerdt, M. Shapiro, J. Molloy, G. Koudis, C. Voigt, and M. E. Stettler, "Aviation contrail climate effects in the north atlantic from 2016 to 2021," *Atmospheric Chemistry and Physics*, vol. 22, no. 16, pp. 10 919–10 935, 2022.

[15] R. Teoh, U. Schumann, A. Majumdar, and M. E. Stettler, "Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adoption," *Environmental Science & Technology*, vol. 54, no. 5, pp. 2941–2950, 2020.

[16] A. M. Frias, M. Shapiro, Z. Engberg, R. Zopp, M. Soler, and M. Stettler, "Feasibility of contrail avoidance in a commercial flight planning system: an operational analysis," *Environmental Research: Infrastructure and Sustainability*, vol. 4, no. 1, p. 015013, 2024.

[17] J. Sun and E. Roosenbrand, "Fast contrail estimation with OpenSky data," *Journal of Open Aviation Science*, vol. 1, 2023. doi: 10.59490/joas.2023.7264

[18] X. Olive, J. Sun, M. Strohmeier, and G. Tresoldi, "OpenSky Report 2023: Low Altitude Traffic Awareness for Light Aircraft with FLARM," in *Proceedings of the 42th Digital Avionics Systems Conference (DASC)*, Barcelona, Spain, Oct. 2023. doi: 10.1109/DASC58513.2023.10311202

[19] M. Schafer, X. Olive, M. Strohmeier, M. Smith, I. Martinovic, and V. Lenders, "OpenSky Report 2019: Analysing TCAS in the Real World using Big Data," in *Proceedings of the 38th Digital Avionics Systems Conference (DASC)*, San Diego, CA, Sep. 2019. doi: 10.1109/DASC43569.2019.9081686

[20] X. Olive, A. Tanner, M. Strohmeier, M. Schäfer, M. Feridun, A. Tart, I. Martinovic, and V. Lenders, "OpenSky Report 2020: Analysing in-flight emergencies using big data," in *Proceedings of the 39th Digital Avionics Systems Conference (DASC)*, 2020. doi: 10.1109/DASC50938.2020.9256787

[21] J. Sun, X. Olive, M. Strohmeier, M. Schafer, I. Martinovic, and V. Lenders, "OpenSky Report 2021: Insights on ADS-B Mandate and Fleet Deployment in Times of Crisis," in *Proceedings of the 40th Digital Avionics Systems Conference (DASC)*, San Antonio, TX, 2021. doi: 10.1109/DASC52595.2021.9594361

[22] M. Xapelli, T. Lüscher, G. Tresoldi, M. Strohmeier, and V. Lenders, "A first look at exploiting the automatic dependent surveillance-contract protocol for open aviation research," *Journal of Open Aviation Science*, vol. 1, no. 2, 2023. doi: 10.59490/joas.2023.7229

[23] X. Olive, "traffic, a toolbox for processing and analysing air traffic data," *Journal of Open Source Software*, vol. 4, no. 39, Jul. 2019. doi: 10.21105/joss.01518

[24] H. Hersbach, B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, and I. Rozum, "ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS)," 2018.

[25] T. A. Gowan, J. D. Horel, A. A. Jacques, and A. Kovac, "Using cloud computing to analyze model output archived in zarr format," *Journal of Atmospheric and Oceanic Technology*, vol. 39, no. 4, pp. 449–462, 2022.

[26] U. Schumann, K. Graf, and H. Mannstein, "Potential to reduce the climate impact of aviation by flight level changes." *3rd AIAA Atmospheric Space Environments Conference*, 2011. doi: 10.2514/6.2011-3376

[27] K. P. Hoinka, M. E. Reinhardt, and W. Metz, "North atlantic air traffic within the lower stratosphere: Cruising times and corresponding emissions," *Journal of Geophysical Research: Atmospheres*, vol. 98, no. D12, pp. 23 113–23 131, 1993.

[28] D. Avila, L. Sherry, and T. Thompson, "Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous united states," *Transportation Research Interdisciplinary Perspectives*, vol. 2, p. 100033, 2019.

[29] B. Sridhar, N. Y. Chen, and H. K. Ng, "Fuel efficient strategies for reducing contrail formations in united states airspace," in *29th Digital Avionics Systems Conference*. IEEE, 2010, pp. 1–A.